



UNIVERSITAT DE
BARCELONA

Determinant physical factors of stroke velocity and their relationship with fatigue in young tennis players

Joshua Colomar Axup

ADVERTIMENT. La consulta d'aquesta tesi queda condicionada a l'acceptació de les següents condicions d'ús: La difusió d'aquesta tesi per mitjà del servei TDX (www.tdx.cat) i a través del Dipòsit Digital de la UB (diposit.ub.edu) ha estat autoritzada pels titulars dels drets de propietat intel·lectual únicament per a usos privats emmarcats en activitats d'investigació i docència. No s'autoritza la seva reproducció amb finalitats de lucre ni la seva difusió i posada a disposició des d'un lloc aliè al servei TDX ni al Dipòsit Digital de la UB. No s'autoritza la presentació del seu contingut en una finestra o marc aliè a TDX o al Dipòsit Digital de la UB (framing). Aquesta reserva de drets afecta tant al resum de presentació de la tesi com als seus continguts. En la utilització o cita de parts de la tesi és obligat indicar el nom de la persona autora.

ADVERTENCIA. La consulta de esta tesis queda condicionada a la aceptación de las siguientes condiciones de uso: La difusión de esta tesis por medio del servicio TDR (www.tdx.cat) y a través del Repositorio Digital de la UB (diposit.ub.edu) ha sido autorizada por los titulares de los derechos de propiedad intelectual únicamente para usos privados enmarcados en actividades de investigación y docencia. No se autoriza su reproducción con finalidades de lucro ni su difusión y puesta a disposición desde un sitio ajeno al servicio TDR o al Repositorio Digital de la UB. No se autoriza la presentación de su contenido en una ventana o marco ajeno a TDR o al Repositorio Digital de la UB (framing). Esta reserva de derechos afecta tanto al resumen de presentación de la tesis como a sus contenidos. En la utilización o cita de partes de la tesis es obligado indicar el nombre de la persona autora.

WARNING. On having consulted this thesis you're accepting the following use conditions: Spreading this thesis by the TDX (www.tdx.cat) service and by the UB Digital Repository (diposit.ub.edu) has been authorized by the titular of the intellectual property rights only for private uses placed in investigation and teaching activities. Reproduction with lucrative aims is not authorized nor its spreading and availability from a site foreign to the TDX service or to the UB Digital Repository. Introducing its content in a window or frame foreign to the TDX service or to the UB Digital Repository is not authorized (framing). Those rights affect to the presentation summary of the thesis as well as to its contents. In the using or citation of parts of the thesis it's obliged to indicate the name of the author.



UNIVERSITAT DE
BARCELONA

inefc

*DOCTORAL THESIS – HDK02 – PHYSICAL ACTIVITY, PHYSICAL
EDUCATION AND SPORT*

**DETERMINANT PHYSICAL FACTORS OF STROKE
VELOCITY AND THEIR RELATIONSHIP WITH FATIGUE IN
YOUNG TENNIS PLAYERS**

Joshua Colomar Axup

2022

Thesis supervisors

Ernest Baiget Vidal, PhD

Francisco Corbi Soler, PhD

Thesis tutor

Xavier Iglesias Reig, PhD

Ernest Baiget Vidal, PhD, National Institute of Physical Education (INEFC), University of Barcelona (UB), Barcelona, Spain. Declares:

The doctoral thesis entitled: “***Determinant physical factors of stroke velocity and their relationship with fatigue in young tennis players***” presented by Joshua Colomar Axup to obtain a doctoral degree has been completed under my supervision and meets the technical and rigorous requirements in order to be presented.

I hereby sign this document,

Signature

Barcelona, March 2022

Francisco Corbi Soler, PhD, National Institute of Physical Education (INEFC), University of Lleida (UdL), Lleida, Spain. Declares:

The doctoral thesis entitled: “***Determinant physical factors of stroke velocity and their relationship with fatigue in young tennis players***” presented by Joshua Colomar Axup to obtain a doctoral degree has been completed under my supervision and meets the technical and rigorous requirements in order to be presented.

I hereby sign this document,

Signature

Barcelona, March 2022

TABLE OF CONTENTS

+ Supervisor's letters.....	3
+ List of publications.....	9
+ List of abbreviations.....	13
+ List of tables.....	15
+ List of figures.....	17
+ Acknowledgments.....	19
+ Abstract	23
+ Framework	31
+ Physical determinants of stroke velocity	37
- Technical and biomechanical approach.....	39
- Anthropometric characteristics.....	47
- Maximal dynamic isometric strength.....	49
- Power and rate of force development	52
- Muscle contractile properties.....	57
- Range of motion.....	59
+ Training methods for stroke velocity enhancement	63
- Conventional eccentric and concentric resistance training.....	65
- Plyometrics, SSC enhanced and stroke specific training.....	67
- Flywheel-based training.....	71
- Complex training.....	72
+ Influence of training and competition-induced fatigue on determinants of stroke velocity	75
+ Aims and hypothesis	81
+ Methods	85
+ Publications	89
- Study 1.....	90
- Study 2.....	100
- Study 3.....	124
- Study 4.....	142
- Study 5.....	156
- Study 6.....	182
- Study 7.....	196
- Study 8.....	222
+ Discussion	255
+ Conclusions	277
+ Limitations and future research	281
+ References	283



LIST OF PUBLICATIONS

All studies presented in the corresponding section that are open access publications are shown in their original format. Studies still pending acceptance or under review are shown in a format similar to the requested by the selected journal. Studies are presented in a specific order following the main objectives of this thesis and not necessarily in chronological order.

STUDY 1

Influence of strength, power, and muscular stiffness on stroke velocity in junior tennis players.

Citation:

Colomar J, Baiget E, Corbi F. Influence of Strength, Power, and Muscular Stiffness on Stroke Velocity in Junior Tennis Players. *Front Physiol.* 2020;11:196. Published 2020 Mar 6.

doi:10.3389/fphys.2020.00196

Journal information:

Frontiers in Physiology

ISSN: 1664-042X

Category: Physiology

Impact Factor: 4.566

Quartile: Q1

STUDY 2

Relationship between isometric force-time variables and serve velocity in young tennis players.

Citation:

Colomar J, Baiget E, Corbi F. 2022. Relationship between isometric force-time variables and serve velocity in young tennis players. Sports Biomechanics. [Under review].

doi: -

STUDY 3

Alterations in mechanical muscle characteristics and postural control induced by tennis match-play in young players.

Citation:

Colomar J, Corbi F, Baiget E. 2021. Alterations in mechanical muscle characteristics and postural control induced by tennis match-play in young players. PeerJ 9:e11445.

doi: 10.7717/peerj.11445

Journal information:

PeerJ

ISSN: 2167-8359

Category: Multidisciplinary sciences

Impact Factor: 2.984

Quartile: Q2

STUDY 4

Inter-limb muscle property differences in junior tennis players.

Citation:

Colomar J, Corbi F, Baiget E. 2022. Inter-limb muscle property differences in junior

tennis players. Journal of Human Kinetics [published in press].

doi: 0.2478/hukin-2022-0026

Journal information:

Journal of Human Kinetics

ISSN: 1640-5544

Category: Sport Sciences

Impact Factor: 2.193

Quartile: Q3

STUDY 5

Force-time curve variable outcomes following a simulated tennis match in junior players.

Citation:

Colomar J, Baiget E, Corbi F. 2022. Force-time curve variable outcomes following a simulated tennis match in junior players. Journal of Sports Science and Medicine. [Under review].

doi: -

STUDY 6

Acute effects of in-step and wrist weights on change of direction speed, accuracy, and stroke velocity in junior tennis players.

Citation:

Colomar J, Baiget E, Corbi F, Muñoz J (2020) Acute effects of in-step and wrist weights on change of direction speed, accuracy, and stroke velocity in junior tennis players. PLOS ONE 15(3): e0230631.

doi: 10.1371/journal.pone.0230631

Journal information:

PLoS One

ISSN: 1932-6203

Category: Multidisciplinary sciences

Impact Factor: 3.240

Quartile: Q2

STUDY 7

Improving serve velocity in the young tennis player. Program design and training.

Citation:

Colomar J, Baiget E, Corbi F. 2022. Improving serve velocity in the young tennis player. program design and training. Strength and Conditioning Journal. [Under review].

doi: -

STUDY 8

Determinant physical factors of tennis serve velocity. A brief review

Citation:

Colomar J, Baiget E, Corbi F. 2022. Determinant physical factors of tennis serve velocity. A brief review. Journal of Strength and Conditioning Research. [Under review].

doi: -

LIST OF ABBREVIATIONS

- SV** – Serve velocity
- ROM** – Range of motion
- GRF** – Ground reaction forces
- BH** – Body height
- BM** – Body mass
- BMI** – Body mass index
- MDS** – Maximal dynamic strength
- MIS** – Maximal isometric strength
- SHIR** – Shoulder internal rotation
- SHF** – Shoulder flexion
- SHE** – Shoulder extension
- SHER** – Shoulder external rotation
- SHABD** – Shoulder horizontal abduction
- SHADD** – Shoulder horizontal adduction
- RFD** – Rate of force development
- IMP** – Impulse
- PRFD** – Peak rate of force development
- SSC** – Stretch-shortening cycle
- MBT** – Medicine ball throw
- CMJ** – Countermovement jump
- IMTP** – Isometric mid-thigh pull
- WRF** – Wrist flexion
- RM** – Repetition maximum
- GIRD** – Glenohumeral internal rotation deficit
- PAPE** – Post-activation potentiation enhancement
- ITN** – International Tennis Number
- SJ** – Squat jump
- MVC** – Maximal voluntary contraction



LIST OF TABLES

Table 1 - Segment contribution (%) to racquet velocity.

Table 2. Isometric force-time curve variables included in the stepwise multiple regression analysis to explain the variance on mean SV.



LIST OF FIGURES

- Figure 1A** – Stages of the tennis serve and technical determinants of velocity. A = loading; B = cocking. Adapted from Kovacs and Ellenbecker (2011).
- Figure 1B** - Stages of the tennis serve and technical determinants of velocity. C = acceleration; D = impact. Adapted from Kovacs and Ellenbecker (2011).
- Figure 2** – Segment angular velocity differences between elite and high-performance players. Adapted from Landlinger et al., (2010).
- Figure 3** – A = Closed stance one-handed backhand; B = Open stance two-handed backhand. Adapted from Roetert et al., (2009).
- Figure 4** – Height of the ball impact during serve.
- Figure 5** – Maximal isometric strength (MIS) testing of relevant serve motion joint positions
- Figure 6** – Force-time curve variables. Adapted from Baiget et al., (2021).
- Figure 7** – Medicine ball throw (MBT) testing.
- Figure 8** – Serve kinetic chain. Adapted from Kovacs and Ellenbecker (2011).
- Figure 9** – Elbow and shoulder ROM during serve.
- Figure 10** – Trunk rotation and upper arm rotation differences in one-handed and two-handed backhands. Adapted from Genevois et al., (2015).
- Figure 11** – Diagram of main physical determinants of tennis serve velocity.
- Figure 12** – Traditional resistance training exercise examples.
- Figure 13** – Plyometric-based training program example.
- Figure 14** – Power-based training program examples.
- Figure 15** – Flywheel-based resistance training exercise examples.
- Figure 16** – Complex training setting example.
- Figure 17** – Goal and study synthesis of the project.
- Figure 18** – Multiple regression analysis including fitness characteristics variables and relation to SV. Adapted from Fett et al., (2020).
- Figure 19** – Importance of the inclusion of upper and lower body joint positions in force-time curve testing for stroke velocity assessment.
- Figure 20** - Quadrant chart showing relationship between SHIR and IMTP values of players that serve above and below group average SV.
- Figure 21** - Mechanical muscle property measurement in relaxed state.
- Figure 22** - Generally unaltered measures of stiffness from pre to post 80-minute

simulated match play. Bold line is group mean values.

Figure 23 - Mechanical muscle property differences between dominant and non-dominant limbs (n = 34). A = stiffness; B = tone; C = elasticity; D = time to relaxation.

Figure 24 - Pre- and post-match measurements of RFD at different time intervals at different joint positions. IR90° = shoulder internal rotation; ER90° = shoulder external rotation; ADD = shoulder horizontal adduction; ABD = shoulder horizontal abduction; ES = effect size.

Figure 25 - Light wrist weights ranging 50 to 200 g used in study 6.

- All figures are authors own work or have the pertinent permissions to be reproduced.

ACKNOWLEDGEMENTS

Unas palabras a todos aquellos y aquellas que me han acompañado y ayudado en este proceso;

Als meus directors de tesi, no se m'acudeixen dues millors persones per guiar-me en aquest camí.

Al Dr. Ernest Baiget. Des del primer dia que et vaig proposar iniciar aquest procés tot han estat facilitats i confiança. A banda del referent professional que ets, si d'alguna manera hem puc considerar investigador o docent és en gran mesura a tot el que m'has transmès. Moltíssimes gràcies per tot.

Al Dr. Francesc Corbi, per la teva capacitat resolutiva, la predisposició a oferir-me ajuda sense dubtes i el teu coneixement i professionalitat. El teu suport ha anat molt més enllà del que podia imaginar.

Gràcies als dos per tant.

A mis compañeros/as y amigos/as de la Academia Sánchez-Casal. Sin vuestra ayuda habría sido imposible. Gracias por tantas charlas, tanto aprendizaje sin saberlo, tantas discusiones y tantos momentos. Miquel, Jordi, Gina, Martina, Víctor, Sergi's, Fernando, Adrián, Carla, Sara, Joel, Pol...De todos y todas he aprendido y disfrutado cada minuto.

Al Marcel·lí Massafret. Aquest treball no existiria sense el teu inestimable suport. Ets un referent i el 'pare' professional de molts de nosaltres, però per sobre de tot ets una gran persona i un amic. Per sempre agraït.

A Ferran, Joshua y Rubén. No habéis sido solo acompañantes en este viaje, si no amigos y pilares esenciales en mi vida. No cabe en mil hojas el agradecimiento que

os debo. Gracias eternas por todo, compañeros.

A todos los entrenadores, jugadores y profesionales de la Academia Sánchez-Casal sin los que habría sido imposible llevar a cabo este proyecto. Gracias por la predisposición a adaptar horarios, cambiar entrenamientos, utilizar instalaciones y material sin dudarlo.

A la Universitat de Vic, peça clau del meu aprenentatge i creixement aquests últims anys. Però sobre tot als professionals que estic tenint la sort de conèixer. Esperem que això sigui punt de partida de projectes i vivències. Agraït de que s'hagin creuat els nostres camins.

A mis amigos Pau, Xavi, Nico, Juan Carlos, Dani, Cacus...no sabéis lo importantes que son nuestras quedadas y esos fines de semana que dan la vida. Gracias por ser la mejor compañía y distracción, por todos los momentos y los que faltan por llegar.

A Laura. Estas páginas existen en gran medida por ti. Por encima de todo, gracias por el tiempo que nos regalamos.

A mi familia, a los que están y a los que siempre nos acompañaran. A mis primos, primas, tíos, tías, cuñado. To my aunties and cousins... *Family is everything.*

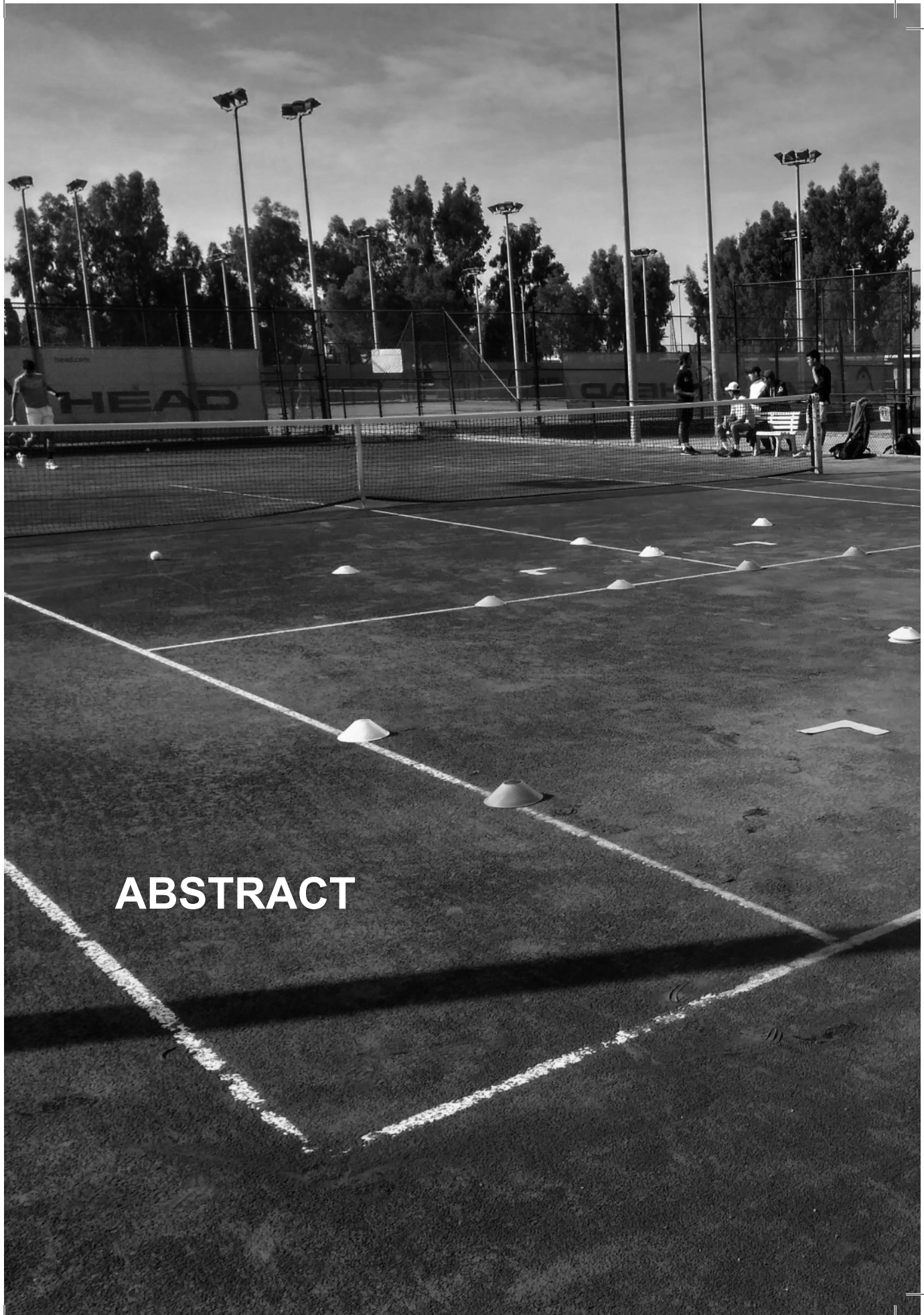
To my mum. I wouldn't be able to write in just a few words the care, love, and attention you give to us. You made me the person I am today and I'm sure that will make you prouder than these pages. Thank you for always believing in me and supporting anything I do. I love you to the moon and back.

A mi padre. Eres mi referente y a quien primero acudo. Gracias por enseñarme el valor del trabajo, el esfuerzo y la paciencia. Gracias por enseñarme que lo más

importante en la vida es ser una buena persona, y tu eres la mejor. Te quiero.

A mi hermana. Gracias por apoyarme a diario sin dudarlo ni un segundo. Eres la mejor hermana mayor que alguien pudiera tener. No sabes lo importante que es ese afecto y ayuda que siempre me transmites. Esto solo son unas hojas, pero quiero que sirvan para que sepas que soy yo quien te admira y está orgulloso de ti. Love you.





ABSTRACT



Determinant physical factors of stroke velocity and their relationship with fatigue in young tennis players

Several physical abilities are considered as determinant performance factors that can differentiate the level and success of a tennis player. Alongside technical proficiency, tactical awareness and certain psychological traits, some physical capacities stand out as essential for improved performance. Among these aspects, stroke velocity seems highly relevant in all age groups and in both male and female participants. The ability to apply speed to the ball, especially in the serve, seems to give the player the capacity to dominate the point and therefore a higher advantage during match-play. Previous literature has intended to establish the main physical traits that differentiate faster and slower strokes. It seems clear that these actions are of a multifactorial nature and that the outcome is the consequence of the summation of technical aspects, the anthropometric characteristics of the player, range of motion values and strength and power levels. Nevertheless, there is a certain interest in defining those physical aspects that determine velocity production in the various tennis strokes, alongside examining the possible differences between players of different ages and levels. Added, how these variables are affected by tennis competition seems essential towards training approaches and effective recovery strategies.

This thesis aims at establishing those strength and power variables determinant for stroke velocity. Also, it intends to offer insights on novel measurements that may also be relevant contributors to velocity production and how these may be stimulated by new training methodologies. Last, how these determinant aspects are affected by

fatigue induced by match-play will also be examined.

Towards these goals, eight studies were carried out. Studies 1 and 2 correlated strength and power measurements to stroke velocity. Studies 3, 4 and 5 examined match-induced changes in the relevant variables. Study 6 approached a novel training method towards velocity enhancement and studies 7 and 8 were reviews of the literature.

Results of this research show that maximal dynamic strength does not seem to positively correlate to stroke velocity in young participants. On the other hand, isometric force-time curve variables such as the rate of force development and impulse in specific joint positions of the kinetic chain seem to be relevant to perform faster strokes in these populations. This indicates the importance of a player's capacity to produce high levels of strength in short periods of time in multiple joint positions present in the motion. Because of this, training approaches that perform fast movements with light weights may be a valid option towards stroke velocity increases, although further research is needed to establish specific load prescriptions and injury risk. Also, contractile properties seem in some way relevant for velocity production, although an increased or decreased level of this variable may have a different effect on velocity production depending on the muscle group analysed. Last, single bouts of simulated match-play seem an insufficient load to elicit changes in determinant factors of stroke velocity, indicating that young players may need greater playing volumes or repetitive events to negatively affect these key variables.

Key words: serve velocity, strength, power, training, physical determinants.

Factores determinantes de la velocidad de golpeo y su relación con la fatiga en tenistas jóvenes

La velocidad de golpeo es un factor determinante del rendimiento en todos los grupos de edad y tanto en el tenis masculino como femenino. Parece claro que la capacidad de aplicar velocidad a la bola es de naturaleza multifactorial y que el resultado es la consecuencia de la suma de los aspectos técnicos, las características antropométricas, el rango de movimiento y los niveles de fuerza. No obstante, existe cierto interés por definir aquellos aspectos físicos que condicionan la velocidad en los distintos golpes, además de examinar las posibles diferencias entre jugadores de distintas edades y niveles. Conjuntamente, la forma en que estas variables se ven afectadas por la competición parece esencial para enfocar el entrenamiento y las estrategias de recuperación.

Esta tesis tiene como objetivo establecer aquellas variables de fuerza y potencia determinantes para la velocidad de golpeo. Además, ofrecer información sobre nuevas variables que también pueden ser relevantes para la producción de velocidad y cómo pueden entrenarse con nuevas metodologías de entrenamiento. Por último, también se examinará cómo estos aspectos determinantes se ven afectados por la fatiga inducida por la competición. Para ello, se llevaron a cabo ocho estudios.

Los resultados muestran que la fuerza dinámica máxima no parece correlacionarse positivamente con la velocidad de golpeo. Por otro lado, las variables isométricas derivadas de la curva fuerza-tiempo parecen ser relevantes para realizar golpes más rápidos. Esto indica la importancia de la capacidad de un jugador/a de producir

altos niveles de fuerza en cortos períodos de tiempo en múltiples posiciones articulares presentes en el movimiento deportivo. Además, ciertas propiedades contráctiles parecen ser relevantes para la producción de velocidad, aunque un mayor o menor nivel de esta variable puede tener un efecto positivo o negativo dependiendo del grupo muscular analizado. Por último, partidos simulados de unos 80 minutos parecen ser una carga física insuficiente para provocar cambios en los factores determinantes, lo que indica que los jugadores jóvenes pueden necesitar mayores volúmenes de juego o competiciones repetidas para afectar negativamente estas variables.

Palabras clave: velocidad de servicio, fuerza, potencia, entrenamiento, factores determinantes.

Factors determinants de la velocitat de colpeig i relació amb la fatiga en tennistes joves

La velocitat de colpeig és un factor determinant del rendiment en tots els grups d'edat i tant al tennis masculí com femení. Sembla clar que la capacitat d'aplicar velocitat a la bola és de naturalesa multifactorial i que el resultat és la conseqüència de la suma dels aspectes tècnics, les característiques antropomètriques, el rang de moviment i els nivells de força. No obstant això, hi ha un cert interès per definir aquells aspectes físics que condicionen la velocitat en els diferents cops, a més d'examinar les possibles diferències entre jugadors de diferents edats i nivells. Conjuntament, la manera com aquestes variables es veuen afectades per la competició sembla essencial per enfocar l'entrenament i les estratègies de recuperació.

Aquesta tesi té com a objectiu establir aquelles variables de força i potència determinants per a la velocitat de colpeig. A més, oferir informació sobre noves variables que també poden ser rellevants per a la producció de velocitat i com es poden entrenar amb noves metodologies d'entrenament. Per acabar, també s'examinarà com aquests aspectes determinants es veuen afectats per la fatiga induïda per la competició. Per això, es van dur a terme vuit estudis.

Els resultats mostren que la força dinàmica màxima no sembla correlacionar-se positivament amb la velocitat de colpeig. D'altra banda, les variables isomètriques derivades de la corba força-temps semblen ser rellevants per fer cops més ràpids. Això indica la importància de la capacitat d'un jugador de produir alts nivells de força en curts períodes de temps en múltiples posicions articulars presents al moviment

esportiu. A més, sembla que certes propietats contràctils poden ser rellevants per a la producció de velocitat, encara que un major o menor nivell d'aquesta variable pot tenir un efecte positiu o negatiu depenent del grup muscular analitzat. Finalment, partits simulats d'uns 80 minuts semblen ser una càrrega física insuficient per provocar canvis en els factors determinants, cosa que indica que els jugadors joves poden necessitar més volums de joc o competicions repetides per afectar negativament aquestes variables.

Paraules clau: velocitat de servei, força, potència, entrenament, factors determinants



FRAMEWORK



INTRODUCTION

Any tennis point during competition starts with a serve. This specific shot is the only action of the game that fully depends on the player's capacity to perform efficiently and effectively since the ball is put into play by the athletes themselves. Due to this particularity of the sport, the serve is often considered the most decisive action of the game and can greatly affect the outcome and result, as players can dominate a rally or win the point directly through an ace (Fitzpatrick et al., 2019; Gillet et al., 2009; Kovacs & Ellenbecker, 2011; Ulbricht et al., 2016). This action is of paramount importance as studies show a player's competitive level is directly correlated to serve speed (SV) (Girard et al., 2005). In addition to this, the serve is the most repeated shot in competition and during a typical serving game, it accounts for 45% to 60% of all strokes (Johnson & McHugh, 2006). It must be said that in men's tennis this situation occurs more often than in women's tennis, being more decisive in terms of winning a greater number of points if the service is precise (O'Donoghue & Ingram, 2001) Nevertheless, velocity is increasing in women's tennis, and serves exceeding $200\text{km}\cdot\text{h}^{-1}$ can sometimes be seen in professional competitors (Fett et al., 2020). If we add to this the frequency of service actions per match, the importance is even more accentuated. Typically, a tennis player performs about 7-8 services per game on serve and about 31 games per match in a three-set competition. If to this load we add the participation in about 6/7 matches per week/tournament in the case of reaching the final rounds, total volume can result in more than 1000 serves per competition, with its consequent importance and influence on the game (Johnson & McHugh, 2006).

Although in a slightly different manner, groundstroke performance can certainly affect

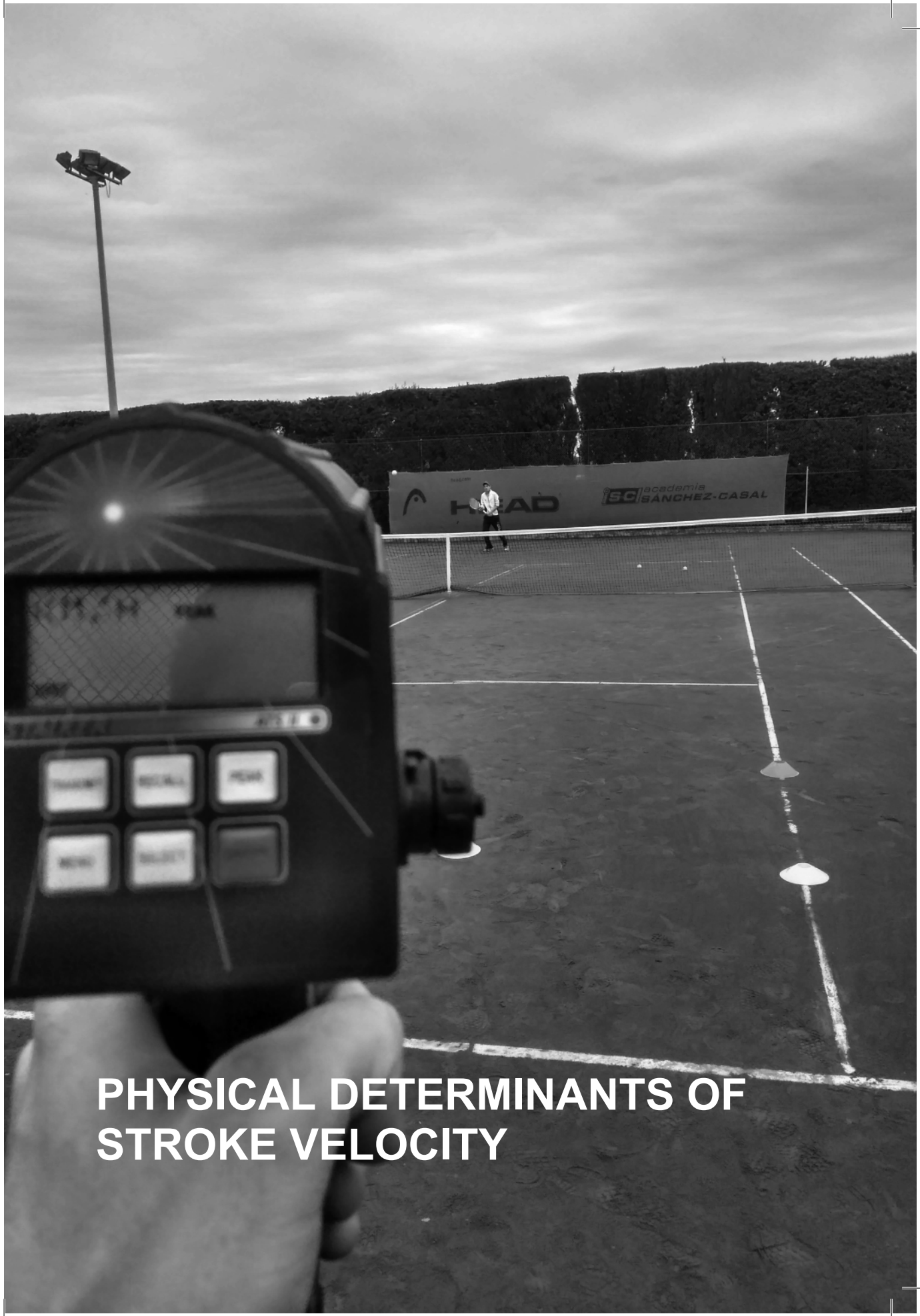
the game and determine dominance and initiative during points (Landlinger et al., 2012). While a higher hitting speed in these actions may not always be the best tactical choice, data suggests both women and men's tennis have evolved from a more technical slow-paced sport towards an explosive and highly dynamic discipline (Fernandez-Fernandez et al., 2014; Kovacs, 2006; Reid et al., 2015). Due to this reason, the nature of the game has changed and shorter points with greater power-based output from a physical perspective have seemed to appear (Galé-Ansodi et al., 2017; Gale-Watts & Nevill, 2016). In this regard and as mentioned, hitting at a greater speed in groundstrokes may not be necessarily the best option in some competitive situations, but the capacity to produce faster and more powerful strokes seems of extreme interest for the modern tennis player. Added to this, men (Fernandez-Fernandez et al., 2009; Landlinger et al., 2012; Pluim, 2006) and women (Kraemer et al., 1995, 2003) with a greater level in junior and highly competitive contexts show higher hitting speeds generally in all strokes in comparison to players ranked lower (Gillet et al., 2009), most likely benefiting from being able to perform these actions when required. While the rationale explaining the importance of high hitting speeds could seem addressed to professional high-level players, junior athletes also seem to benefit from these enhanced capacities (Fett et al., 2020; Ulbricht et al., 2016).

As knowledge around strength and conditioning methods and techniques increases, coaches and practitioners have the option to directly impact the players' game through an enhanced velocity of main tennis actions. With such a goal in mind, underpinning the determinants that affect the capacity of young tennis players to develop velocity and apply it to their strokes while competing seems of great

importance to address physical training appropriately. Notwithstanding, tennis strokes are considered complex motor actions involving many body structures and segments benefiting from energy transfer through what is known as the kinetic chain (Kibler et al., 2007). As with any complex motor skill, many physical characteristics affect the outcome and the importance of these key factors may vary between playing levels, age, or gender (Fett et al., 2020; Girard & Millet, 2009). Many studies have attempted to identify these parameters suggesting four main pillars have the potential to affect the velocity of a stroke. Biomechanical patterns or technique, range of motion (ROM), anthropometry, and strength or power levels seem the most important factors towards increased speed (Baiget et al., 2016; B. Elliott, 2006; Fett et al., 2020; Palmer et al., 2018; Vaverka & Cernosek, 2013). Different investigations have given a clear idea of which specific parameters are mostly present in those players that hit faster, although most studies have focused on experienced male competitive players that show specific playing and physical characteristics. There is a lack of literature regarding the extent and the influence of each one of these main physical parameters and the inclusion of further indicators in assessments. Also, a perspective of how these physical parameters affect differently if analysing younger participants could be of great interest. Alongside this, besides identifying those parameters that better predict a faster stroke in different populations, training programs and interventions have been studied to increase velocity production throughout the improvement of the aforementioned physical capacities. Diverse training methods and equipment (i.e., ballistic, plyometric, traditional resistance, flywheel-based, etc) have been concluded effective to increase hitting velocity in certain populations (Barber-Westin et al., 2010; Behringer et al., 2013; Canós et al., 2022; Fernandez-Fernandez et al., 2016; Genevois et al., 2013; Kraemer et al.,

2003). However, the individualization of these approaches, the periodization, and organization of the program, alongside identifying the more efficient training methods in terms of improvement seem essential to be able to achieve the desired outcome (Canós et al., 2022; Fernandez-Fernandez et al., 2018; Kraemer et al., 2003). Parallely, providing coaches and practitioners with novel and effective training methods that increase velocity production could be of interest.

In the same way, the main physical determinants of stroke velocity can be greatly affected by fatigue derived from competition. Competitive tennis, even at young ages, requires players to participate in numerous matches, multiple draws, and a high volume of events year-round. Competitions are usually organized on consecutive days and can even take part in one same day when referring to younger players (Gescheit et al., 2015). These specific needs give importance to the players' capacity to recover effectively after these competitive bouts. As well as identifying the determining factors influencing velocity production in main strokes, how these variables are affected by competition seems of extreme importance to address training and recovery effectively.



PHYSICAL DETERMINANTS OF STROKE VELOCITY



Several studies have aimed at establishing the principal determinants of velocity in the main tennis strokes. However, as a complex motor skill, many aspects influence the outcome and different authors have approached this issue from different perspectives. Following a thorough review, investigations seem to agree on grouping these determinant characteristics into four main groups. Technique and biomechanics, anthropometric characteristics, strength and power levels, and range of motion capacities seem to include all identified physical factors affecting stroke velocity. Consequently, this work will initially aim at reviewing the literature towards an understanding of those aspects that mostly differentiate players that can produce faster strokes. Parallely, a critical analysis will be performed to identify those aspects still not clear or not yet investigated regarding the previously mentioned main pillars.

TECHNICAL AND BIOMECHANICAL APPROACH

From a technical perspective, tennis strokes, like any other motor skill, seem to demand a certain technical execution to achieve the most efficient and effective results. More specifically regarding the capacity of a player to produce faster strokes, several studies have aimed at identifying the key biomechanical aspects an effective serve, forehand, or backhand should include. Much more thoroughly than groundstrokes, the serve has been studied to provide players and coaches with optimal technical indications and aspects identified with faster servers (B. Elliott, 2006; B. Elliott et al., 1995; Fleisig et al., 2003, 2003; Hernández-Davó et al., 2019; Kovacs & Ellenbecker, 2011; Martin et al., 2013; Reid et al., 2008; Roetert, Ellenbecker, et al., 2009; Roetert, Kovacs, et al., 2009). As a key starting point, the speed of the head of the racquet and posterior transfer to the ball is the main aspect technical proficiency aims at. Towards this, the height of impact and the amount of

momentum and forward rotation applied to the ball seems the principal contributors towards increasing the head of the racquet's speed. The role of angular velocity vectors of the upper arm, forearm, and hand in generating this speed seems essential (B. Elliott et al., 1995). Specifically, hand flexion, trunk rotation, upper arm flexion and abduction, alongside the internal rotation of the shoulder are of paramount importance to produce fast speeds. This internal rotation motion has been identified as a major contributor to speed as it is mainly in charge of accelerating the upper arm and building up angular velocity in the swing to impact. However, this mainly accounts for the moment of impact in the upper arm, while the serve is a complex motor skill involving several body structures and phases. In this line, arm pronation is responsible for racquet orientation while elbow extension has a high influence on impact height, which is another contributor to head racquet speed (B. Elliott, 2006; B. Elliott et al., 1995). However, as a skill involving not only the upper arm, other body segments have also been identified as key elements for velocity production. Trunk rotation plays a main role in this matter, and authors have identified the side positioning of the trunk as an enabler of producing extra rotation in the horizontal plane to produce a shoulder-over-shoulder orientation increasing available space and energy storage to transfer to the consequent structure and phase of the serve. Also, authors point out the importance of pelvic and lower limb drive as the starting point of the kinetic chain to produce velocity to the serve. Extension moments in the lower limbs and internal rotation motion in the back hip seem essential towards this goal (B. Elliott, 2006; Reid et al., 2008; Sweeney et al., 2012). Because of the fact of being a skill with several phases, the preferred biomechanical layout for faster serves or strokes depends on which specific stage of the stroke is being analyzed. Kovacs and Ellenbecker (2011) suggested the use of a

multi-stage analysis of the serve involving eight stages. Depending on the phase, biomechanical demands vary. Those phases responsible for velocity build-up seem to be the loading, cocking, acceleration, and impact phases (Figures 1A and 1B). During the loading phase, kinematics mainly refers to lower body positions in which the authors identify two main techniques (i.e., the foot-back and the foot-up). Although the foot-up seems to generate greater vertical forces which would be interesting to transfer throughout the kinetic chain, no ball velocity differences are observed between these two techniques. The foot-back style provides greater upward and forward push-up while the foot-up provides a stable axis of rotation on which players rely to generate momentum. Also, during the loading phase, the importance of shoulder and pelvis lateral tilt has been identified, as this specific alignment facilitates the development of angular momentum through lateral trunk flexion during forward swing (Kovacs & Ellenbecker, 2011). The cocking phase is known for the importance of driving the racquet down and behind the torso allowing greater storage of elastic energy and an increased path before impact. Maximal shoulder external rotation is reached and a close parallel position between racquet and trunk seems important (Figure 1A).

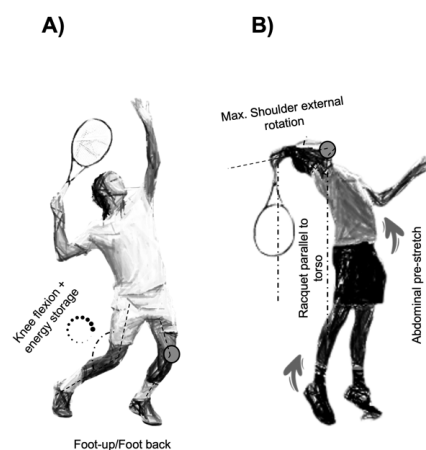


Figure 1A. Stages of the tennis serve and technical determinants of velocity. A = loading; B = cocking.

Accelerating the racquet from this position until impact is known as the acceleration phase. A rapid rotation force occurs from the lumbar spine and forceful concentric internal rotation movements oversee generating velocity. Trunk rotation, elbow extension, shoulder internal rotation, and hand flexion are the main contributors to momentum in this phase (B. Elliott, 2006; B. Elliott et al., 1995; Fleisig et al., 2003; Martin et al., 2013; Reid et al., 2008). During contact, the best kinematic models indicate that the shoulder should be slightly abducted and the elbow, wrist, and lead knee somewhat flexed. It is suggested that optimal impact point should happen at 110° angle of elevation between the upper arm and trunk (Kovacs & Ellenbecker, 2011) (Figure 1B).

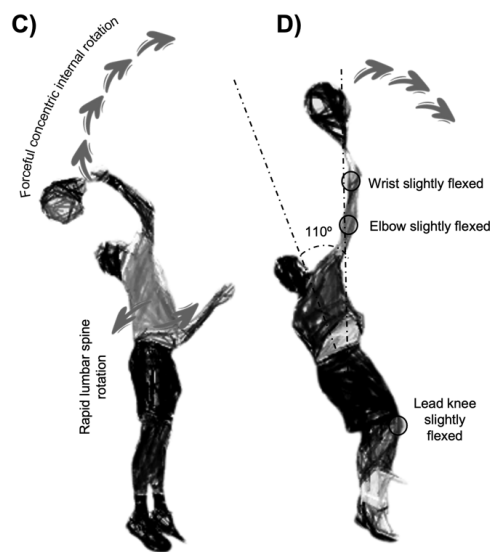


Figure 1B. Stages of the tennis serve and technical determinants of velocity. C = acceleration; D = impact.

Last, all these structures bear a great level of eccentric forces towards decelerating the movement, although no velocity is being generated from this phase onwards. In short, depending on the serving model followed and the specific phase of the motion, certain biomechanical and technical needs are present towards generating faster

serves, however, it seems clear that literature establishes knee extension and lower leg drive, hip and trunk rotation and elbow extension, shoulder internal rotation, and hand/wrist flexion as the major contributors to angular momentum towards transferring speed to the head of the racquet and posteriorly to the ball (Table 1).

	Elliot et al., 1995	Springings et al., 1994	Tanabe et al., 2007
N° Players	11	1	66
Trunk Flexion	9,7 ± 1.8	7,4	-
Shoulder Internal Rotation	12,9 ± 4.1	30	41,1 ± 14.7
Shoulder Horizontal Flexion and Abduction	12,9 ± 5.9	24	6,4 ± 6.4
Elbow Extension	14,2 ± 6.4	-	3,2 ± 3.2
Elbow Pronation	5,2 ± 4.1	15	3,6 ± 3.6
Wrist Flexion	30,6 ± 9.1	26	31,7 ± 7.5
Wrist Ulnar Deviation	0,6 ± 1.2	-	0,8 ± 5.9

Table 1. Segment contribution (%) to racquet velocity.

These motions and body positions seem to be the most correlated to successful fast serves and performed by those players capable to apply speed to the ball effectively (Fleisig et al., 2003). In this line, main aspect differentiating younger and lower ranked players with their more experienced peers appears to be the spatial position of the hand with respect to the hip before impact. Added to this, external rotation range of motion levels alongside the capacity to reach high velocity in internal rotation and elbow extension motions seem to affect to a great extent the capacity to produce fast serves (Hernández-Davó et al., 2019).

Regarding groundstrokes, some investigations have also analyzed the preferred technical patterns to increase velocity production (Bahamonde & Knudson, 2003; Genevois et al., 2015; Landlinger et al., 2010; Roetert, Kovacs, et al., 2009). First, the tactical situation and moment of play do not necessarily imply the use of maximal velocity. Nevertheless, being able to generate high velocity groundstrokes when needed remains important for the modern tennis player and is a distinctive trait of higher and lower ranked players (Landlinger et al., 2010, 2012). Faster groundstrokes, as happens regarding the serve, rely on greater angular velocity of the segments implied in the motion (i.e., legs, pelvis or hip, trunk, upper arm, elbow, and wrist) Figure 2.

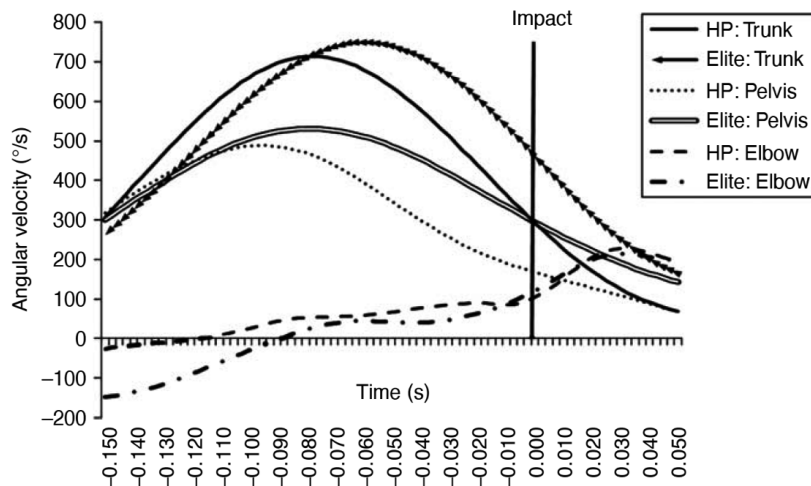


Figure 2. Segment angular velocity differences between elite and high-performance players. Adapted from Landlinger et al., (2010).

From a starting point involving leg positioning, the fact that a player uses a closed or open stance directly affects velocity. Linear momentum is generated from the ground reaction forces (GRF) generated and transferred upwards through the kinetic chain. Closed stances take longer to be executed but they seem to generate greater linear and angular momentum as the rotation of the legs, hips, trunk, and upper arm

segments seem to benefit from this back to forward rotational movement (Bahamonde & Knudson, 2003). On the other hand, in the open stance, linear momentum is diminished, and the generation of velocity relies on rotation of segments in a shorter period. Although closed stances seem to benefit from greater rotations and energy build up, tennis has become a fast-paced sport and time to execute strokes is limited. Players adapt to these issues and can perform fast groundstrokes in open stance positions (Figure 3). In this line, other kinematic peculiarities appear determinant for velocity production. In the backswing motion, the fact of using a traditional straight form allows more control to the player over the ball, but literature suggests the loop backswing allows further energy storage over an increased racquet pathway (Roetert, Kovacs, et al., 2009). In any case, for more power and efficiency, the motion should be fluid and coordinated from the backswing position towards the impact spot. Regarding acceleration or forward swing, ideal technical indications vary between suggesting the individual segments (i.e., upper arm, forearm, and hand) move relative to each other to generate velocity or pivoting as a single unit over the rotational axis to generate speed to the shot (Bahamonde & Knudson, 2003). The previous phases could be similarly approached regardless speaking of the forehand or backhand strokes. Nevertheless, when analyzing the later, some differences appear as this stroke can be performed using a two-handed or one-handed style. Although the one-handed form seems to develop more momentum relying on upper arm segment rotations, the two-handed backhand can also achieve high values of velocity based on trunk rotation, although slightly limited in open stance positions (Genevois et al., 2015) (Figure 3). Regardless the style, trunk rotation seems essential to transfer ground reaction forces to upper body segments. Optimal rotation facilitates force production at the shoulder and clear

relationships have been found between trunk angular velocities and racquet speed (Bahamonde & Knudson, 2003). In short, evident differences appear when speaking of different stances, styles, groundstrokes, or even tactical contexts. Nevertheless, the use of energy transfer from the ground to the head of the racquet seems essential and the effective segmental coordination and rotation of the legs, hips and trunk followed by the upper arm, shoulder, forearm, and hand clearly determine the outcome of the groundstroke's velocity (Bahamonde & Knudson, 2003; Genevois et al., 2015; Landlinger et al., 2010).



Figure 3. A = Closed stance one-handed backhand; B = Open stance two-handed backhand. Adapted from Roetert et al., (2009).

ANTHROPOMETRIC CHARACTERISTICS

Anthropometric characteristics influence the capacity of a player to produce velocity to a stroke. In this sense, longer limbs may aid in enhancing the lever arm and apply higher speed to the ball. In the same way, a greater mass could apply a superior acceleration to the racquet and therefore result in a faster shot. Interestingly, some anthropometric traits are due to appear as the athlete develops chronologically and biologically, while on the other hand, certain qualities can be affected and modified through effective training. With this idea in mind, it seems interesting for coaches and professionals to have knowledge around which anthropometric characteristics are directly linked with faster strokes, and therefore have a clear picture towards talent identification and certain attributes that may be worth achieving through a structured physical development program.

Literature has mainly focused on those anthropometric characteristics that relate to faster serves, as it is the most studied shot due to its importance. Specifically, body height (BH) has been pointed out as the most important factor affecting the capacity to produce high velocity serves. Notwithstanding, the height of the impact location (Figure 4) seems to be the determinant aspect that determines if a serve can be performed at a higher or lower speed (Vaverka & Cernosek, 2013). Hitting the ball in a higher spot allows the tennis player to have more available space to produce speed and achieve a better trajectory which translates into faster SV (Vaverka & Cernosek, 2013). When establishing a higher impact spot as the determinant factor affecting SV, some anthropometric characteristics mainly correlate to the capacity of a player to achieve these higher locations. On the one hand, BH seems to be the factor most affecting SV in male competitors, with a greater influence than seen in female players

(Fernandez-Fernandez et al., 2019; Fett et al., 2020). Although these differences exist, and correlations seem more solid when referring to men, many investigations have also recognized a strong relationship between first and second serves in both sexes (Bonato et al., 2014; Fett et al., 2020; Hayes et al., 2021; Palmer et al., 2018; Vaverka & Cernosek, 2013). These studies also show that the sub-maximal nature of the second serve (in which the player probably emphasizes tactical decisions and secures the success of the shot) has a lower relation to BH than first serves (Vaverka & Cernosek, 2013). Besides height, arm length (AL) and the overall span of the arm-racquet complex can also influence impact point height and therefore serve velocity (Fett et al., 2020; Hayes et al., 2021). Literature has found positive associations ($r = 0.56$) between the AL and SV in all groups of ages and genders (Bonato et al., 2014; Fett et al., 2020). It seems logical to find these positive relations as longer limbs do not only increase the height of impact but allow the player to transfer greater power throughout the tangential and achieve a greater SV (Bonato et al., 2014; Fett et al., 2020; Hayes et al., 2021).



Figure 4. Height of the ball impact during serve.

Other anthropometric traits have been investigated concerning SV. Body mass (BM) ($\text{♂ } r = 0.44^{**} - 0.57^{**}$ and $\text{♀ } r = 0.35^{**} - 0.39^{**}$) and body mass index (BMI) ($r = 0.12$

– 0.40**; $r = 0.577^{**}$) have been found to correlate positively to the capacity of producing speed in several studies in both men and women (Fett et al., 2020; Hayes et al., 2021; Wong et al., 2014). Nevertheless, this relation did not seem as strong when referring to elite players (Baiget et al., 2022). Following allometric theory, an increment in BM in accordance with BH can traduce into an increment in torque production (Wong et al., 2014). Therefore, an increment in BM with close control on fat ratios and lean mass development may assist in the capacity of producing faster strokes (Baiget et al., 2022). Nonetheless, and contrary to BH, BM has shown stronger relations to SV in female populations (Fernandez-Fernandez et al., 2019; Fett et al., 2020). It might seem that the specific demands of female competition (i.e., lower shot frequency) may request profiles to shift towards players with a tendency to endomorph body types (Fett et al., 2020), unlike male players, which possibly rely more thoroughly on higher impact locations and other related physical factors influencing SV. Last, and as a factor to consider, while traits such as BH and AL may be useful tools for talent identification and long-term development control, important aspects such as BM and BMI may be modifiable parameters through training. Programs should be optimized to improve muscle growth and fat to lean mass ratios trying not to induce detrimental effects on speed and agility actions.

MAXIMAL DYNAMIC AND ISOMETRIC STRENGTH

Besides the importance of anthropometric parameters in achieving greater velocity production in tennis strokes, knowledge around strength related factors affecting speed has received thorough attention in the literature. Different strength aspects have been identified to affect to some extent all strokes.

Theoretically, the need for maximum dynamic strength (MDS) during a shot seems low, as the action is performed at maximal velocity with a relatively lightweight implement such as the racquet. (i.e., between 200-400 g) (Kraemer et al., 2003). In this line, studies correlating MDS or isokinetic strength values and stroke speed did not find significant positive associations between these variables (Cohen et al., 1994; Kraemer et al., 2003). Enhanced MDS may aid in other important aspects such as muscular balance, local muscle endurance, or overall strength gains (Kovacs & Ellenbecker, 2011), but does not seem to have a direct influence on stroke velocity. Other strength indicators such as maximal isometric strength (MIS) tested via handgrip, which is a common measure in children to estimate upper-body strength, have previously been related to faster serves (Fett et al., 2020). Nevertheless, MIS tested at different joint positions present in the kinetic chain of the stroke motion has been a more common choice to establish some influence on the velocity outcome. Although there are mechanical and neural differences between a dynamic and static muscular action, and isometric testing may be deemed inappropriate for assessing dynamic performance (Fernandez-Fernandez et al., 2014), conducting these tests at specific joint angles may be suitable (Bazyler et al., 2015). Most investigations found the shoulder internal rotation (SHIR) as the main contributor to greater SV (Baiget et al., 2016, 2021; Cools et al., 2014; B. Elliott et al., 1995; Hayes et al., 2021). This seems logical as the internal rotation plays a great role as a key element to developing high racquet velocities (B. Elliott, 2006). As a complex motion throughout a kinetic chain that builds-up energy from the legs to the tip of the racquet (Kibler et al., 2007), other positions involved in the motion have also been tested. Shoulder flexion-extension (SHF and SHE), leg and back extension, and shoulder external rotation (SHER) showed low to moderate correlations with serve velocity in Baiget et

al., (2016), probably indicating that although these movements are part of the motion, isolated variables without the combination of other aspects are not a strong predictor. When conducting a multivariate analysis to predict serve velocity in the same study, the authors found that 55% of the SV was explained by the combination of SHIR and SHF MIS. Notwithstanding, these findings do not seem to be as clear when referring to groundstrokes. Literature is scarce when investigating the associations between groundstroke velocity and MIS in SHIR or positions more specific to the forehand and backhand such as shoulder horizontal abduction (SHABD) and adduction (SHADD). How this specific level of maximum strength influences groundstrokes has not been thoroughly addressed either in high level, competitive or younger unexperienced players. Narrowing down to just one physical aspect when speaking of thoroughly complex motor actions such as tennis groundstrokes in which generating maximal velocity is not always the preferred option, that imply the use of diverse body structures and abilities (i.e., core, legs, GRF), and that rely strongly on technical proficiency may not be the best option. Most likely, as expressed when discussing the serve, isolated variables do not explain velocity production by themselves. Instead, the combination of not only physical aspects, but technical and coordinative skills may establish the overall capacity of the player to produce speed to the shot. Last, as some authors point out (Baiget et al., 2016), investigations finding strong associations between MIS values and SV were performed with elite or high skilled players that respond to professional populations. Interestingly, various conclusions can be drawn out after analyzing the importance and influence of different strength and power variables in junior and more experienced competition players of a greater level (Fett et al., 2020; Girard & Millet, 2009; Kraemer et al., 2003). As previous research suggests, there is a possibility that competitors of different characteristics

rely on different parameters that affect velocity production. It may be that younger or lower-ranked players may use to a further extent greater technical dominance of the action or favorable anthropometric traits over absolute strength and power levels, which would be more determinant in older competition and elite populations (Fett et al., 2020; Girard & Millet, 2009; Kraemer et al., 2003). Yet, to our knowledge, not many studies have investigated the relationship between MIS values in upper and lower body positions in young participants, especially related to groundstrokes.



Figure 5. Maximal isometric strength (MIS) testing of relevant serve motion joint positions

POWER AND RATE OF FORCE DEVELOPMENT

Besides maximal strength indicators, other parameters derived from the force-time curve of the athlete have been studied. The rate of force development (RFD), impulse (IMP), and isometric force at different times of contraction have been considered key neuromuscular performance aspects in power-based actions (Baiget et al., 2021). Although the combination of all phases of the serve (i.e., preparation or cocking, acceleration, contact, and deceleration) lasts around 650 ms, the acceleration phase in which force and power need to be built up, lasts just around 80 ms (Kibler et al., 2007). Similarly, groundstrokes do not have a pronounced preparation phase and on some occasions, the available time to build up power is

extremely short. Therefore, the ability to generate high levels of power in short periods seems a skill tennis players would certainly benefit from. Baiget et al., (2021) tested the relationship between SV and RFD or impulse at different short time intervals (i.e., 0-250 ms) in competition players. Authors found evidence on how a greater level of these variables, the ability to produce force rapidly and accumulate it during a given period, especially in rotational movements and positions present in the kinetic chain, seems to be determinant to generate high speed serves. Similarly, to MIS levels, early stages of contraction (<100 ms) during the SHIR or SHF explained around 50% of the SV variability, suggesting the combination of multiple positions, body structures and other aspects not involving strength parameters should explain the totality of stroke performance. However, although rapid force production seems to have potential to be considered a key physical factor affecting stroke velocity, no studies to our knowledge have included the assessment of these variables in young participants of lower playing level. Moreover, as previously mentioned, tennis strokes are considered complex motor skills involving the body globally. Although strong associations may have been found regarding the upper limb structures and joint positions, if rate of force development or impulse values of the lower body affect to a similar extent velocity production remains unknown. Hayes et al., (2018) found the influence of impulse at different time intervals (i.e., 100 and 200 ms) in an isometric mid-thigh pull test to correlate positively with SV, although to our knowledge no further investigations have attempted to study peak rate of force development (PRFD), RFD at short intervals or IMP in other time frames in predominantly lower body positions.

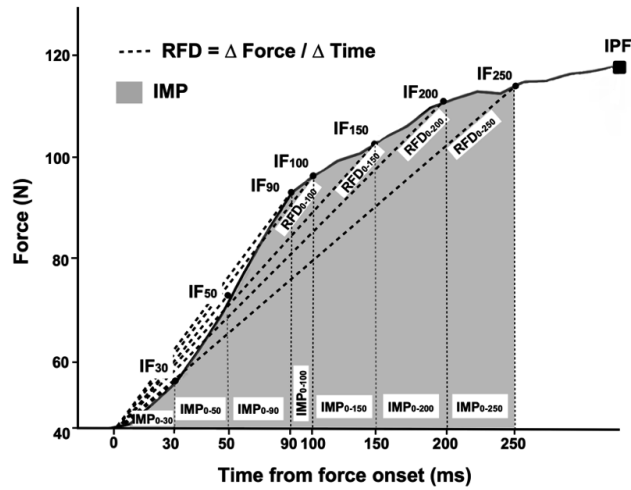


Figure 6. Force-time curve variables. Adapted from Baiget et al., (2021).

Although certain isometric force-time curve values seem to have a strong association with velocity production, literature has previously considered the stretch-shortening cycle (SSC) nature of the action as highly relevant. As previously indicated, tennis strokes are highly dynamic actions performed at high speeds with relatively light weights or loads to mobilize. The technical execution of these motions demands a pre-stretching of the main muscle groups involved in the kinetic chain and important elastic energy storage to emphasize the rebound capacity of the muscle. Therefore, other testing procedures have intended to mimic these demands and establish relations between power output and velocity production. Medicine ball throws (MBT) are a useful tool to assess these power demands (Fernandez-Fernandez et al., 2019; Fett et al., 2020). A big number of studies have found positive correlations between MBT distance and speed and serve and groundstrokes velocity (Delgado-García et al., 2019; Fernandez-Fernandez et al., 2019; Fett et al., 2020; Terraza-Rebollo et al., 2017a). These associations have been found to be strong in female ($r = 0.2 - 0.63$)

(Fett et al., 2020) and male populations ($r = 0.42 - 0.64$) (Fernandez-Fernandez et al., 2019). Nevertheless, at younger ages, these associations seem to present a stronger interaction in male participants (Fernandez-Fernandez et al., 2019; Fett et al., 2020). However, some authors hypothesize that the importance of purely physical capacities such as upper body power, although obviously determinant for velocity production, might not be such a relevant aspect in young or lower-ranked competitors, as they still rely more thoroughly on technical proficiency and anthropometric advantages rather than strength levels (Fett et al., 2020; Girard & Millet, 2009; Kraemer et al., 2003). Assessing these values in a wide range of populations including different playing levels, age and gender may be of interest.



Figure 7. Medicine ball throw (MBT) testing.

Although the influence of upper body MIS, RFD, IMP, and power output seems clear, the influence of the lower body is not as well-defined. The height of the jump a tennis player can perform while serving may aid in reaching a higher impact spot. As discussed previously, this gives more space to the player for an optimal ball trajectory and can traduce in faster serves (Dossena et al., 2018; Kovacs & Ellenbecker, 2011). In this line, having greater leg strength and power levels could be beneficial for serving faster. However, research that has investigated the relationship between countermovement jumps (CMJ) or leg extension MIS and SV did not find

strong associations between the two variables (Baiget et al., 2016; Bonato et al., 2014; Dossena et al., 2018). Moreover, the height of ball impact does not seem relevant in groundstroke velocity production and jumping height has not been thoroughly studied in literature as data is scarce when referring to groundstrokes. It could be that the ability to sprint and move faster on the court to get into a good position before hitting the groundstroke may give more time to the player and influence on some extent velocity production if needed, but this is speculative. Despite this, some investigations found a positive effect of certain lower body strength measurements and SV. Knee extension velocity ($r = 0.75$) and strength ($r = 0.36$) were predictors of those players that served faster (Pugh et al., 2003; Wong et al., 2014). Also, IMP during the isometric mid-thigh pull (IMTP) ($r = 0.87$), jumping height while performing a CMJ ($r = 0.72$; 0.77) or hop tests ($r = 0.31$ - 0.36) have previously established significant correlations to speed production (Hayes et al., 2021; Palmer et al., 2018). The mentioned studies give importance to GRF and the ability of players to transfer built-up strength and power from lower to the upper body. Generating greater levels of strength in the legs translates in higher ground reaction forces (Girard & Millet, 2009; Kibler et al., 2007; Palmer et al., 2018), and, if the transfer throughout the kinetic chain is effective, the outcome of the stroke will be benefited. Because of the complexity of maintaining the built-up strength levels and transferring them to the racquet head with minimum energy waste, literature seems to agree on suggesting the lower body has a coordinative role in the serve motion. Although producing high levels of strength and power seems important, the transfer of this energy suggests the legs be more likely used for coordinative and technical purposes rather than affecting stroke velocity directly. Regarding these strength transfer needs; some studies have also agreed on establishing the contribution of the

trunk as a force transfer link and stabilization of body structures. Literature relating core strength levels and stroke velocity are scarce, although Wong et al., (2014) found positive relations between peak velocity of hip extension and SV ($r = 0.56$).



Figure 8. Serve kinetic chain.

MUSCLE CONTRACTILE PROPERTIES

Besides strength and power measurements that directly influence the outcome of a stroke's speed, other complex neuromuscular factors may influence highly dynamic actions that are based on the effective use of the SSC. Enhanced values of mechanical stiffness of the muscle-tendon unit have been suggested as beneficial for actions that rely on these characteristics such as jumping, sprinting, or agility (Brughelli & Cronin, 2008). Stiffness, known as the resistance of an object or body to deformation or changes in length may aid in producing faster strokes, as the capacity of a structure to absorb and re-use rapidly big amounts of elastic energy for a given force could be beneficial towards actions that rely on storage and rapid transfer of energy (Kalkhoven & Watsford, 2018). In the same way, derived muscle property parameters such as muscle tone (mechanical tension in a relaxed muscle), elasticity

(recovery of the muscle's initial shape after contraction or removal of an external force), and time to relaxation (time for the muscle to restore its initial shape after external force) (Ko et al., 2018), may to some extent affect velocity production. To date, some studies have investigated the influence of these parameters on diverse performance aspects concluding an enhanced level is determinant for predominantly lower body actions such as bounding, jumping, and sprinting (Kalkhoven & Watsford, 2018; Pruyn et al., 2014). A global movement such as a tennis stroke is performed rapidly with a great influence of diverse SSC throughout the kinetic chain. Nevertheless, the action is not performed in response to a rebound against the floor or a surface but instead, energy is built up from the lower body towards the head of the racquet to develop speed (Kibler et al., 2007). There could be benefits from an enhanced or specific level of muscle mechanical properties, but literature is scarce in this sense. These measurements have not been thoroughly investigated in striking, hitting, or throwing motions. Sheehan et al., (2019) measured the influence of individual muscle stiffness and vertical stiffness on clubhead speed in male golfers finding a greater level of lower body values positively correlated to speed and carry distance. As suggested by the authors, stiffer systems may reduce the time needed to reduce the 'slack' from the elastic component and therefore reduce electromechanical delay and enhance rate of force development (Sheehan et al., 2019). Alongside this, derived neuromechanical factors such as tone, elasticity, or time to relaxation may also influence to some extent the capacity of a player to produce power and therefore affect velocity production. Interestingly, as tennis motions are complex skills influenced by ROM or technical parameters, stiffer structures may aid in generating greater power but counterproductively affect biomechanical key factors that guarantee effective strokes. Pruyn et al., (2012) found

a relationship between leg stiffness and soft tissue injuries in Australian footballers, suggesting increased peak shock forces provoked by greater levels may interpose technical proficiency or limit ROM in certain body structures (Brazier et al., 2019). In short, the level of certain mechanical muscle properties could affect velocity production, but a sweet spot seems to be necessary to benefit from these characteristics without high jacking technique, ROM, or increase injury risk because of extremely stiff structures. In any case, no studies to our knowledge have attempted to correlate neuromechanical muscle values and stroke velocity in young tennis players.

RANGE OF MOTION

Alongside strength and power measurements, ROM has shown some relationship to stroke velocity, mainly during the serve (Cohen et al., 1994; Palmer et al., 2018; Wong et al., 2014). Increased mobility around joints that are directly implicated in the shot motion (i.e., shoulders or hips) seems to be important to serve faster. In a similar way to the ability to achieve higher impact points when serving, an increased ROM in the acceleration phase may give the player more available space and time to develop power and apply a greater acceleration to the racquet. General shoulder ROM has been deemed important towards being able to generate velocity (Wong et al., 2014), and specific aspects such as an increased wrist flexion (WRF) ($r = 0.338^*$) and SHIR ($r = 0.324^*$) have been linked to enhanced serving (Cohen et al., 1994). Regarding the lower body, similar outcomes appear around the hip ($r = 0.39$), as an increased ROM may promote certain degrees of freedom for the lower extremities during the dynamic loading and preparation during the acceleration phase.



Figure 9. Elbow and shoulder ROM during serve.

While an increased ROM, especially to be able to reach certain shoulder positions seems to be important to perform faster serves, these particularities are not as clear when speaking of groundstrokes. Literature is scarce when analysing the effects of increased or decreased levels of mobility on forehand or backhand speeds. Rather than identifying specific joint positions that increase velocity production, literature has found certain ROM levels to affect relevant biomechanical aspects that indirectly influence the speed of the stroke. For instance, knee positioning and ROM in the closed stance position were representative of higher skilled players that performed faster forehands (Nesbit et al., 2008). Nevertheless, the level of ROM was not directly correlated to velocity but instead affected key biomechanical factors such as movement of the body centre of mass or hip and trunk angular momentum, therefore affecting racquet speed (Nesbit et al., 2008). Moreover, some biomechanical differences based on certain ROM abilities affect factors used to develop speed in different style groundstrokes. The two-handed forehand relies thoroughly on trunk rotation to generate speed to the tip of the racquet and consequently to the ball. On the other hand, the one-handed fashion seems to develop speed relying on the

segmental rotation of the upper limbs (Genevois et al., 2015). These characteristics depend on certain levels of ROM to be performed efficiently. However, it seems that if certain levels of range of motion are guaranteed, it will be the players' technical capacity and style of play that will determine the capacity to produce faster groundstrokes (Landlinger et al., 2010; Nesbit et al., 2008). Although with caution, it may be that there are optimal ROM values around specific joints that positively influence biomechanical factors that result in higher racquet and ball velocities when executing a forehand or backhand. In short, higher-ranked players may perform faster strokes relying on specific degrees of ROM to perform technically better than lower-ranked players and therefore achieve higher velocity production.



Figure 10. Trunk rotation and upper arm rotation differences in one-handed and two-handed backhands. Adapted from Genevois et al., (2015).

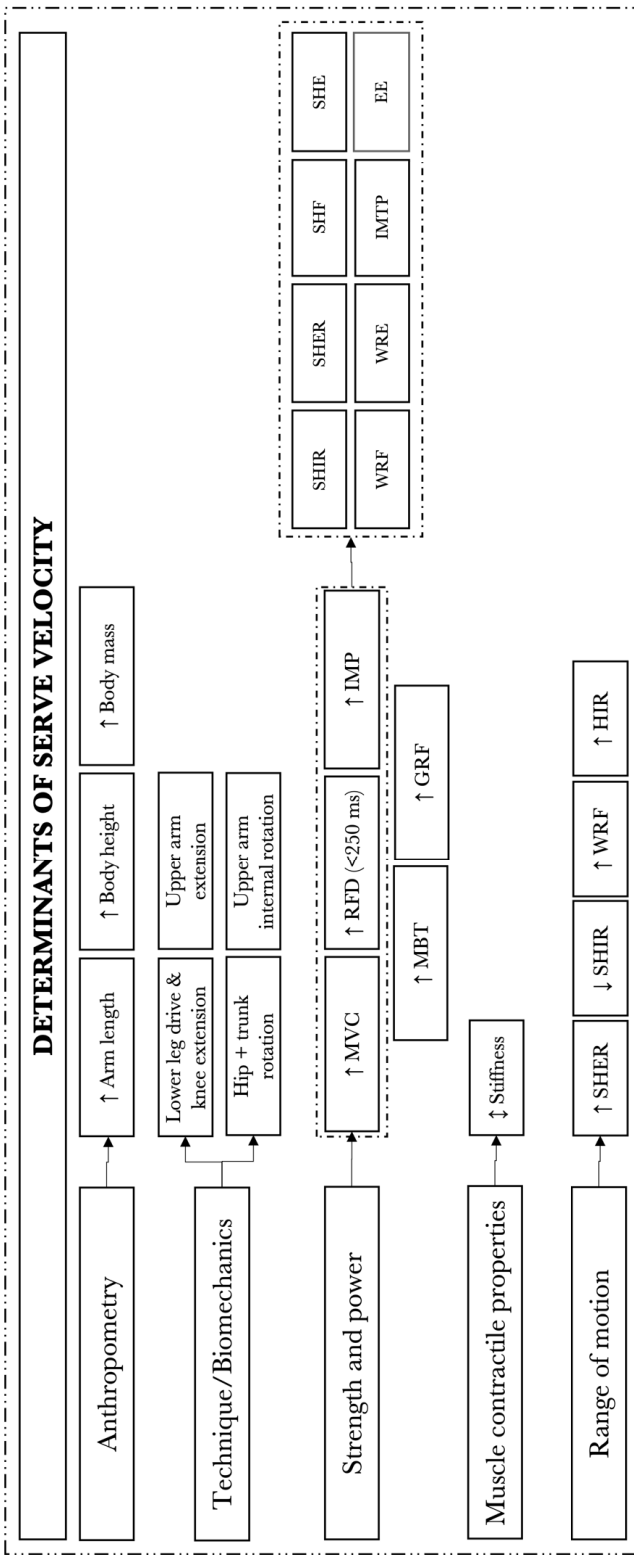


Figure 11. Diagram of main physical determinants of tennis serve velocity. MVC = maximal voluntary contraction; RFD = rate of force development; IMP = impulse; MBT = medicine ball throws; GRF = ground reaction forces; SHIR = shoulder internal rotation; SHER = shoulder external rotation; SHF = shoulder flexion; SHE = shoulder extension; WRF = wrist flexion; WRE = wrist extension; EE = elbow extension; IMTP = isometric mid-thigh pull; HIR = hip internal rotation



TRAINING METHODS FOR STROKE VELOCITY ENHANCEMENT



As discussed, the multifactorial nature of velocity production during tennis strokes has resulted in the use of diverse training methods aiming at improving determinant physical factors. Nonetheless, it remains unclear which program obtains greater results, following which frequency, volume, or intensity. Also, sex, age and level differences clearly affect the effectiveness of the program and research has aimed at solving these issues. In this line, finding those traditional methodologies that positively affect stroke velocity is of paramount importance alongside analysing new training methods that adapt to the physical characteristics present during play.

CONVENTIONAL ECCENTRIC AND CONCENTRIC RESISTANCE TRAINING

Programs including strength exercises around the shoulder joint, as it seems the most important during tennis strokes, have resulted in positive outcomes. (Mont et al., 1994) tested the effectiveness of a concentric or eccentric based resistance program using an isokinetic dynamometer three times a week during six weeks. Both programs seemed to be useful tools to improve SV increasing values around 11%. (Treiber et al., 1998) also found that following a program based on *TheraBand*[®] and lightweight dumbbell training was sufficient to increment torque in SHIR (23.8%) and SHER (17.8%), alongside SV (6 – 7.9%). The mentioned studies found improvements in experienced populations of a certain age and level. Canós et al., (2021) found that 8 weeks of training using traditional guided machines enhanced upper body power levels (i.e., MBT velocity) but SV remained unaltered in junior participants. In this same line, Behringer et al., (2013) did not find the same outcome when testing a resistance training program (around 65 – 85% RM) compared to a plyometric setting during 8 weeks in young competitors. Contrary, only the plyometric

group improved SV. Authors hypothesize the necessity of having a certain technical level to obtain improvements following this kind of training, and although they seem to be beneficial for improving velocity production, this seems to happen as important factors such as muscle balance, motor control, neural drive or motor unit discharge rate are affected by this type of training.



Figure 12. Traditional resistance training exercise examples.

When speaking of training methodologies aiming at increases in SV following maximal loads, some particularities should be considered. Although maximal strength values do not seem to have a direct relationship to stroke velocity (Kraemer et al., 2003), the development of these levels may have a residual positive effect on speed (Kovacs & Ellenbecker, 2011). Previously, contrary to results when directly testing the relationship between MDS levels and SV, literature has found that following a traditional resistance training program was moderately useful to enhance velocity production (Kraemer et al., 2003; Treiber et al., 1998). The use of heavy loads (4 to 10 repetition maximum (RM)) seems to improve neural factors that create adaptations that may indirectly benefit velocity production, as an increase in these values is associated with an enhanced relative strength and derived power abilities (Fernandez-Fernandez et al., 2014). Regardless tennis abilities seem to be directly influenced by muscular power, this potential is promoted by the increase of the force

component of the power equation (Reid & Schneiker, 2008). If the intended velocity of movement is maximal, increases in muscle size and type II muscle fibers will appear as an adaptation to heavy-loaded training (Reid & Schneiker, 2008). Also, these programs have been considered useful to reduce fat percentages and increasing muscle mass indexes (Kraemer et al., 2000, 2003), which could evoke changes in BM that would positively affect stroke velocity, as reviewed in the anthropometric characteristics section. Concluding, considering that tennis is a high asymmetrical sport with several muscle imbalances (Sanchis-Moysi et al., 2010, 2017), resistance training programs aiming at increasing overall strength values could be beneficial to reduce these sport-specific adaptations. An increased load of unilateral predominant actions such as the serve has been associated with glenohumeral internal rotation deficits (GIRD), imbalances at the abdominal and lower back level and an increased injury likelihood (Moreno-Pérez et al., 2015). In a highly specialized context as youth tennis, programs that aim at optimizing performance should include training contents towards minimizing negative early sport-specialization adaptations (Lloyd et al., 2016). Following this line, resistance training exercises have proven to be effective in reducing side-to-side asymmetries (Bishop et al., 2018), which could be important not to directly increase SV but to minimize non-desired effects of training and match-play, that may compromise the youth athlete's long-term development.

PLYOMETRICS, STRETCH SHORTENING CYCLE ENHANCED AND STROKE SPECIFIC TRAINING

Although conventional resistance training seems to result in certain gains in velocity production, especially in experienced populations, literature has identified the

enhancement of power values using exercises and techniques that emphasize the SSC more useful. This follows a certain logic as improved levels of power and explosiveness allow to generate greater velocities and transfer these to the racquet resulting in faster strokes (B. Elliott, 2006). Plyometric training has the potential to influence these gains and seems a useful method to mimic the contraction and velocity demands of competition (Behringer et al., 2013; Fernandez-Fernandez et al., 2013, 2016; Genevois et al., 2013; Pardos-Mainer et al., 2017). Fernández-Fernández et al., (2013) identified a significant improvement (4.9%) in SV following 6-weeks of elastic tubing exercises alongside MBT. In the same line, Fernández-Fernández et al., (2016) also found similar increases following a program including throws, upper and lower plyometric exercises. Both mentioned studies were performed with junior tennis players ranging ages around 12-13 years old. As the authors point out, short-term training programs with minimum equipment and effort resulted in performance improvements in young tennis players. As previously discussed, it may be that conventional resistance training programs may enhance stroke velocity in the long term, especially when referring to experimented players with a good training background. On the other hand, when referring to young participants, exercises and programs that focus on the explosive and coordinative traits of the tennis stroke may be more beneficial. Strengthening this idea, Behringer et al., (2013) found significant increases (3.78%) in SV in adolescent players following a plyometric design for 8 weeks, while those subjects performing a machine-based program did not obtain significant improvements. In short, exercises that involve the implication of several muscle groups, full ROM, rotations and fast execution, mimic what happens on court seem important to observe significant gains in stroke velocity (Baiget et al., 2021), especially when referring to younger

participants that may still not benefit from a higher loaded conventional resistance training program. Therefore, MBT programs may be one of the training methods that better address these concerns. The SSC nature of the throwing action has a greater transfer to specific on court actions than methods that establish movements at constant velocities and resistance throughout the totality of motion (Wooden et al., 1992).



Figure 13. Plyometric-based training program example.

Nevertheless, multiple variations of MBT can be found across exercise prescriptions, while high-velocity rotational movements may also be achieved using other equipment and devices. These specific exercise requirements seem essential towards effective improvements in determinant strength factors affecting serve velocity as it stimulates the player's rate of force development capacity. Being able to produce high levels of strength alongside a big amount of contractile impulse in short periods of time of under 250 ms in specific upper arm motions has been found to have a strong relationship to SV (Baiget et al., 2021). Because of this, regardless the methodology and the training mean that the coach selects, some specific indications may be essential towards improvement. That is, RFD and IMP may be effectively achieved either prescribing high-speed and low load or low-speed and high load resistance training as long they include explosive muscle contraction by achieving

maximal intended velocity execution (Baiget et al., 2021). Following the idea of encouraging technical resemblance, some studies have focused on methods that mimic motion and technique in specific situations towards SV improvements. (Ferrauti & Bastiaens, 2007) tested the effectiveness of a complex-throwing intervention of heavy or light ball-throws on SV, finding decrements in the high-loaded group and no changes in the light-throw participants. Genevois et al., (2013) compared an overloaded racquet-based program and a MBT design. Despite the medicine ball group showed further improvements (11%) in SV than the overloaded group (5%), this last design did not have a detrimental effect on precision as happened when performing MBT. Notwithstanding, it should be mentioned that overloading the racquet or limb may negatively affect joint angular velocity and upper body structures in consequence (Whiteside et al., 2014) as identified in previous overloaded throwing programs (Melugin et al., 2021). Therefore, this type of training may be recommended and could be useful in preparation stages away from competition, however, further studies are needed to assess if the benefits are worth the risk and especially establish well defined prescriptions.



Figure 14. Power-based training program examples.

FLYWHEEL-BASED RESISTANCE TRAINING

Following the idea of offering training methods that resemble the motion and specific strength application, approaches using flywheel devices have also been investigated. These devices enhance the eccentric part of contraction (Tous-Fajardo et al., 2016), and although few investigations have attempted to study the effects of an eccentrically enhanced program using flywheels on tennis performance values these could be a valid option to address specific characteristics of strokes mentioned previously. Tennis strokes, due to their execution, demand a great deal of power output and players take advantage of the SSC to enhance velocity (Behringer et al., 2013). Towards this goal, the efficient use of pre-stretch and eccentric contraction to load energy to use in the following concentric phase, it would seem reasonable to include in velocity enhancement programs exercises that involve these aspects. Eccentrically overloaded tasks have proven to induce certain neuromuscular adaptations, typically in the form of increases in overall strength, muscle power, and hypertrophy (Maroto-Izquierdo et al., 2017). Therefore, as devices such as flywheels or conical pulleys have been suggested to improve power-based actions, stroke velocity may also be increased following these training approaches. Canós et al., (2021) found improvements in upper body power indicators tested via MBT after a flywheel-based program. Nevertheless, SV remained unaltered most likely due to insufficient exercises simulating the serve physical needs included in the program. That is, exercises may have lacked to include rotations, various muscle groups, high velocities, and sufficient variability to induce significant changes. Although improvements were not found in the mentioned study, other training programs and layouts would be of great interest to conclude if flywheel-based programs are useful to enhance velocity production.



Figure 15. Flywheel-based resistance training exercise examples.

COMPLEX TRAINING

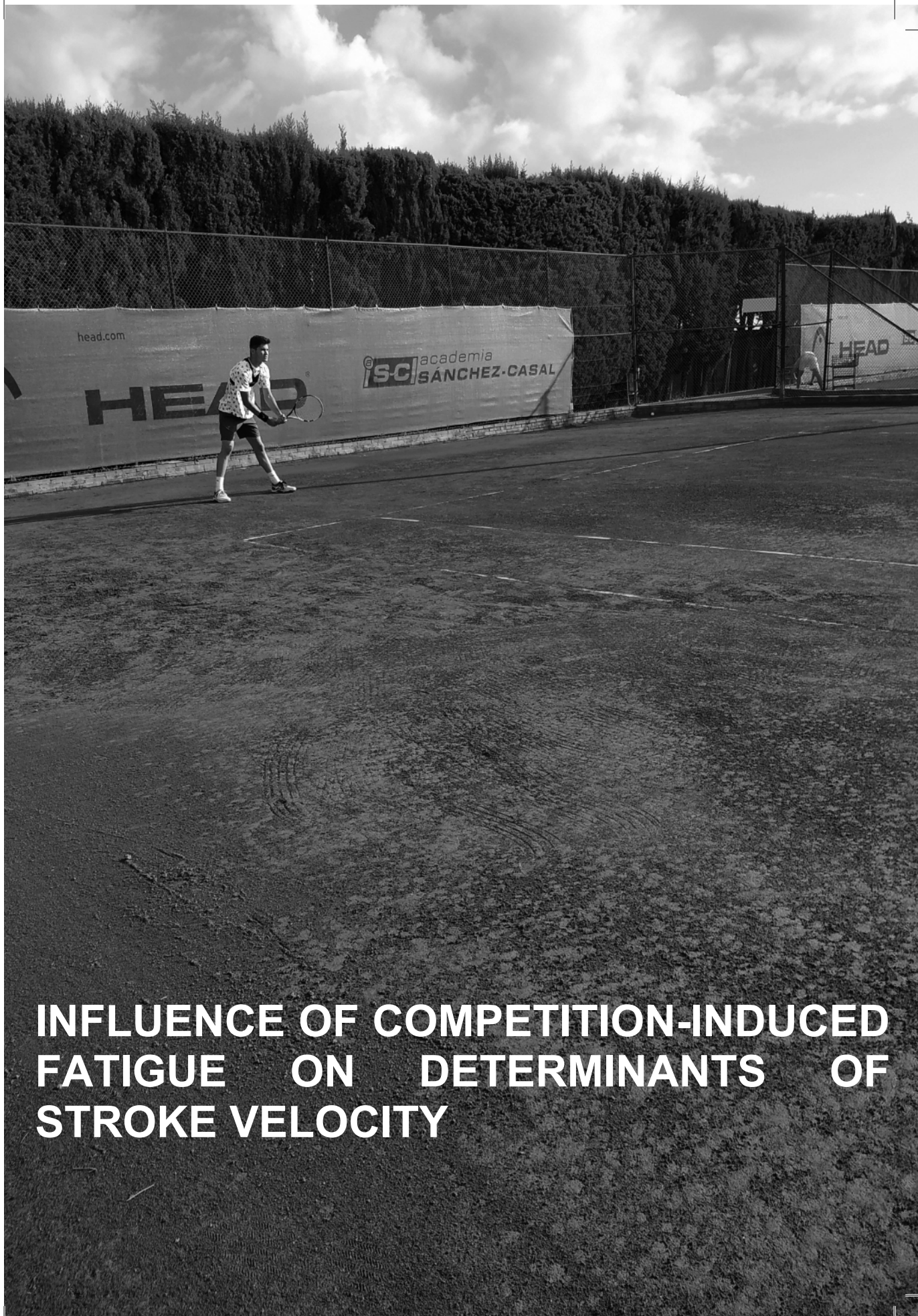
Research points out that the way training is organized may have a certain influence on stroke velocity outcomes (Canós et al., 2022; Kraemer et al., 2003). Competitive calendars and the low availability for training has made literature focus on searching the best options towards working strength, power, and explosiveness in limited training sessions. In this line, it has been suggested that the inclusion of transfer exercises following conventional resistance training tasks may elicit the benefits of complex training layouts (Ebben, 2002). This term is known as the completion of a high load resistance activity towards the enhancement of a posterior plyometric or ballistic action (Finlay et al., 2021). Conventionally used in warm-up protocols to achieve an enhanced performance in the immediate posterior competition, it may also be an interesting option to induce greater power levels in training and achieve stroke velocity improvements in the long term. The rationale behind this phenomenon suggests that increases in muscle temperature, intramuscular fluid accumulation and the beneficial changes in neural mechanisms elicited by heavy loaded exercises will evoke a post-activation performance enhancement (PAPE) that could be used towards more powerful exertions (Finlay et al., 2021). A delayed window of action is

associated to an effective PAPE, and this may depend on the initial exercise performed, the subsequent motion and the individual characteristics of the athlete. Literature has mainly focused on lower body activities, although some research has given some insight on predominantly upper body-based actions towards immediate performance enhancements. Non-specific exercises (i.e., bench press) seem to induce moderate PAPE responses in posterior similar actions (Ulrich & Parstorfer, 2017). On the other hand, sport-specific conditioning activities found a greater induced post-activation performance enhancement when performing overweight implement throws (Montoya et al., 2009) or cable-pulley specific movements (Asencio et al., 2020). Specifically in tennis, Terraza-Rebollo et al., (2017) did not observe any improvements following a non-specific high loaded exercise (3 sets of 3 repetitions at 80% 1RM) in the form of a bench press, a half squat, or the combination of both in SV. These results are in line with moderate or low PAPE outcomes after general strength exercises observed previously (Finlay et al., 2021). In a more serve-specific layout, including six upper body ballistic exercises (i.e., a combination of elastic tubing exercises and overweight implement throws), (Gelen et al., 2012) found improvements in the subsequent SV of young tennis players (1 – 3 %), suggesting PAPE may be more effectively achieved when including resistance training in the form of plyometric or power-based exercises. Nevertheless, these results intended to obtain an immediate PAPE for the following serve velocity enhancement. Contrary, literature is scarce regarding the effectiveness of complex training interventions, especially in predominantly upper body or throwing and striking motions and youth populations. Which exercises induce effective PAPE, with which load prescription and after which specific window of action, remains to be further studied. In any case, the acute neural adaptations achieved by heavy-loaded

resistance training exercises and the possibility of an increased strength and power production in subsequent tasks (Seitz & Haff, 2016) seems of great interest to include in velocity production programs for the young tennis player.



Figure 16. Complex training setting example.



INFLUENCE OF COMPETITION-INDUCED FATIGUE ON DETERMINANTS OF STROKE VELOCITY



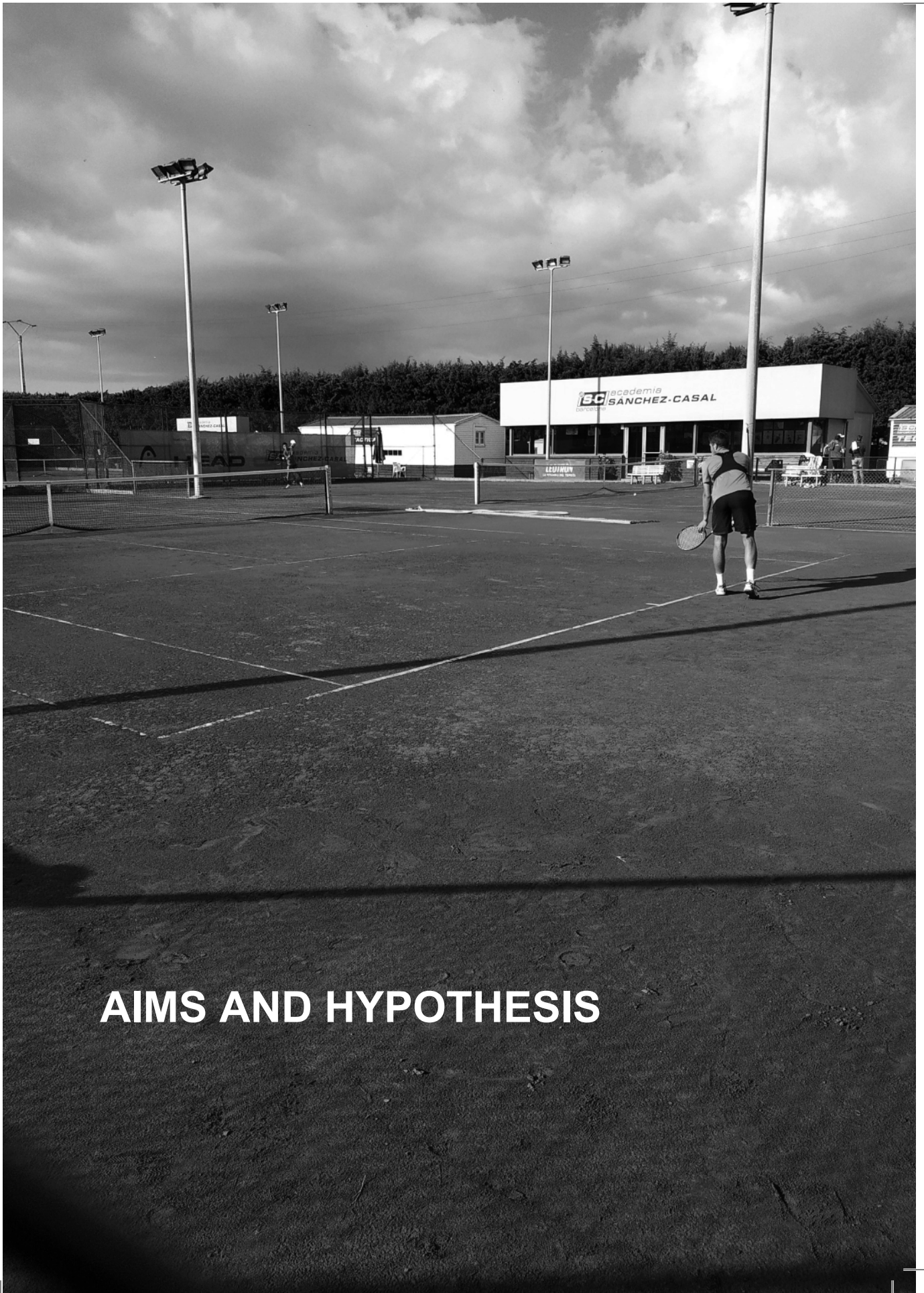
Tennis training and competition has the potential to impair the determinant physical capacities that affect stroke velocity. As these actions are clearly of a multifactorial nature, fatigue is considered a triggering aspect that could negatively affect any of the mentioned aspects. Muscle impairment, soreness, loss of functionality and metabolic exhaustion are directly related to declines in muscular strength and may result in reductions in velocity production (Mendez-Villanueva et al., 2007). Previous research has established precision as the main aspect negatively affected by fatigue (Davey et al., 2002; Gescheit et al., 2015; Rota et al., 2014). Rota et al., (2014) found reductions (-11.7% - 30%) in serve precision after performing maximal intermittent activities, attributed to lactate accumulations. Nevertheless, besides accuracy, competitive or high intensity loads in certain body regions and especially affecting strength and power values could also be main contributors to stroke velocity reductions (Davey et al., 2002). However, these impairments do not seem to affect all competitors in the same way. (Terraza-Rebollo & Baiget, 2021) found no reductions in accuracy or SV following a resistance training or MBT protocol, suggesting although impairments could have appeared in strength and power levels, players may rely on different neuromuscular parameters to maintain performance during the serve. In this sense, experienced players may be able to find strategies to avoid reductions in the capacity to produce fast strokes during fatiguing situations. (Maquirriain et al., 2016) and (Moreno-Pérez et al., 2019) did not observe reductions in precision or speed of elite tennis players after a 5-set match. On the contrary, research has found reductions in SV (3.9 – 4% and 2 km·h⁻¹) in competition tennis players of lower age (Gallo-Salazar et al., 2019) and level (Martin et al., 2016; Rota et al., 2014; Tooth et al., 2020). Yet, investigations are limited when examining the influence of fatigue on stroke velocity in young competitors, making of great interest

further studies on the topic. Following which specific competition and match-play volume and loads and which key physical parameters are mainly affected by these aspects seems essential towards effective recovery strategies, training prescription and organization.

Literature has not only studied fatigue caused by the direct effect of punctual tennis practice or competition, but also prolonged or repetitive bouts of play. The organization model tennis follows (i.e., consecutive matches in the same day or week) has proven to negatively affect SV (Gallo-Salazar et al., 2017; Gescheit et al., 2015). Gallo-Salazar et al., (2017) concluded reductions in this aspect after playing two consecutive matches in junior players. Reasons among which velocity reductions could be explained are the loss of functionality around the shoulder joint caused by maintained and repeated aggressive actions in short periods of time (Martin et al., 2016; Moreno-Pérez et al., 2019). These studies show that shoulder strength deficits and ROM impairments in SHIR and SHER values after performing a high volume of tennis practice or competition. Authors agree and recommend the application of intervention programs including strategies to re-establish values before competition, especially in younger and not so experienced populations without the sufficient expertise and level to take advantage of technical proficiency or more accurate tactical decisions to replace reductions in velocity production. Nevertheless, these recommendations focus on those aspects previously investigated and concluded to reduce performance following specific competitive loads. These include reductions in ROM and maximal voluntary contraction around the shoulder joint, and an increase in perceived soreness and damage. Little literature is available regarding how other physical parameters that define stroke velocity production are affected by match-

play. Thus, including intervention studies that involve pre and post competition measurements of force-time curve variables, muscle contractile properties alongside central fatigue indicators such as balance or aspects that could affect movement competency would be of great interest.





AIMS AND HYPOTHESIS



MAIN GOALS

1.1. To define the main physical factors determining stroke velocity in young tennis players.

1.2. To investigate the acute and chronic effects of prolonged tennis training and competition-induced fatigue on main physical factors affecting stroke velocity.

SECONDARY GOALS

2.1. To establish how physical factors affecting stroke velocity are influenced by age and playing level.

2.2. To examine new programs and training methods towards enhancing velocity production in main tennis strokes.

HYPOTHESIS

Based on previous literature focused on more experimented, older participants of a greater competitive level, it was hypothesized that young tennis players would present a strong relationship between isometric force-time curve variables and stroke velocity, while maximal levels of strength and power would not be as strongly associated. Furthermore, it was expected to find significant reductions of key variables that affect velocity production after performing competitive bouts of match-play. Last, the use of light wrist weights would positively acutely affect velocity production without a detrimental effect in precision in young competitors.

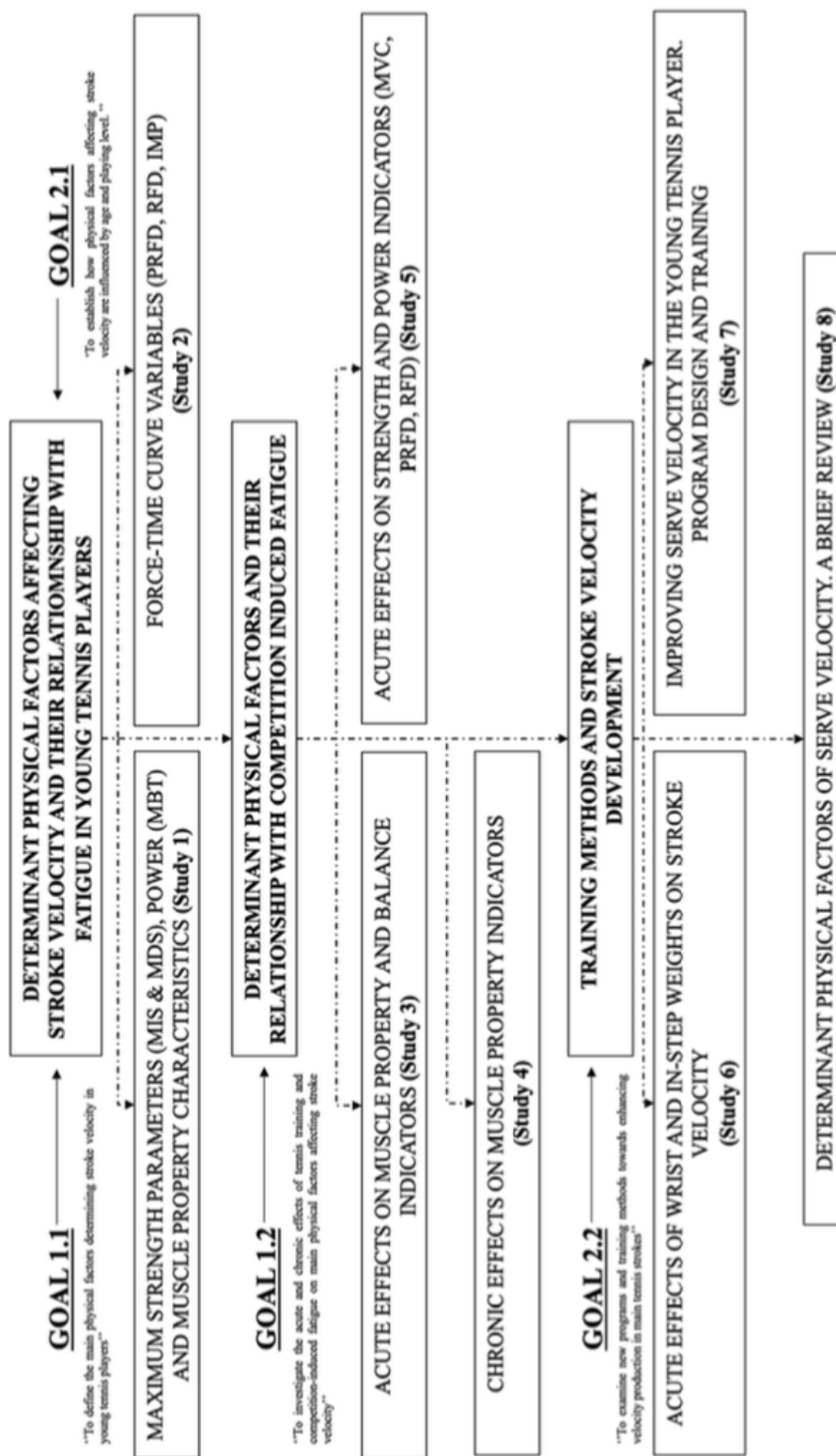


Figure 17. Goal and study synthesis of the project.



METHODS



Six studies were conducted to test the mentioned hypothesis. Four studies were cross-sectional (studies 1, 2, 4 and 6) and two investigations were quasi-experimental pre-post non-randomized interventions (studies 3 and 5). The remaining two studies were literature reviews (studies 7-8).

Following, copies of the papers are presented and consist of the main body of the document. Manuscripts are featured in a specific order following the main objectives of this thesis and not necessarily in chronological or acceptance order. Also, specific methodological designs are presented in each section of the included papers.





PUBLICATIONS

STUDY 1

Influence of Strength, Power, and Muscular Stiffness on Stroke Velocity in Junior Tennis Players

Citation:

Colomar J, Baiget E, Corbi F. Influence of Strength, Power, and Muscular Stiffness on Stroke Velocity in Junior Tennis Players. *Front Physiol.* 2020;11:196. Published 2020 Mar 6.

doi:10.3389/fphys.2020.00196

Journal information:

Frontiers in Physiology

ISSN: 1664-042X

Category: Physiology

Impact Factor: 4.566

Quartile: Q1



Influence of Strength, Power, and Muscular Stiffness on Stroke Velocity in Junior Tennis Players

Joshua Colomar^{1,2*}, Ernest Baiget³ and Francisco Corbi⁴

¹ National Institute of Physical Education (INEFC), University of Barcelona, Barcelona, Spain, ² Sports Science Department, Academia Sánchez-Casal, Barcelona, Spain, ³ Sports Performance Analysis Research Group (SPARG), University of Vic - Central University of Catalonia, Vic, Spain, ⁴ National Institute of Sport and Physical Education (INEFC), University of Lleida, Lleida, Spain

OPEN ACCESS

Edited by:

Miguel-Angel Gomez-Ruano,
Polytechnic University of Madrid,
Spain

Reviewed by:

Erika Zemková,
Comenius University, Slovakia
Souhail Hermassi,
Qatar University, Qatar
Hamdi Chtourou,
University of Sfax, Tunisia
Spyridon Methenitis,
National and Kapodistrian University
of Athens, Greece

*Correspondence:

Joshua Colomar
joshuacolomar@gmail.com

Specialty section:

This article was submitted to
Exercise Physiology,
a section of the journal
Frontiers in Physiology

Received: 12 November 2019

Accepted: 20 February 2020

Published: 06 March 2020

Citation:

Colomar J, Baiget E and Corbi F
(2020) Influence of Strength, Power,
and Muscular Stiffness on Stroke
Velocity in Junior Tennis Players.
Front. Physiol. 11:196.
doi: 10.3389/fphys.2020.00196

Objective: The main aim of this study was to establish the relationship between strength, power characteristics, individual muscle stiffness, international tennis number (ITN), and stroke velocity (StV) in junior tennis players.

Methods: Twenty one junior male tennis players (mean \pm SD; age, 17.0 ± 0.8 years; height, 1.8 ± 0.1 m; body mass, 72.3 ± 5.8 kg; BMI 22.1 ± 1.5 kg/m²), with an ITN ranging from 2 to 4, performed measurements regarding muscle stiffness of selected muscles involved in tennis strokes. StV (serve, forehand, and backhand), strength (maximum isometric strength) and power (medicine ball throws, squat jump, countermovement jump, and bench press) measurements were also performed (ICC = 0.803–0.998; CV = 0.3–6.4).

Results: Moderate inverse correlations were found between serve velocity (SV) and ITN ($r = -0.43$; $p = 0.05$), and large positive correlations were observed between pectoralis majoris stiffness (PMStiff) ($r = 0.53$; $p = 0.01$), isometric wrist flexion ($r = 0.58$; $p = 0.006$) and ITN, respectively. PMStiff was moderately inversely correlated to forehand velocity (FV) ($r = -0.45$; $p = 0.03$) and gastrocnemius (GStiff) and infraspinatus stiffness (IStiff) positively to SV ($r = 0.45$; $p = 0.04$; $r = 0.42$; $p = 0.05$). No significant correlations were found regarding strength and power measurements.

Conclusion: Greater stiffness values may enhance StV, especially when transferring power from lower to upper body. On the other hand, high scores could interfere in technical parameters that are key for velocity production in complex tennis strokes. Strength and power values proved to correlate poorly to StV in this particular sample of junior tennis players, possibly due to the multifactorial nature of tennis strokes and the possibility that they become more important as age and level increase.

Keywords: serve, forehand, backhand, speed, testing

INTRODUCTION

Today's tennis is considered as a fast-paced, explosive and highly dynamic sport (Roetert et al., 2009b; Fernández-Fernández et al., 2014). High hitting velocities, specifically in the serve, can decide the game and are directly related to the tennis player's level (Gillet et al., 2009; Ulbricht et al., 2016). This action has been considered the most important shot, due to the possibilities to dominate the rally or win the point directly through an ace (Gillet et al., 2009; Kovacs and Ellenbecker, 2011). On the other hand, groundstroke velocity has received less attention by literature, although some data on the matter suggest an increased hitting velocity when comparing professional and youth high-performance players (Landlinger et al., 2012). Achieving higher velocity production in strokes could be an important factor on which players may benefit in order to improve performance and achieve higher competitive levels. Moreover, tennis strokes are considered highly complex motor skills which require force production and the ability to transfer these forces throughout the entire body in what is known as the kinetic chain (Kibler, 2009, 2014). Thus, further knowledge around specific determinants of stroke velocities and how they influence performance could be of interest for practitioners.

Because of the aforementioned characteristics, it is commonly been accepted that these strokes are affected by several parameters such as technique (Roetert et al., 2009a,b), anthropometrics (Söğüt, 2014; Bonato et al., 2015), strength, power (Baiget et al., 2016; Fett et al., 2018; Palmer et al., 2018) biological (Sanchis-Moysi et al., 2010), and range of movement (ROM) characteristics (Palmer et al., 2018), making the action of a multi-factorial nature. Several studies have focused on biomechanical and kinematic factors influencing hitting performance (Elliott et al., 1995; Roetert et al., 2009a,b), establishing the speed of the racquet head, internal rotation of the upper arm, wrist flexion and moment of ball impact as some of the major contributors to generate velocity (Elliott et al., 1995). Also, anthropometrics such as height and body mass have been related positively with serve speed in professional and young players (Söğüt, 2014; Bonato et al., 2015; Fett et al., 2018). Regarding strength values, literature traditionally has focused on analyzing isokinetic data at certain joint positions and degrees that mimic the serve action (Ellenbecker and Roetert, 2003), obtaining moderate positive correlations especially on those positions that resemble the serve motion. More recently, investigations have also aimed to assess strength values adding maximal isometric strength testing to experimental methods, especially in the shoulder complex (Cools et al., 2014; Baiget et al., 2016; Fett et al., 2018; Hayes et al., 2018). When assessing SV, it has been accepted as a contributor to velocity production, but few investigations have aimed to the relationship between maximal isometric strength and forehands or backhands. Further research regarding groundstrokes could be of interest as previous studies have shown a strong relationship between isometric strength and performance (Baiget et al., 2016). When focusing on dynamic strength, some interesting data has recently been analyzed, indicating upper body strength and power as important contributors of the junior tennis player's serve (Fett et al., 2018; Palmer et al., 2018). Nevertheless, as the majority of investigations

have established strength and power as contributors to SV in elite players, it seems interesting to further focus on these measurements regarding young competitive players and especially analyzing the groundstrokes. Taking into account these actions as determinant factors differentiating elite from sub-elite players (Landlinger et al., 2012), it seems important to study associations between strength and power characteristics and groundstrokes, as we find regarding SV in literature.

Furthermore, the influence of complex neuromuscular factors has hardly been studied in relation to any tennis specific stroke. Enhanced values of mechanical stiffness, that can be defined as the resistance of an object or body to deformation or change in length (Brughelli and Cronin, 2008), have been suggested as beneficial for actions that rely on the stretch shortened cycle (SSC) such as jumping, sprinting or agility (Brughelli and Cronin, 2008). Due to the greater capacity of a compliant structure to absorb and re-use rapidly greater amounts of elastic energy for a given force (Kalkhoven and Watsford, 2018), this quality could be beneficial or have influence on tennis strokes, as they are complex skills that involve SSC actions in the entire kinetic chain. On the other hand, an increased or non-sufficient level of the mentioned stiffness could interpose technical aspects or the capacity to produce velocity to the stroke (Brazier et al., 2017). Because of this, studies have started to investigate neuromechanical factors such as individual muscle stiffness and their contribution to performance aspects (Sheehan et al., 2018). The majority of investigations on stiffness have aimed at actions involving the lower body (Pruyn et al., 2014; Kalkhoven and Watsford, 2018), making this phenomenon still unclear when speaking of how it affects predominantly upper body motions. Added to this, investigations have aimed to establish specific predictors of tennis actions, yet to the best of our knowledge, none concerning the relationship between muscle stiffness characteristics and stroke velocity (StV), especially on groundstrokes and junior tennis players.

In short, the influence of specific strength and power parameters on StV, especially groundstrokes, and how muscle mechanical properties affect dynamic actions seems of importance for professionals. Therefore, the aim of this study was to examine the relationship between strength and power characteristics, individual muscle stiffness values, international tennis number (ITN) and StV in competitive junior tennis players. Our working hypothesis was that a strong positive association will exist between strength and power characteristics, ITN and all strokes, as seen previously in SV (Baiget et al., 2016; Fett et al., 2018; Hayes et al., 2018; Palmer et al., 2018). Also, due to the beneficial effects of enhanced stiffness in explosive actions (Brughelli and Cronin, 2008), a higher level of this property in the muscle groups tested will correlate to faster StV.

MATERIALS AND METHODS

Participants

Twenty-one junior male tennis players (mean \pm SD; age, 17.0 \pm 0.8 years; height, 1.8 \pm 0.1 m; body mass, 72.3 \pm 5.8 kg; BMI 22.1 \pm 1.5 kg/m²) with an ITN ranging from 2 to 4

(advanced level) participated in this study. A *priori* power analysis for a Pearson correlation was conducted in G*power to estimate a sufficient sample size. With the alpha level set at 0.05, using a large target effect size (ES) of 0.6, a power of 0.80 and two tails, it was determined that 19 subjects would be needed. The player's ITN was established by the consensus of three coaches accredited with RPT (Registro Profesional de Tenis) level 3, following the ITN Description of Standards (ITN, 2019). Subjects had a weekly volume of training of 25 h/week⁻¹ of which 5 accounted for fitness training and 20 for technical and tactical sessions. The mean training background of the players was 10.1 ± 1.7 years, which focused on tennis-specific training (i.e., technical and tactical skills), aerobic and anaerobic training (i.e., on- and off-court exercises), and strength training. Inclusion criteria for all subjects required each participant to have a minimum of 1 year experience in strength training and 5 years of tennis training and competition. Participants were excluded from the study if they had history of upper extremity surgery, shoulder, back or knee pain and/or rehabilitation for the past 12 months. All subjects were informed in advance about the characteristics of the study and, before their participation, the participants or their legal tutors, in the case of being underage, voluntarily signed an informed consent. The study was conducted following the ethical principles for biomedical research with human beings, established in the Declaration of Helsinki of the AMM (2013) and approved by the Ethics Committee of the Catalan Sports Council (26/2018/CEICEGC).

Experimental Design

This was a cross-sectional laboratory study with uninjured participants. The collection of data took place in May during a normal in-season training week in groups of 4 or 5 players and on 4 separate testing sessions, executed from 8 a.m. to 2 p.m. approximately, before the player's afternoon normal technical-tactical training. On session 1, participants were assessed for 1 repetition maximum (1RM) on the bench press exercise. On session 2, participants were assessed for individual muscle stiffness (Stiff) via muscle natural oscillation. On session 3, participants were assessed for maximal StV on the forehand, backhand and serve actions. On session 4, participants were assessed using strength tests including bench press peak power (Wmax), maximal isometric strength (IsoMax) in 5 different positions, squat jump (SJ), countermovement jump (CMJ), and medicine ball overhead throw (MBT), following that order. Sessions 2, 3, and 4 were separate 2 h apart and session 1 was executed 24 h before. Players performed one tennis technical-tactical training session of 90 min between sessions 1 and 2 and ceased activity for at least 14 h before resuming the testing protocol. The use of pain-relieving strategies (e.g., foam rolling, massage, ice baths, etc.) was not allowed during testing in order to avoid interferences with the results. Players were allowed to consume water *ad libitum*. Isotonic and energetic drinks were not allowed during the tests. The order of the sessions was established this way with the intention of avoiding the influence of stiffness, strength and power testing on the StV protocol. In order to ensure a better precision and reproducibility of singles measurements, the intra-session reliability of stiffness, strength, power and StV

values was determined using a test-retest design. Thus, the same testing procedure that was carried out in the current study was repeated twice in the strength and power (1RM, Wmax, IsoMax, SJ, CMJ, and MBT), three times in the StV (forehand, backhand, and serve) and five times in stiffness measurements in all tennis players. Two familiarization sessions of all the strength and power tests were completed during the 2 weeks prior to the application of the protocol.

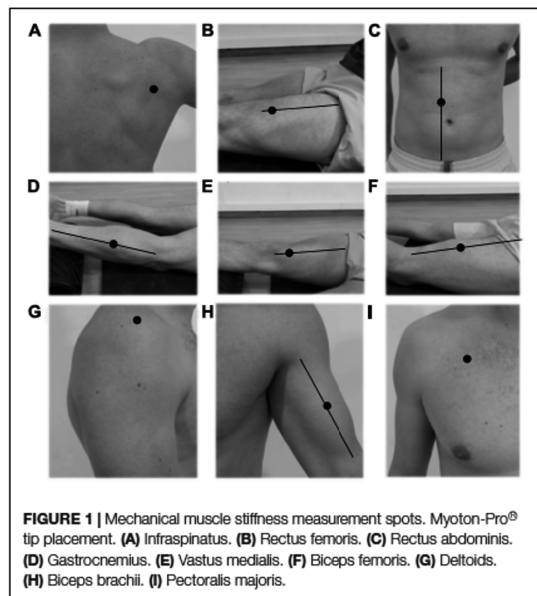
Procedures

1-Repetition Maximum Estimation

Maximum dynamic strength was estimated in session 1 using the load-velocity relationship via a progressive load test (Jidovtseff et al., 2011). All subjects were tested in four progressive loads in the bench press exercise. The number of series performed were executed in the following manner; eight repetitions with 20 kg of load; eight repetitions with 30 kg; eight repetitions with 35 kg, and eight repetitions with 40 kg. Participants had 5 min rest between sets. For each load, players were indicated to raise the bar as quickly as possible without releasing it. If eight repetitions were not performed, as many as the subject performed were recorded. The test recorded only the concentric phase of the exercise so the bar had an initial position of 3 cm above the nipple line. During the whole movement, the subjects had their backs on the bench and their hips flexed at 90°. The best repetition was recorded for the analysis of the maximum speed achieved. 1RM was estimated using a regression line plotted through the known load (X) and average velocity (Y). From this linear regression, the slope, theoretical average velocity at 0 kg, and theoretical load at 0 m/s⁻¹ were calculated by means of a linear transducer (CLTP, Chronojump Bioscosystem®, Barcelona, Spain) (Jidovtseff et al., 2011). This encoder has been previously validated showing it has a valuable and reliable system for measuring movement velocity and for estimating power in strength and conditioning training exercises (Garnacho-Castaño et al., 2014).

Contractile Properties Measurement

In session 2, individual muscle stiffness was recorded on the dominant side of the body using a hand-held myometer (Myoton-Pro, Myoton AS, Tallinn, Estonia). The dominant extremity or side of the body was established based on upper body dominance. Before the assessment, body marks were established for the nine measurement points using the SENIAM electrode placement guides (Freriks et al., 1999; Konrad, 2005; Figure 1). The muscle groups chosen were those mostly involved in the hitting actions (Girard et al., 2005) attending to the whole kinetic chain; pectoralis major (PM); biceps brachii (B); infraspinatus (I); deltoids (D); rectus abdominis (RA), the rectus femoris (RF); vastus medialis (VM); biceps femoris (BF), and the lateral head of the gastrocnemius (G). The measurements were made with a state of muscle relaxation and the subjects lying down (RA), seated (PM, B, I, D) or in anatomical position (RF, VM, BF, G), depending on the test point. The tip of the Myoton-Pro was placed perpendicular to all measurement zones sampling at 15 ms with a force of 0.58 N and measured the damped natural oscillations cause by the probe impact. The device's accelerometers operated



at 3,200 Hz, offering an average value of five consecutive measurements. The Myoton-Pro reliability is expressed in Table 1, and shows excellent test-retest values ($ICC = 0.95-0.99$; $CV = 0.3-0.9$) as shown previously in other investigations (Zinder and Padua, 2013).

Maximum Hitting Velocity

In session 3, subjects performed a standardized warm-up that included mobility exercises, 5 min of free rallies and 5-10 progressive serves. Each subject executed a series of 6 flat serves on each side of the court with 60 s of rest between sets and 12 forehands and 12 backhands (crossed-court) without alternating strokes. Only the serves that were in the serve box and the groundstrokes that landed in the court were counted. StV was determined using a hand-held radar gun [Stalker ATS II, United States, frequency: 34.7 GHz (Ka-Band) ± 50 MHz] and peak velocity was registered for further analysis. The radar was positioned in the center of the baseline, 2 m behind the line and at an approximate height of 2 m for the serves and behind the player following the trajectory of the ball for groundstrokes. Hitting as hard and precise as possible to the "T" was indicated when serving and cross-court when hitting groundstrokes. Immediate feedback was provided to the subjects to encourage maximum effort. To avoid variability performing groundstrokes, balls were fed by a ball-throwing machine (Pop-Lob Airmatic 104, France) at a constant speed ($68.6 \pm 1.9 \text{ km h}^{-1}$).

Strength and Power Measurements

In session 4, the participants were asked to perform five maximum isometric tests following a protocol similar to that offered by Baiget et al. (2016). The different positions tested

were: internal shoulder rotation with the elbow and shoulder flexed 90° (IsoIR), horizontal shoulder abduction (IsoAbd), horizontal shoulder adduction (IsoAdd), wrist flexion (IsoWrF), and extension (IsoWrE). The test was performed sitting on an Ercolina machine (Technogym Company[®], Cesena, Italy). The participants sat in a position with a 90° hip flexion and the back resting on a bench. All the participants were fastened with a harness on the chest to avoid unwanted movements. Only the dominant extremity was evaluated. The maximum isometric force peak was recorded using a strain gauge sampling at 80 Hz (Chronojump, Boscosystem[®], Barcelona, Spain). Positions were established before each test using a goniometer. Subjects performed three maximal voluntary contractions for 3-6 s and spaced by 1-min rest between attempts. Regarding upper body, peak power (Wmax) was assessed with a linear transducer (CLTP, Chronojump, Boscosystem[®], Barcelona, Spain) and analyzed with Chronojump Software (v1.8) using a load based on each participant's 1RM. Each subject performed eight repetitions on the bench press exercise without verbal encouragement given. Following the literature (Soriano et al., 2017) the load was set at 50% of the 1RM since it seems closest to optimal for the development of the peak power in the bench press. Only the propulsive concentric phase of the exercise was analyzed. During the whole movement, the subjects had their backs on the bench and their hips flexed at 90° . No bouncing or arching the back was allowed. MBT were evaluated using 3 external loads of 1, 2, and 3 kg. The participants placed themselves behind a line and performed three throws with each of the balls, spaced by 1 min of rest between them. Throws had to be performed with both hands, above the head, without jumping or taking advantage of the momentum of the legs or falling with the feet in front of the throwing line. MBT seem to be useful for testing tennis players as they show high external validity, because they involve the coordination of body segments (i.e., kinetic chain) (Fernández-Fernández et al., 2014). Regarding lower body, CMJ and SJ in order to assess lower body power were performed on a contact platform (Chronojump, Boscosystem[®], Barcelona, Spain). Each participant executed three maximum jumps spaced by 45 s of passive rest. The best trial (i.e., highest jump height) was used for the subsequent analysis.

Statistical Analyses

The values presented are expressed as mean \pm SD and 95% confidence intervals (95% CI). The normality of the distributions and homogeneity of variances were assessed with the Shapiro-Wilk test, all variables showed normal distributions except for ITN. The reliabilities of test measurements were assessed using intraclass correlation coefficients (ICCs), the standard error of measurements (SEM), and the coefficient of variation (CV). All of stiffness, strength, power and serve, forehand, and backhand velocity measurements reached an acceptable level of reliability and are presented in Table 1. Pearson correlation coefficients were used to examine the relations between serve, forehand and backhand velocity and strength, power, and stiffness variables. Strength, power and stiffness

DISCUSSION

This study aimed to analyze strength (maximum isometric strength) and power (medicine ball throws, SJ, CMJ, and bench press peak power) characteristics alongside ITN as possible determinants of StV, including serve and groundstrokes, in junior tennis players. The main finding was that an increased gastrocnemius (GStiff), infraspinatus (IStiff), and decreased pectoralis majoris stiffness (PMStiff) may have some positive influence over performance in serve (SV) and forehand velocity (FV) respectively. Also, SV was inversely correlated to ITN. Moreover, strength and power values proved to be weak predictors of StV in this particular sample of junior tennis players. These results indicate that players of these characteristics that are able to reach higher velocity production in the serve and groundstrokes don't specifically rely on the assessed strength and power characteristics.

In other investigations it has been shown that physical aspects such as strength and power are determinant for producing ball velocity (Fett et al., 2018; Palmer et al., 2018), also when comparing players of different levels (Girard et al., 2005; Ulbricht et al., 2016). Non-significant positive results have been found between some physical indicators such as isokinetic strength and SV (Ellenbecker, 1991) but recent findings restate the importance of strength and power characteristics for velocity production on both, national young tennis players (Fett et al., 2018) and highly competitive players (Baiget et al., 2016). These differences in results with the present study could be explained by the variance of the analyzed subjects. The cited investigations carried out assessments with highly skilled players that respond to elite population (Baiget et al., 2016; Fett et al., 2018). Added to the fact that the players participating in this study were of a different level (ITN 2/4 vs. 1/2) than those present in other investigations (Baiget et al., 2016), there could also be an influence due to the age (17.0 ± 0.8 vs. $9.4\text{--}17.9$ age range) (Fett et al., 2018) of the subjects for contrary results. Younger players may still rely more thoroughly on technique and coordinative skills while serving or hitting rather than on strength values that may become more important as both age and level increases. As suggested in literature, this may indicate that although SV is highly related to tennis performance, velocity production may depend more importantly on strength and power parameters as the player grows and the performance level raises (Girard, 2009).

Studies focused on SV have generally established positive results between MBT and velocity production in young tennis players (Fett et al., 2018). MBT have even been established as fundamental indicators of whole-body explosive power regardless of throwing technique (Fernández-Fernández et al., 2014). Surprisingly, no correlations were found between the overhead MBT and StV in this study. Leaving aside the lack of positive results between MBT and SV, results regarding FV and BV may be explained by methodological issues. MBT testing focused on the overhead motion only, and, although the conducted test assessed three different loads (1, 2, and 3 kg), it did not contemplate mimicking the forehand or the backhand motion (i.e., throwing the medicine ball with one or two hands

from the side of the body), as previously studied and found positively correlated with SV (Ulbricht et al., 2016; Fett et al., 2018). On the other hand, consistent with findings in other studies (Kraemer et al., 2003), poor correlations were found for the bench press exercise and either groundstrokes or SV. This, most likely, is explained by the lack of movement similarity and, unlike the MBT testing, the low specificity of the action. Also, muscle involvement in the bench press exercise is reduced to fewer groups than in tennis specific strokes.

Regarding maximal isometric values, no correlations with any of the actions measured were found besides results indicating a positive association between maximal isometric wrist flexion and a higher ITN score. Previous studies have positively correlated isometric strength values with throwing (Ferragut et al., 2011; Freeston et al., 2016) or even tennis specific motions in both, upper and lower body (Fett et al., 2018; Hayes et al., 2018). The findings in this investigation are consistent with those present in other works that found no relation between isometric measurements and tennis actions (Bonato et al., 2015). However, and given that the positions measured are rather different than those focused on the grip, results are surprising. Due to the similarity of the positions tested and those present and involved in the kinetic chain at the wrist, elbow and shoulder, it was expected to obtain certain positive relations between both variables. As literature points out, increased levels of maximal isometric strength, evaluated during multi-joint actions, are likely to be positively related to dynamic performances (Juneja et al., 2010) such as the serve and groundstrokes (Baiget et al., 2016). However, the discrepancy could be explained by the fact that the participants were similar in age but not in level (ITN 1-2 vs. ITN 2-4 or high-performance vs. elite) to those present in other studies (Baiget et al., 2016; Hayes et al., 2018). It would be possible that these players still rely more on coordinative aspects while serving or hitting rather than on strength values that may increase with age and level (Girard, 2009). Moreover, the ability to apply a high amount of force in a short time (i.e., rate of force development) could be of greater importance over absolute values of strength when referring to explosive dynamic actions such as the analyzed strokes.

Lower body power variables analyzed (i.e., SJ and CMJ) did not correlate with any of the StV variables. Although the contribution of the legs is considered widely as one of the main parameters supporting the effectiveness of the kinetic chain (Kibler, 2009), these results indicate that strength values such as explosiveness and power may not be as determinant as coordinative aspects involved in tennis strokes (Bonato et al., 2015; Dossena et al., 2018). Strong consistency has been found in other investigations stating vertical jumps as predictors of sprinting times and lower body strength/power values in tennis players (Kraemer et al., 2003; Girard et al., 2005). Nevertheless, regarding actions such as strokes, this does not seem as clear. As predominantly lower body actions could benefit from enhanced strength and power values, regarding upper body actions such as serves and groundstrokes, legs might provide a coordinative and timing contribution to velocity-production (Bonato et al., 2015; Dossena et al., 2018; Fett et al., 2018).

Regarding muscle stiffness, results indicate moderate positive correlations between GSTiff, IStiff and SV, PMStiff, and ITN, and inverse correlations between PMStiff and FV. As far as we know, no previous studies have attempted to correlate individual stiffness values and StV, although in other investigations, some findings indicate the importance of stiffness when we refer to actions that rely on the SSC (Brughelli and Cronin, 2008; Pruyn et al., 2014; Kalkhoven and Watsford, 2018; Sheehan et al., 2018). Generally, literature has found positive evidence linking greater stiffness values to enhanced sprinting or jumping, mainly lower body actions (Brughelli and Cronin, 2008; Kalkhoven and Watsford, 2018). This happens because of the athlete's capacity to store more elastic energy during ground contact and generate greater force output at push-off, increasing jump height and running speed (Brazier et al., 2017). On the other hand, in predominantly upper body motions as tennis strokes, research is scarce. The study carried out by Sheehan et al. (2018), found a strong relationship between vertical stiffness assessed via a unilateral leg hop test and the club head speed in male golfers. When analysing upper body muscle groups, no significant results regarding pectoralis majoris, latissimus dorsi, flexor carpi ulnaris, and club head speed were found. No measurements of vertical stiffness were included in the study design of this investigation, limiting the findings regarding the influence of muscle stiffness of the lower body and its relation to velocity production. Nevertheless, the strong and consistent correlations between stiffness and dynamic performance observed in other investigations (Sheehan et al., 2018), may indicate that greater stiffness values in lower body muscles could be beneficial for performance in motions taking place predominantly in the upper body. In this line, the fact that a higher level of stiffness of the gastrocnemius benefits SV could follow the same idea, as energy storage and transfer from lower to upper body is key for tennis actions (Kibler, 2009). Regarding purely upper body muscle stiffness values, results are similar to those seen in other studies (Sheehan et al., 2018), observing small correlations with StV. Greater levels of PMStiff seem to have a certain negative influence on FV and ITN, suggesting that a greater level of stiffness in the upper body, far from being beneficial could interpose velocity production in junior tennis players. This matches findings in literature (Sheehan et al., 2018), suggesting that tendencies for compliancy might be favorable for motions involving the SSC in the upper body. As complex motor skills such as the tennis groundstrokes rely, among other aspects, on the principle of coordination of individual impulses and an effective kinetic chain (Kibler, 2009, 2014), high levels of upper body stiffness could be counterproductive for these particular actions, affecting execution. Moreover, tightness and increased external rotation when compared to the non-dominant side have been well established as contributors of shoulder internal rotation deficit (Marcondes et al., 2013), which generally can lead to shoulder injury in overhead athletes (Moreno-Pérez et al., 2015). It could be, as it appears when speaking of lower body actions, that an increased or non-sufficient level of stiffness could contribute to a greater injury risk, due to increased shock, peak forces and reduced ROM (Brazier et al., 2017).

As a general idea, stiffness values may be beneficial to reduce electromechanical delay and enhance rate of force development, as could be the case of moderate positive correlations found here between IStiff and SV. On the other hand, stiffness could interfere in technical parameters that are key for velocity production in complex tennis strokes and increase injury likelihood due to restrictions in ROM. In any case, this is speculative and additional work is required to state a conclusion on the matter. The fact that stiffness measures were collected individually and in a relaxed state that differs highly with that present during competition may be a reason for generally poor correlations found in this study. Therefore, future investigations may explore upper body stiffness in a more "global" manner, as it has generally been done concerning lower body (i.e., hopping tests) and try to measure muscle stiffness in different contraction regimes.

This study showed some limitations. Maximal speed measurements, especially in groundstrokes, don't take into account technical and tactical aspects on which skilled players may rely on in order to reach greater performance (i.e., spin or shot placement).

PRACTICAL APPLICATIONS

As specific values of stiffness remain unclear, this study suggests practitioners include control and evaluation of stiffness as it may have influence in performance or injury risk. Moreover, due to multiple aspects affecting StV, designing programs that include technical and tactical assessment alongside strength and power enhancement, coordinative training and biomechanical aspects seems essential to enhance velocity production. Performance in these actions are affected by several aspects and the influence of them over StV may vary depending on the athlete's age and level.

CONCLUSION

In conclusion, an increased GSTiff and IStiff seem to correlate to greater SV and high values of PMStiff affect negatively the player's FV. Greater stiffness values of the gastrocnemius may enhance StV, possibly supporting power transfer from lower to upper body. On the other hand, enhanced levels in muscles surrounding the shoulder complex could interfere in technical parameters that are key for velocity production in complex tennis strokes. Also, SV is inversely correlated to ITN, indicating that players with a higher number in this rating seem to serve faster. Moreover, strength and power values proved to correlate poorly to StV in this particular sample of junior tennis players. Results indicate that athletes of these characteristics that are able to reach higher velocity production in the serve and groundstrokes don't specifically rely on the assessed strength and power characteristics, possibly due to the multifactorial nature of tennis strokes and the possibility that they become more important as age and level increase.

DATA AVAILABILITY STATEMENT

All datasets generated for this study are included in the article/supplementary material.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Catalan Sports Council Research Committee. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

REFERENCES

- Baiget, E., Corbi, F., Fuentes, J. P., and Fernández-Fernández, J. (2016). The relationship between maximum isometric strength and ball velocity in the tennis serve. *J. Hum. Kinet.* 53, 63–71. doi: 10.1515/hukin-2016-0028
- Bonato, M., Maggioni, M. A., Rossi, C., Rampichini, S., La Torre, A., and Merati, G. (2015). Relationship between anthropometric or functional characteristics and maximal serve velocity in professional tennis players. *J. Sports Med. Phys. Fit.* 55, 1157–1165.
- Brazier, J., Maloney, S., Bishop, C., Read, P., and Turner, A. (2017). Lower extremity stiffness: considerations for testing, performance enhancement, and injury risk. *J. Strength Cond. Res.* 33, 1156–1166. doi: 10.1519/JSC.0000000000002283
- Brughelli, M., and Cronin, J. (2008). A review of research on the mechanical stiffness in running and jumping: methodology and implications. *Scand. J. Med. Sci. Sport* 18, 417–426. doi: 10.1111/j.1600-0838.2008.00769.x
- Cools, A. M., Palmans, T., and Johansson, F. R. (2014). Age-related, sport-specific adaptations of the shoulder girdle in elite adolescent tennis players. *J. Athl. Train.* 49, 647–653. doi: 10.4085/1062-6050-49.3.02
- Dossena, F., Rossi, C., La Torre, A., and Bonato, M. (2018). The role of lower limbs during tennis serve. *J. Sports Med. Phys. Fit.* 58, 210–215. doi: 10.23736/S0022-4707.16.06685-8
- Ellenbecker, T., and Roetert, E. P. (2003). Age specific isokinetic glenohumeral internal and external rotation strength in elite junior tennis players. *J. Sci. Med. Sport* 6, 63–70. doi: 10.1016/s1440-2440(03)80009-9
- Ellenbecker, T. S. (1991). A total arm strength isokinetic profile of highly skilled tennis players. *Isokinet Exerc. Sci.* 1, 9–21. doi: 10.3233/ies-1991-1103
- Elliott, B. C., Marshall, R. N., and Noffal, G. J. (1995). Contributions of upper limb segment rotations during the power serve in tennis. *J. Appl. Biomech.* 11, 433–442. doi: 10.1123/jab.11.4.433
- Fernández-Fernández, J., Ulbricht, A., and Ferrauti, A. (2014). Fitness testing of tennis players: how valuable is it? *Br. J. Sports Med.* 48(Suppl. 1), i22–i31. doi: 10.1136/bjsports-2013-093152
- Ferragut, C., Vila, J. A., Abrales, F., Argudo, F., Rodriguez, N., and Alcaraz, P. E. (2011). Relationship among maximal grip, throwing velocity and anthropometric parameters in elite water polo players. *J. Sports Med. Phys. Fit.* 51, 26–32.
- Fett, J., Ulbricht, A., and Ferrauti, A. (2018). Impact of physical performance and anthropometric characteristics on serve velocity in elite junior tennis players. *J. Strength Cond. Res.* 34, 192–202. doi: 10.1519/JSC.0000000000002641
- Freeston, J. L., Carter, T., Whitaker, G., Nicholls, O., and Rooney, K. B. (2016). Strength and power correlates of throwing velocity on subelite male cricket players. *J. Strength Cond. Res.* 30, 1646–1651. doi: 10.1519/jsc.0000000000001246
- Freriks, B., Hermens, H., Disselhorst-Klug, C., and Rau, G. (1999). The recommendations for sensors and sensor placement procedures for surface electromyography. *Seniam* 8, 13–54.

AUTHOR CONTRIBUTIONS

JC, EB, and FC contributed to the conceptualization, methodology, and review. EB contributed to the statistical analysis. JC contributed to the writing of the original draft preparation.

ACKNOWLEDGMENTS

We thank all the players and coaches for their enthusiastic participation. We would like to thank Academia Sánchez-Casal Barcelona. This work was supported by the National Institute of Physical Education of Catalonia (INEFC).

- Garnacho-Castaño, M. V., López-Lastra, S., and Maté-Muñoz, J. L. (2014). Reliability and validity assessment of a linear position transducer. *J. Sport Sci. Med.* 14, 128–136.
- Gillet, E., Leroy, D., Thouvaireq, R., and Stein, J. F. (2009). A notational analysis of elite tennis serve and serve-return strategies on slow surface. *J. Strength Cond. Res.* 23, 532–539. doi: 10.1519/JSC.0b013e31818efc29
- Girard, O. (2009). Physical determinants of tennis performance in competitive teenage players. *J. Strength Cond. Res.* 29, 1867–1872. doi: 10.1519/JSC.0b013e3181b3df89
- Girard, O., Micallef, J. P., and Millet, G. P. (2005). Lower-limb activity during the power serve in tennis: effects of performance level. *Med. Sci. Sports Exerc.* 37:1021.
- Hayes, M. J., Spits, D. R., Watts, D. G., and Kelly, V. G. (2018). The relationship between tennis serve velocity and select performance measures. *J. Strength Cond. Res.* 10. doi: 10.1519/JSC.0000000000002440 [Epub ahead of print].
- Hopkins, W. G., Marshall, S. W., Batterham, A. M., and Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Med. Sci. Sports Exerc.* 41, 3–12.
- ITN, (2019). *International Tennis Federation Description of Standards*. Available from: www.tennisplayandstay.com/media/131801/131801.pdf (accessed October 30, 2019).
- Jidovtseff, B., Harris, N. K., Crielaard, J. M., and Cronin, J. B. (2011). Using the load-velocity relationship for 1RM prediction. *J. Strength Cond. Res.* 25, 267–270. doi: 10.1519/JSC.0b013e3181b62c5f
- Juneja, H., Verma, S. K., and Khanna, G. L. (2010). Isometric strength and its relationship to dynamic performance: a systematic review. *JESP* 6, 60–69.
- Kalkhoven, J. T., and Watsford, M. L. (2018). The relationship between mechanical stiffness and athletic performance markers in sub-elite footballers. *J. Sports Sci.* 36, 1022–1029. doi: 10.1080/02640414.2017.1349921
- Kibler, B. (2009). The 4000-watt tennis player: power development for tennis. *Med. Sci. Tennis* 14, 5–8.
- Kibler, B. (2014). Understanding the kinetic chain. *Aspetar. Sport Med. J.* 3, 492–497.
- Konrad, P. (2005). *The ABC of EMG. A Practical Introduction to Kinesiological Electromyography*. Scottsdale, AZ: Noraxon INC.
- Kovacs, M., and Ellenbecker, T. (2011). An 8-stage model for evaluating the tennis serve: implications for performance enhancement and injury prevention. *Sports Health* 3, 504–513. doi: 10.1177/1941738111414175
- Kraemer, W. J., Hakkinen, K., Triplett-Mcbride, N. T., Fry, A. C., Koziris, L. P., Ratamess, N. A., et al. (2003). Physiological changes with periodized tennis players. *Med. Sci. Sports Exerc.* 35, 157–168.
- Landlinger, J., Stöggl, T., Lindinger, S., Wagner, H., and Müller, E. (2012). Differences in ball speed and accuracy of tennis groundstrokes between elite and high-performance players. *Eur. J. Sport Sci.* 12, 301–308. doi: 10.1080/17461391.2011.566363
- Marcondes, F. B., Jesus, J. F., de Bryk, F. F., Vasconcelos, R. A., and Fukuda, T. Y. (2013). Posterior shoulder tightness and rotator cuff strength assessments in painful shoulders of amateur tennis players. *Brazi. J. Phys. Ther.* 17, 185–193. doi: 10.1590/S1413-35552012005000079

- Moreno-Pérez, V., Moreside, J., Barbado, D., and Vera-García, F. J. (2015). Comparison of shoulder rotation range of motion in professional tennis players with and without history of shoulder pain. *Man Ther.* 20, 313–318. doi: 10.1016/j.math.2014.10.008
- Palmer, K., Jones, D., Morgan, C., and Zeppieri, G. (2018). Relationship between range of motion, strength, motor control, power, and the tennis serve in competitive-level tennis players: a pilot study. *Sports Health* 10, 462–467. doi: 10.1177/1941738118785348
- Pruyn, E., Watsford, M., and Murphy, A. (2014). The relationship between lower-body stiffness and dynamic performance. *Appl. Physiol. Nutr. Metab.* 39, 1144–1150. doi: 10.1139/apnm-2014-0063
- Roetert, E. P., Ellenbecker, T. S., and Reid, M. (2009a). Biomechanics of the tennis serve: implications for strength training. *Strength Cond. J.* 31, 35–40. doi: 10.1519/ssc.0b013e3181af65e1
- Roetert, E. P., Kovacs, M., Knudson, D., and Groppe, J. (2009b). Biomechanics of the tennis groundstrokes: implications for strength training. *Strength Cond. J.* 31, 41–49. doi: 10.1519/ssc.0b013e3181aff0c3
- Sanchís-Moysi, J., Olmedillas, H., Guadalupe-Grau, A., Alayón, S., Carreras, A., Dorado, C., et al. (2010). The upper extremity of the professional tennis player: muscle volume, fiber-type distribution and muscle strength. *Scand. J. Med. Sci. Sports* 20, 524–534. doi: 10.1111/j.1600-0838.2009.00969.x
- Sheehan, W. B., Watsford, M. L., and Pickering Rodriguez, E. C. (2018). Examination of the neuromechanical factors contributing to golf swing performance. *J. Sports Sci.* 37, 458–466. doi: 10.1080/02640414.2018.1505185
- Söğüt, M. (2014). Ball speed during the tennis serve in relation to skill level and body height. *Pamukkale J. Sport Sci.* 7, 51–57.
- Soriano, M. A., Suchomel, T. J., and Marin, P. J. (2017). The optimal load for maximal power production during upper-body resistance exercises: a meta-analysis. *Sport Med.* 47, 757–768. doi: 10.1007/s40279-016-0626-6
- Ulbricht, A., Fernandez-Fernandez, J., Mendez-Villanueva, A., and Ferrauti, A. (2016). Impact of fitness characteristics on tennis performance in elite junior tennis players. *J. Strength Cond. Res.* 30, 989–998. doi: 10.1519/JSC.0000000000001267
- Zinder, S. M., and Padua, D. A. (2013). Reliability, validity, and precision of a handheld myometer for assessing in vivo muscle stiffness. *J. Sport Rehabil.* 20, 1–8.
- Conflict of Interest:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Copyright © 2020 Colomar, Baiget and Corbi. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.



STUDY 2

Relationship between isometric force-time variables and serve velocity in young tennis players

Citation: Colomar J, Baiget E, Corbi F. 2022. Relationship between isometric force-time variables and serve velocity in young tennis players. Sports Biomechanics. [Under review].

doi: -

Journal information:

ISSN: -

Category: -

Impact Factor: -

Quartile: -

RELATIONSHIP BETWEEN ISOMETRIC FORCE-TIME CURVE VARIABLES AND SERVE VELOCITY IN YOUNG TENNIS PLAYERS

ABSTRACT

This study aimed at a) examine the associations between serve velocity (SV) and maximal isometric voluntary contraction (MVC), peak rate of force development (PRFD), rate of force development (RFD) and impulse (IMP) at different stages of contraction and b) to establish a prediction equation based on the relationship between these variables. Sixteen players performed four maximum isometric tests in positions involved in the tennis serve motion. Variables tested included MVC, PRFD, RFD and IMP at 50, 100, 150 and 200 ms while performing a 90° shoulder internal rotation (SHIR), shoulder flexion (SHF), horizontal shoulder abduction (SHABD) and an isometric mid-thigh pull (IMTP). Significant ($p \leq 0.05$) moderate-to-very-large correlations were found between SV, MVC and PRFD. RFD at different time intervals showed positive associations with SV, except in the SHF0-200ms and IMTP0-200ms. Accordingly, IMP values positively correlated to SV in all positions except in the SHIR0-50ms and the IMTP in late contraction stages. The multiple regression analysis showed that 79% of the variance in SV was determined by the combination of IMTP PRFD and SHF IMP0-200ms. Results indicate that the capacity to develop power in short periods of time (<200 ms) positively influence SV in young participants.

Key words: power, serve, impulse, rate of force development, strength

INTRODUCTION

The tennis serve, and particularly serve velocity (SV) has been established as the most important performance factor in both competition (Fitzpatrick et al., 2019) and junior (Ulbricht et al., 2016) tennis players. Diverse variables influence the outcome of the serve and as a complex motor action, efficacy and efficiency are affected by various parameters such as anthropometric characteristics, technical proficiency, range of motion and strength and power levels (Elliott, 2006; Fett et al., 2020; Gillet et al., 2009; Hayes et al., 2018; Kovacs & Ellenbecker, 2011; Palmer et al., 2018).

Specifically, regarding neuromuscular parameters, maximal dynamic strength (MDS) values or isokinetic measurements do not seem to correlate strongly to the capacity of generating high speed serves either in junior players (Colomar et al., 2020) or college participants (Cohen et al., 1994; Kraemer et al., 2000). On the other hand, maximal isometric voluntary contraction (MVC) tested in specific joint positions involved in the serve kinetic chain seem to have a positive relationship with SV (Baiget et al., 2016; Hayes et al., 2018). Although static measurements may not represent in the best way highly dynamic and fast actions such as the serve (Fernandez-Fernandez et al., 2014), research has found strong associations between certain joint settings (i.e., shoulder internal rotation or shoulder and wrist flexion) and SV, especially when accounting the combination of various positions present in the motion (Baiget et al., 2016, 2021; Cools et al., 2014; Hayes et al., 2018). Added to this, explosive actions such as the serve involve an evident high number of stretch-shortening cycles (SSC), the coordination of many body segments and the effective use of elastic energy (Elliott, 2006). Moreover, the available time for force production can be as short as 80 ms during the concentric phase of the serve

(Kibler et al., 2007). This fact highlights the importance not only of achieving high values of MVC, but also force-time characteristics such as the rate of force development (RFD) or impulse (IMP) during the serve action (Girard et al., 2014; Hayes et al., 2018). Baiget et al., (2021) found that these variables correlated highly with SV, suggesting the capacity of generating force in short periods of time is significantly related to producing high speed serves, especially around specific shoulder positions and in time intervals as short as 50 ms. However, considering the serve a complex movement involving many body segments, force-time variables concerning predominantly lower body measurements have not been studied thoroughly. The role of the legs during the serve has been established as an important link to transfer energy from lower to upper body (Kibler et al., 2007). At the moment of impact, the amount of speed applied to the ball is mainly attributed to shoulder internal rotation and wrist flexion movements, yet literature points out a relevant importance to the lower body in developing speed (Girard & Millet, 2009). In this line, research has found relations between jumping height (Dossena et al., 2018; Hayes et al., 2018), isokinetic strength in leg extensors (Wong et al., 2014) or impulse during an IMTP test (Hayes et al., 2018) and SV in competition players. Despite this, to our knowledge no specific measures regarding force production in different time intervals and their relation to SV have been studied in lower body joint positions.

Interestingly, diverse outcomes result when analyzing and comparing the importance and influence of different strength values in young and more experienced competition players of a greater level (Colomar et al., 2020; Fett et al., 2020; Kramer et al., 2016). As previous research suggests, it may be that competitors of different characteristics

rely more thoroughly on different parameters that affect velocity production. In short, it is hypothesized that younger or lower ranked players may use to a further extent technique or favorable anthropometric traits over absolute strength and power levels, which would be more determinant in older competition and elite populations (Colomar et al., 2020; Fett et al., 2020; Girard & Millet, 2009; Kramer et al., 2016). However, literature is scarce when investigating the relationship between force-time variables such as RFD and IMP and SV in young participants.

Thus, the goals of this study were a) to examine associations between SV and MVC, peak rate of force development (PRFD), RFD and IMP at different stages of contraction in specific joint positions involved in the serve kinetic chain and b) to develop a prediction model based on the relationship between these variables. Based on previous literature (Baiget et al., 2021), we hypothesized SV would positively correlate to greater values of MVC, RFD and IMP, especially in early phases of contraction (<100 ms) in both upper and lower body joint positions.

MATERIALS AND METHODS

Participants

Sixteen (8 female and 8 male) junior tennis players (mean \pm SD; age, 14.1 ± 1.2 years; height, 1.71 ± 0.07 m; body mass, 62.6 ± 7.5 kg; BMI 21.1 ± 2.1 kg/m²) participated in the study. Players had a tennis training experience of 7.5 ± 1.4 years and an International Tennis Number (ITN) of 3 (advanced level). ITN was established by the consensus of two coaches accredited with RPT (Professional Tennis Registry) level 3, following the ITN Description of Standards (www.internationaltennisnumber.com). Participants had a weekly training volume of

20 h·week⁻¹ comprising 3h of technical and tactical tennis practice and 1h of physical conditioning per day from Monday to Friday. One subject was left-handed while all other participants had a dominant right extremity. Fifteen players performed a two-handed backhand, while the remaining player executed a one-handed form. Inclusion criteria required to have at least 1-year of participation in a structured fitness program and a minimum of 5-years of tennis training and competition. Participants were excluded from the study if they had any back, upper or lower extremity discomfort or undergone rehabilitation or surgery in the past 3 months. All participants were informed about the characteristics of the study and voluntarily signed an informed consent. In the case of being underage, their legal tutors signed the form. The study was conducted following the ethical principles for biomedical research with human beings, established in the Declaration of Helsinki of the AMM (2013) and approved by an accredited Ethics Committee.

Experimental design

The experimental design was conducted as summarized in Figure 1. The study was divided into two testing sessions performed on the same day and separated by 10 minutes. Participants performed the force-time testing followed by the SV assessment. Players were allowed to consume water ad libitum. Energetic drinks were not allowed during the trials. Participants did not exercise for at least 18h before the protocol took place. They were indicated to maintain their habitual routine, to avoid excitatory substances (i.e., coffee or tea) and vigorous exercise during the previous day to the testing sessions. All measurements were performed in the morning, approximately from 7:30 am to 8:30 am. The experiments were performed in competition period.

Insert Figure 1 around here

Testing procedures

Force-time characteristics assessment

Participants were asked to perform four MVC tests of relevant joint positions involved in the serve kinetic chain. Positions tested were (a) internal shoulder rotation with the elbow and shoulder flexed 90° (SHIR), (b) shoulder flexion (SHF), (c) horizontal shoulder abduction (SHABD) and (d) mid-thigh pull (IMTP) as indicated in Figure 1. Prior to testing, participants performed two submaximal attempts of 3 seconds of the selected positions at approximately 50%-75% maximal effort, separated by 60 seconds each (Comfort et al., 2019). SHIR, SHF and SHABD tests were performed similar to Baiget et al., (2016), on a Ercolina machine (Technogym Company, Cesena, Italy), participants sat with a 90° hip flexion and the back resting on a bench and fastened with a harness to avoid extra movement of other body segments. Only the dominant extremity was registered. For the IMTP, tests were performed using a portable alternative to a force plate using a strength gauge attached to a heavy metal base, similar to the protocol offered by James et al., (2017). Mid-thigh position was determined before testing by marking the midpoint distance between the knee and hip joints (i.e., between the iliac crest and the patella), as it seems athletes adopt their preferred hip and knee angles for the test (Comfort et al., 2015). The height of the bar was adjusted up or down to make sure it was in contact with the mid-thigh. Preferred grip was allowed. Participants were indicated to perform 1 second of quiet standing followed by a maximal effort for 5 seconds (Comfort et al., 2019). The force-time curve was registered using a strain gauge sampling at 80 Hz and the relevant

analysis software (Chronojump, Boscosystem, Barcelona, Spain). MVC and PRFD were defined as the peak value attained during the 5 seconds. Moreover, force outputs at 50, 100, 150 and 200 ms from the start of the pull were determined for each trial (Comfort et al., 2015). RFD was calculated with the following equation: $RFD = \Delta Force / \Delta Time$. Participants performed two trials spaced by 2 min rest between attempts. To avoid that the order of the evaluations could influence fatigue, tests were performed as expressed in Figure 1. All variables reached good to excellent test-retest values (ICC = 0.823 – 0.982; CV = 0.23 – 0.72)

Serve velocity (SV)

Testing was performed on a tennis hard court under stable wind conditions (< 2 m·s⁻¹) using new tennis balls (Head ATP Pro, Spain). Before the assessment, participants performed a standardized warm-up including mobility exercises, 5 minutes of free rallies and 10 progressive serves. Each player executed 8 serves (2 sets of 4 serves on each side of the court) with 2 minutes of rest between sets and 10 seconds between serves. Only the serves that landed in the serve box were included in the analysis. SV was determined using a hand-held radar gun (Stalker ATS II, USA, frequency: 34.7 GHz [Ka-Band] ± 50 MHz). The radar was positioned in the center of the baseline, 2 m behind the line and at an approximate height of 2 m following the trajectory of the ball. Players were asked to hit as hard as possible and direct feedback was delivered to the participants to encourage effort.

Statistical Analyses

Data are reported as mean ± standard deviation (SD). Normality of distributions and homogeneity of variances were assessed with the Shapiro-Wilk test. The reliabilities

of test measurements were assessed using intraclass correlation coefficients (ICCs) and the coefficient of variation (CV). Pearson correlation coefficient was used to examine the relations between SV and MVC, PRFD and RFD at different contraction times in the SHIR, SHF, SHABD and IMTP positions. Correlations were classified as trivial (0–0.1), small (0.1–0.3), moderate (0.3–0.5), large (0.5–0.7), very large (0.7–0.9), nearly perfect (0.9), and perfect (1.0) (Hopkins et al., 2009). Mean SV was used as the dependent variable and force-time variables at different time intervals (MVC, PRFD, RFD and IMP) were the independent predictors in the stepwise multiple regression analysis. The level of significance was set at $p < 0.05$. All statistical analyses were performed using IBM SPSS Statistics 26.0 (SPSS, Inc., Chicago, IL.).

RESULTS

A total of 128 serves were performed of which 48.4% were considered in and therefore used for analysis. Average SV was 138.3 km·h⁻¹. Correlation coefficients between SV and isometric force-time variables are summed up in Table 1. Mean values of the measurements are plotted in Figure 2. Significant ($p < 0.05$) moderate-to-very-large correlations were found between SV, MVC and PRFD. Regarding RFD at different time intervals, significant associations were found in the four tested positions, except in the later stages of contraction (i.e., 200 ms) in the SHF and IMTP. Accordingly, IMP showed positive correlations with SV in all positions except the SHIR at 50 ms and the IMTP at 100, 150 and 200 ms.

****Insert Table 1 around here****

****Insert Figure 2 around here****

A stepwise multiple regression analysis was used to select the most promising isometric time-force curve variables for determination of SV (Table 2). The model reached its best fit after 2 steps and PRFD IMTP was entered first into the model, explaining 61% of the variance in SV. SHF IMP0-200ms was the second-best predictor, contributing a further 18%, which allowed the combined model to account for 79% of the overall variance for SV.

****Insert Table 2 around here****

DISCUSSION AND IMPLICATIONS

The main finding of this investigation was that isometric force-time variables in specific joint positions involved in the tennis serve kinetic chain positively correlate to SV in young tennis players. Moreover, the capacity of producing high levels of force in short periods of time seems to be relevant to enhanced velocity production. The results of the stepwise multiple regression analysis showed that 79% of the variance in SV was determined by the combination of IMTP PRFD and SHF IMP0-200ms, indicating that the combination of high values of RFD and IMP in both upper and lower body structures involved in the serve could be relevant for increasing velocity.

Associations between isometric force-time variables and SV seem to follow previous strength parameters positively correlated to velocity production in older, more experienced competition players. Specifically, regarding absolute values of isometric strength, results in this investigation are in accordance with positive associations between upper body MVC and SV observed previously (Baiget et al., 2016; Hayes et al., 2018), restating the importance of achieving high values of isometric strength in

specific shoulder joint positions involved in the upper arm rotation, also in younger and lower ranked participants. Nevertheless, some investigations found absolute dynamic or isometric strength values did not seem to correlate as strongly to SV (Colomar et al., 2020; Kraemer et al., 2003). Being the serve a complex motor skill that involves multiple characteristics of different nature (i.e., neuromuscular, anthropometrics, technique, and ROM), on which of these skills a player relies on more thoroughly may differ depending on the tested subjects. Most likely, the importance of strength and power values in building speed to the serve varies across ages and playing levels. As previously investigated, the importance of fitness characteristics on SV showed lower heights of determination in the younger age groups (U12) than older players, increasing values as competitors grow (Fett et al., 2020). As suggested, SV may not be an equally predominant factor in pre-adolescent players who may rely more thoroughly on technical factors rather than fitness parameters (Fett et al., 2020). Accordingly, the importance of these variables increases with age, playing level and the maturational status of the player (Girard & Millet, 2009; Kramer et al., 2016). Results here suggest the importance of achieving high values of isometric strength in both the shoulder joint in specific upper arm internal rotation motions and lower body extension movements in teenage participants. Moreover, the serve is a high-speed rotational movement with limited time availability (Kibler et al., 2007). Consequently, the ability to develop the previously mentioned strength values in short periods of time has been deemed essential towards an effective performance (Baiget et al., 2021; Girard et al., 2014; Hayes et al., 2018). Functional measurements of upper and lower body power measured through medicine ball throws (MBT) or jumping height have previously been positively correlated to the capacity of a player to serve faster in competition

participants (Dossena et al., 2018; Fett et al., 2020; Hayes et al., 2018). In this same line, explosive force application (i.e., RFD and IMP) values in short time intervals (< 250 ms) around the shoulder joint have been found to highly influence the outcome of SV (Baiget et al., 2021). Findings in the present study show that younger participants and more experienced competitors, regarding age and level, seem to benefit to a similar extent from an enhanced capacity of developing high values of PRFD and RFD in periods shorter than 200 ms. These findings restate the importance of explosiveness in upper body internal rotational movements and therefore the relevance of neural drive and motor unit discharge rate towards effective force production in early phases of contraction, alongside ideal mechanical muscle characteristics and overall strength to ensure best functioning in the later stages (Andersen et al., 2010; Andersen & Aagaard, 2006). The capacity of producing force and being able to apply it to the rotational movement of the upper arm results in a faster angular momentum of the head of the racquet and the consequent increase in ball speed (Martin et al., 2013). In this line, IMP values showed consistent outcomes and relevant associations with SV in the majority of time intervals and positions tested. Impulse is an indicator of the accumulation of force during a given period (Aagaard et al., 2002). The serve is considered a complex motion relying on the coordination of multiple body segments and the buildup of momentum throughout all phases of the action and contraction time (Myers et al., n.d.). Greater IMP would facilitate greater momentum and as long as force is built up during the force application window of time and transferred effectively throughout the kinetic chain, SV would result enhanced (Baiget et al., 2021). Accordingly, previous investigations testing IMP values in the IMTP position found positive associations between these variables at 100 and 200 ms (Hayes et al.,

2018). Likewise, IMP here was largely correlated in practically all contraction times and positions except the IMTP in later stages (> 100 ms). These outcomes seem to indicate the importance of the buildup and accumulation of force overtime alongside the application of great levels of strength in short periods (i.e., RFD), especially in early phases of contraction and in upper limb joint positions.

Regarding the influence of the legs in building velocity towards a faster serve, to our knowledge this is the first study to examine the associations between force-time curve variables in a predominantly lower body joint position and SV. In the same way as concerning movements around the shoulder, results indicate the importance of MVC (0.716; $p = 0.01$) and PRFD (0.799; $p = 0.001$) in the IMTP position. As previously stated in literature, part of the success to obtain a fast tennis serve can be dependent on an effective buildup of muscle preload and the use of elastic energy in leg extensor muscles towards generating a powerful lower-limb drive (Girard et al., 2005). Obtaining higher values of explosiveness in the lower body will traduce into velocity gradually increasing from legs towards the long-axis rotational elements such as the upper arm or shoulder segments (Girard et al., 2005), if effective coordination throughout the kinetic chain is guaranteed (Kibler et al., 2007). In this line, increased PRFD and RFD values in early stages of muscle contraction were correlated to faster SV, restating that an increased capacity of producing explosive and fast actions in leg extensor movements is relevant to velocity production. In a similar way to the upper limbs, the application of force during the concentric phase of the serve is limited to short time windows. Moreover, the legs seem to be the initial stage of the movement and the starting point of the kinetic chain (Kibler et al., 2007). Because of this, it seems reasonable to find large to very large associations ($r = 0.634 - 0.751$; p

= < 0.01) between the RFD in 50, 100 and 150 ms time frames and SV, indicating those players capable of applying strength in short contraction times in the lower body will most likely benefit from enhanced velocity production. Nonetheless, IMP values in lower body positions did not correlate strongly to SV indicating that the accumulation of force over time did not seem as relevant as the capacity of a player to develop power rapidly.

The multiple regression analysis results indicate the model that best explained SV was the combination of PRFD in the IMTP test and SHF0-200ms, accounting for 79% of variance in SV. These outcomes strengthen the idea that multiple aspects affect a player's capacity to develop speed during the serve. Depending on sex, age, level and the individual characteristics of the player, the importance of these aspects may vary substantially (Fett et al., 2020; Kramer et al., 2016). Nevertheless, as observed in this study regarding strength and power levels, results indicate that the combination of high absolute isometric values and enhanced levels of PRFD involving body structures present in the entire movement (i.e., upper and lower body) translate into a greater capacity of the young tennis player to apply speed to the serve. This reinforces the idea that training methods aiming at enhancing SV throughout power development include not only forceful rotational movements in the upper arm segments but more importantly incorporate to the program exercises that globally implicate the totality of the kinetic chain. Following this idea, added to the fact that force-time variables have proven to be important aspects affecting SV, the importance of technical parameters and coordinative patterns that ensure an efficient serve motion seem to be highly relevant to the young tennis player (Fett et al., 2020; Girard & Millet, 2009). This supports the recommendation of including in velocity

production enhancement programs not only strength and power tasks that involve the totality of the kinetic chain (i.e., upper and lower body) but also include a certain resemblance to the technical motion.

This study had some limitations. Although participants were homogeneous regarding age, training experience and level, the fact that these were 50% boys, and 50% girls may have affected results to some extent, as chronological age during adolescence can result in differences in maturation levels. Also, the strain gauge used for this study sampled at 200 Hz which might be a low frequency for early contraction time measurements such as the 50 ms.

CONCLUSIONS

In conclusion, isometric force-time values (i.e., MVC, PRFD, RFD and IMP at different contraction times) moderate-to-very-largely correlate to SV in young tennis players. Findings suggest explosive force production in joint positions typically involved in the totality of the serve kinetic chain have a high importance in the capacity of young players to apply speed to the ball. Moreover, the combination of an enhanced level of these capacities in various of the tested positions seems to explain a great deal of SV in young participants.

Junior tennis is characterized by high training volumes that are typically organized in several sessions alongside many competitive events. Training availability is limited and knowledge around those physical factors affecting a determinant action such as the serve gains importance for optimal development. Therefore, including program designs that incorporate exercises focused on speed, power and velocity production

should be essential towards effective use of time. Specifically, exercises that elicit the enhancement of RFD (i.e., with maximal intended velocity execution regardless the external load), especially involving SHIR, SHF and SHABD could be beneficial towards SV improvements. In the same way, high speed rotational movements that integrate the presence and coordination of these specific shoulder positions and include the lower body throughout the motion most likely develops PRFD levels and positively influences SV. MBT, cable pulley multiarticular motions and/or flywheel program designs that involve many body segments, include fast execution and a certain demand of coordinated movements throughout the kinetic chain seem valid options toward obtaining the desired effects. Moreover, isometric evaluation is a cheap easy and non-time-consuming tool to effectively evaluate strength levels. Thus, it is suggested that monitoring for player development includes strength and power testing as soon as these characteristics are relevant and affect to a big extent serve performance.

ACKNOWLEDGEMENTS

Authors would like to thank players and coaches for their enthusiastic participation.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

REFERENCES

Aagaard, P., Simonsen, E. B., Andersen, J. L., Magnusson, P., & Dyhre-Poulsen, P. (2002). Increased rate of force development and neural drive of human skeletal muscle following resistance training. *Journal of Applied Physiology*, 93(4), 1318–

1326. <https://doi.org/10.1152/jappphysiol.00283.2002>

Andersen, L. L., & Aagaard, P. (2006). Influence of maximal muscle strength and intrinsic muscle contractile properties on contractile rate of force development. *European Journal of Applied Physiology*, 96(1), 46–52. <https://doi.org/10.1007/s00421-005-0070-z>

Andersen, L. L., Andersen, J. L., Zebis, M. K., & Aagaard, P. (2010). Early and late rate of force development: Differential adaptive responses to resistance training? *Scandinavian Journal of Medicine & Science in Sports*, 20(1), e162–e169. <https://doi.org/10.1111/j.1600-0838.2009.00933.x>

Baiget, E., Colomar, J., & Corbi, F. (2021). Upper-Limb Force–Time Characteristics Determine Serve Velocity in Competition Tennis Players. *International Journal of Sports Physiology and Performance*, Ahead of print, 1–9. <https://doi.org/10.1123/ijsp.2021-0254>

Baiget, E., Corbi, F., Fuentes, J. P., & Fernández-Fernández, J. (2016). The Relationship Between Maximum Isometric Strength and Ball Velocity in the Tennis Serve. *Journal of Human Kinetics*, 53(1), 63–71. <https://doi.org/10.1515/hukin-2016-0028>

Cohen, D. B., Mont, M. A., Campbell, K. R., Vogelstein, B. N., & Loewy, J. W. (1994). Upper Extremity Physical Factors Affecting Tennis Serve Velocity. *The American Journal of Sports Medicine*, 22(6), 746–750. <https://doi.org/10.1177/036354659402200604>

Colomar, J., Baiget, E., & Corbi, F. (2020). Influence of Strength, Power, and Muscular Stiffness on Stroke Velocity in Junior Tennis Players. *Frontiers in Physiology*, 11, 196. <https://doi.org/10.3389/fphys.2020.00196>

Comfort, P., Dos'Santos, T., Beckham, G. K., Stone, M. H., Guppy, S. N., & Haff, G.

- G. (2019). Standardization and Methodological Considerations for the Isometric Midthigh Pull: *Strength and Conditioning Journal*, 41(2), 57–79. <https://doi.org/10.1519/SSC.0000000000000433>
- Comfort, P., Jones, Paul. A., McMahon, J. J., & Newton, R. (2015). Effect of Knee and Trunk Angle on Kinetic Variables During the Isometric Midthigh Pull: Test–Retest Reliability. *International Journal of Sports Physiology and Performance*, 10(1), 58–63. <https://doi.org/10.1123/ijsp.2014-0077>
- Cools, A. M., Palmans, T., & Johansson, F. R. (2014). Age-Related, Sport-Specific Adaptions of the Shoulder Girdle in Elite Adolescent Tennis Players. *Journal of Athletic Training*, 49(5), 647–653. <https://doi.org/10.4085/1062-6050-49.3.02>
- Dossena, F., Rossi, C., Torre, A. L., & Bonato, M. (2018). The role of lower limbs during tennis serve. *The Journal of Sports Medicine and Physical Fitness*, 3. <https://doi.org/10.23736/S0022-4707.16.06685-8>
- Elliott, B. (2006). Biomechanics and tennis. *British Journal of Sports Medicine*, 40(5), 392–396. <https://doi.org/10.1136/bjism.2005.023150>
- Fernandez-Fernandez, J., Ulbricht, A., & Ferrauti, A. (2014). Fitness testing of tennis players: How valuable is it? *British Journal of Sports Medicine*, 48(Suppl 1), i22–i31. <https://doi.org/10.1136/bjsports-2013-093152>
- Fett, J., Ulbricht, A., & Ferrauti, A. (2020). Impact of Physical Performance and Anthropometric Characteristics on Serve Velocity in Elite Junior Tennis Players: *Journal of Strength and Conditioning Research*, 34(1), 192–202. <https://doi.org/10.1519/JSC.0000000000002641>
- Fitzpatrick, A., Stone, J. A., Choppin, S., & Kelley, J. (2019). Important performance characteristics in elite clay and grass court tennis match-play. *International Journal of Performance Analysis in Sport*, 19(6), 942–952.

<https://doi.org/10.1080/24748668.2019.1685804>

Gillet, E., Leroy, D., Thouvarecq, R., & Stein, J.-F. (2009). A Notational Analysis of Elite Tennis Serve and Serve-Return Strategies on Slow Surface: *Journal of Strength and Conditioning Research*, 23(2), 532–539.

<https://doi.org/10.1519/JSC.0b013e31818efe29>

Girard, O., Micallef, J.-P., & Millet, G. P. (2005). Lower-Limb Activity during the Power Serve in Tennis: Effects of Performance Level. *Medicine & Science in Sports & Exercise*, 37(6), 1021–1029.

Girard, O., & Millet, G. P. (2009). Physical Determinants of Tennis Performance in Competitive Teenage Players: *Journal of Strength and Conditioning Research*, 23(6), 1867–1872. <https://doi.org/10.1519/JSC.0b013e3181b3df89>

Girard, O., Racinais, S., & Périard, J. D. (2014). Tennis in hot and cool conditions decreases the rapid muscle torque production capacity of the knee extensors but not of the plantar flexors. *British Journal of Sports Medicine*, 48(Suppl 1), i52–i58. <https://doi.org/10.1136/bjsports-2013-093286>

Hayes, M. J., Spits, D. R., Watts, D. G., & Kelly, V. G. (2018). The Relationship Between Tennis Serve Velocity and Select Performance Measures: *Journal of Strength and Conditioning Research*, 1. <https://doi.org/10.1519/JSC.0000000000002440>

Hopkins, W. G., Marshall, S. W., Batterham, A. M., & Hanin, J. (2009). Progressive Statistics for Studies in Sports Medicine and Exercise Science: *Medicine & Science in Sports & Exercise*, 41(1), 3–13. <https://doi.org/10.1249/MSS.0b013e31818cb278>

James, L. P., Roberts, L. A., Haff, G. G., Kelly, V. G., & Beckman, E. M. (2017). Validity and Reliability of a Portable Isometric Mid-Thigh Clean Pull: *Journal of Strength and Conditioning Research*, 31(5), 1378–1386.

<https://doi.org/10.1519/JSC.0000000000001201>

Kibler, W. B., Chandler, T. J., Shapiro, R., & Conuel, M. (2007). Muscle activation in coupled scapulohumeral motions in the high performance tennis serve. *British Journal of Sports Medicine*, 41(11), 745–749. <https://doi.org/10.1136/bjism.2007.037333>

Kovacs, M. S., & Ellenbecker, T. S. (2011). A Performance Evaluation of the Tennis Serve: Implications for Strength, Speed, Power, and Flexibility Training: *Strength and Conditioning Journal*, 33(4), 22–30. <https://doi.org/10.1519/SSC.0b013e318225d59a>

Kraemer, W. J., H??Kinen, K., Travis Triplett-Mcbride, N., Fry, A. C., Perry Koziris, L., Ratamess, N. A., Bauer, J. E., Volek, J. S., Mcconnell, T., Newton, R. U., Gordon, S. E., Cummings, D., Hauth, J., Pullo, F., Michael Lynch, J., Mazzetti, S. A., & Knuttgen, H. G. (2003). Physiological Changes with Periodized Resistance Training in Women Tennis Players: *Medicine & Science in Sports & Exercise*, 35(1), 157–168. <https://doi.org/10.1097/00005768-200301000-00024>

Kraemer, W. J., Ratamess, N., Fry, A. C., Triplett-McBride, T., Koziris, L. P., Bauer, J. A., Lynch, J. M., & Fleck, S. J. (2000). Influence of Resistance Training Volume and Periodization on Physiological and Performance Adaptations in Collegiate Women Tennis Players. *The American Journal of Sports Medicine*, 28(5), 626–633. <https://doi.org/10.1177/03635465000280050201>

Kramer, T., Huijgen, B. C. H., Elferink-Gemser, M. T., & Visscher, C. (2016). A Longitudinal Study of Physical Fitness in Elite Junior Tennis Players. *Pediatric Exercise Science*, 28(4), 553–564. <https://doi.org/10.1123/pes.2016-0022>

Martin, C., Kulpa, R., Delamarche, P., & Bideau, B. (2013). Professional tennis players' serve: Correlation between segmental angular momentums and ball velocity. *Sports Biomechanics*, 12(1), 2–14. <https://doi.org/10.1080/14763141.2012.734321>

- Myers, N. L., Sciascia, A. D., Westgate, P. M., Kibler, W. B., & Uhl, T. L. (2015). Increasing ball velocity in the overhead athlete: a meta-analysis of randomized controlled trials. *Journal of Strength and Conditioning Research*, 29(10), 2964-2979.
- Palmer, K., Jones, D., Morgan, C., & Zeppieri, G. (2018). Relationship Between Range of Motion, Strength, Motor Control, Power, and the Tennis Serve in Competitive-Level Tennis Players: A Pilot Study. *Sports Health: A Multidisciplinary Approach*, 10(5), 462-467. <https://doi.org/10.1177/1941738118785348>
- Ulbricht, A., Fernandez-Fernandez, J., Mendez-Villanueva, A., & Ferrauti, A. (2016). Impact of Fitness Characteristics on Tennis Performance in Elite Junior Tennis Players: *Journal of Strength and Conditioning Research*, 30(4), 989-998. <https://doi.org/10.1519/JSC.0000000000001267>
- Wong, F. K., Keung, J. H., Lau, N. M., Ng, D. K., Chung, J. W., & Chow, D. H. (2014). Effects of Body Mass Index and Full Body Kinematics on Tennis Serve Speed. *Journal of Human Kinetics*, 40(1), 21-28. <https://doi.org/10.2478/hukin-2014-0003>

STUDY 2 FIGURES AND TABLES

TABLES

Table 1. Correlation coefficients (r) between serve velocity and isometric force-time curve variables (n = 16).

Variable	Serve Velocity (km·h ¹)							
	SHIR		SHF		SHABD		IMTP	
	r	r ²	r	r ²	r	r ²	r	r ²
MVC (N)	0.717†	0.51	0.756‡	0.57	0.523*	0.27	0.716†	0.51
PRFD (N·s⁻¹)	0.667†	0.44	0.689†	0.47	0.6*	0.36	0.799‡	0.64
RFD_{0-50 ms} (N·s⁻¹)	0.606*	0.37	0.628†	0.39	0.733†	0.54	0.728†	0.53
RFD_{0-100 ms} (N·s⁻¹)	0.644†	0.41	0.634†	0.40	0.718†	0.52	0.751‡	0.56
RFD_{0-150 ms} (N·s⁻¹)	0.727†	0.53	0.583*	0.34	0.699†	0.49	0.634†	0.40
RFD_{0-200 ms} (N·s⁻¹)	0.791‡	0.63	0.301	0.09	0.629†	0.4	0.260	0.07
IMP_{0-50 ms} (N·s)	0.448	0.2	0.651†	0.42	0.646†	0.42	0.671†	0.45
IMP_{0-100 ms} (N·s)	0.498*	0.25	0.551*	0.30	0.655†	0.43	0.362	0.13
IMP_{0-150 ms} (N·s)	0.662†	0.44	0.69†	0.48	0.722†	0.52	0.495	0.25
IMP_{0-200 ms} (N·s)	0.359	0.13	0.724†	0.52	0.741†	0.55	0.479	0.23

MVC = maximal isometric voluntary contraction; PRFD = peak rate of force development; RFD = rate of force development; SHIR = shoulder internal rotation; SHF = shoulder flexion; SHABD = horizontal shoulder abduction; IMTP = isometric mid-thigh pull; * = $p < 0.05$; † = $p < 0.01$; ‡ = $p < 0.001$.

Table 2. Isometric force-time curve variables included in the stepwise multiple regression analysis to explain the variance on mean SV.

Step	Independent variables entered	Correlations			SEE	p	Regression equation
		r	r ²	Adj. r ²			
1	PRFD_IMTP	0.80	0.64	0.61	7.7	<0.001	$y = 116.18 + (0.004 \times \text{PRFD_IMTP})$
2	SHF_IMP ₀₋₂₀₀	0.91	0.82	0.79	5.6	<0.001	$y = 102.59 + (0.003 \times \text{PRFD_IMTP}) + (1.433 \times \text{SHF_IMP}_{0-200})$

PRFD_IMTP = isometric mid-thigh pull; SHF_IMP₀₋₂₀₀ = impulse from 0 to 200 ms; Adj. r² = adjusted coefficient of determination; SEE = standard error of estimate.

FIGURES

Figure 1. Testing protocol timeline. SHIR; shoulder internal rotation; SHF = shoulder flexion; SHABD = shoulder horizontal abduction; IMTP = isometric mid-thigh pull; SV = serve velocity.

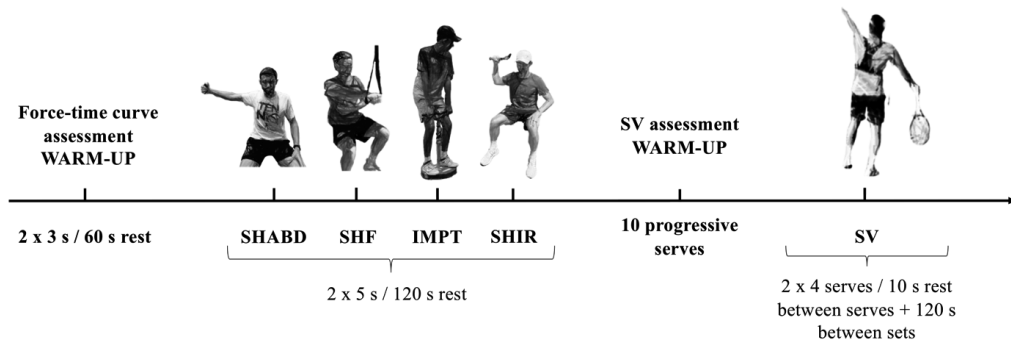
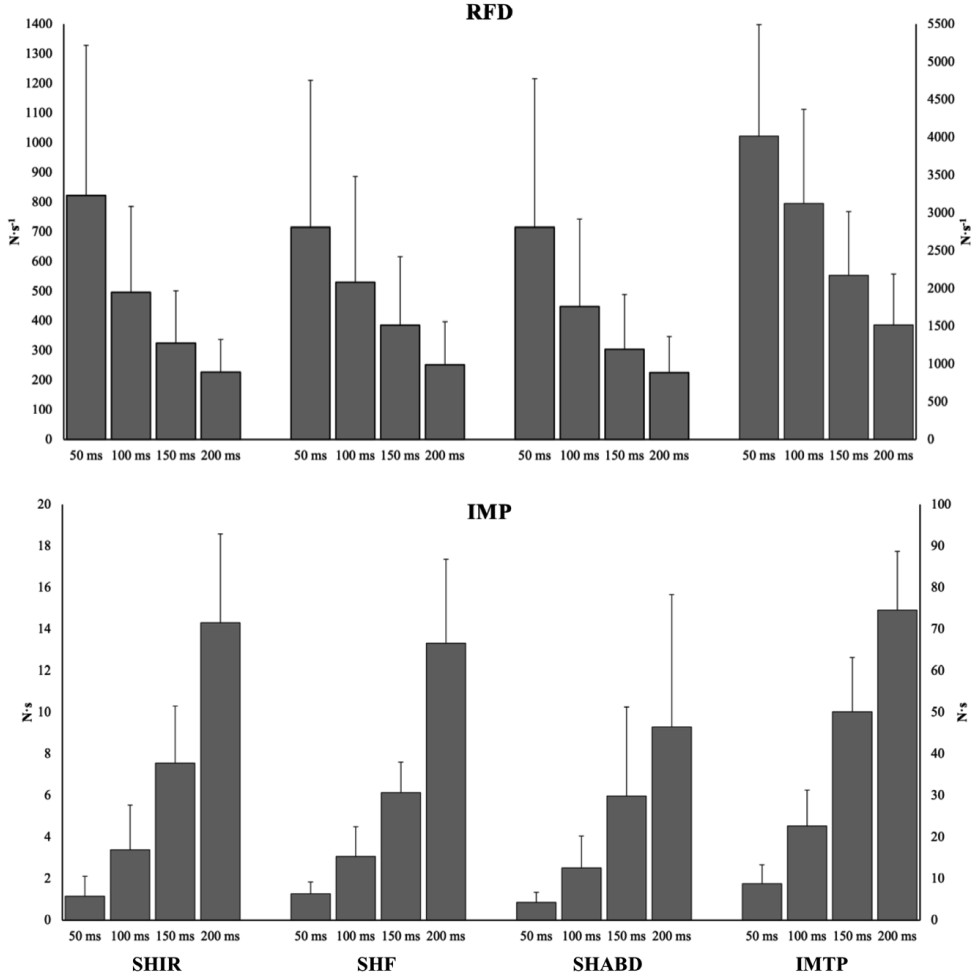


Figure 2. Force-time curve results. Data are presented as mean and SD. SHIR; shoulder internal rotation; SHF = shoulder flexion; SHABD = shoulder horizontal abduction; IMTP = isometric mid-thigh pull; RFD = rate of force development; IMP = impulse.



STUDY 3

Alterations in mechanical muscle characteristics and postural control induced by tennis match-play in young players.

Citation:

Colomar J, Corbi F, Baiget E. 2021. Alterations in mechanical muscle characteristics and postural control induced by tennis match-play in young players. PeerJ 9:e11445.
doi: 10.7717/peerj.11445

Journal information:

PeerJ

ISSN: 2167-8359

Category: Multidisciplinary sciences

Impact Factor: 2.984

Quartile: Q2

Alterations in mechanical muscle characteristics and postural control induced by tennis match-play in young players

Joshua Colomar^{1,2}, Francisco Corbi³ and Ernest Baiget⁴

¹ Institut Nacional d'Educació Física de Catalunya - INEFC Barcelona, Barcelona, Spain

² Academia Sánchez-Casal, Barcelona, Spain

³ Institut Nacional d'Educació Física de Catalunya - INEFC Lleida, Lleida, Spain

⁴ Sports Performance Analysis Research Group (SPARG), Universitat de Vic - Universitat Central de Catalunya, Vic, Spain

ABSTRACT

Background: Central and peripheric fatigue indicators are among the main reasons for performance decline following competition. Because of the impact of these factors on performance, how these variables are affected by match-play could be of interest, especially in young tennis players.

Objective: This study aimed to investigate alterations induced by a simulated tennis match on postural control and muscle characteristics in young tennis players.

Method: Seventeen male junior players took part in pre- and post-competition testing sessions performing postural control (displacement, speed and surface area of center of pressures) and muscle characteristics measurements (tone, stiffness, time to relaxation and elasticity). Between trials, participants played an 80-min simulated tennis match.

Results: No significant differences were observed in any of the tested variables. Moderate-to-large effect sizes (ES) for decreased stiffness and tone and greater time to relaxation were found between pre- and post-conditions in the right rectus abdominis (-9.8%, -4.4% and 7.8%; ES = 0.8, 0.54 and -0.85). Also, a decrease in tone was found in the right vastus medialis (-7.1%; ES = 0.56), while surface area of the center of pressures with eyes open showed trends towards increasing in post-match measurements (55.9%; ES = 0.56).

Conclusion: An 80-min simulated tennis match seems insufficient to elicit significant changes in postural control and mechanical muscle characteristics. Results suggest that physiological responses triggered by match-play were closer to those seen after a moderate activity than those present following a strenuous task.

Subjects Anatomy and Physiology, Kinesiology

Keywords Stiffness, Tone, Posture, Balance

INTRODUCTION

An athlete's capacity to recover and avoid overreaching is of great importance as it has clearly been related to risk of injury and overuse (*Schwellnus et al., 2016*). Competitive tennis requires players to participate in numerous matches, multiple draws and a high

Submitted 5 January 2021

Accepted 21 April 2021

Published 11 May 2021

Corresponding author

Joshua Colomar,
joshuacolomar@gmail.com

Academic editor

Antonie van den Bogert

Additional Information and
Declarations can be found on
page 12

DOI 10.7717/peerj.11445

© Copyright
2021 Colomar et al.

Distributed under
Creative Commons CC-BY 4.0

OPEN ACCESS

volume of events year-round. These matches are usually organized on consecutive days in professional players (Gescheit *et al.*, 2015) and, although of shorter duration, can even take part on one same day when referring to younger players (i.e., U14, U16) (Gallo-Salazar *et al.*, 2017). Although youth athletes seem able to recover faster than adults (Ratel *et al.*, 2015), this particular organization model brings out certain needs when approaching recovery strategies specifically applied to the sport of tennis.

Many investigations have aimed to study the effects of match-play on physical and physiological responses. Research has typically focused on competition simulation following loads closer to highly-competitive tennis events (i.e., 2–4 h during consecutive days), concluding high values of perceived soreness, increased muscle damage, reductions in maximal voluntary contraction (MVC), decreased range of motion (ROM) and velocity production in main strokes (Gallo-Salazar *et al.*, 2017; Gescheit *et al.*, 2015; Martin *et al.*, 2016). Although it seems clear that tennis match-play affects key performance factors, other fatigue indicators and monitoring tools could be important to approach recovery strategies effectively, especially when analyzing loads more often seen in junior tennis, with competition lasting around 1.5 h (Hoppe *et al.*, 2014). Fatigue induced by exercise is determined by a combination of processes that affect not only peripheral but also central levels and result in decreased performance (Girard & Millet, 2009). Focusing on peripheral indicators, although muscle activity via electromyography (EMG) analysis has typically been studied to determine neuromuscular fatigue (Girard & Millet, 2009), muscle contractile characteristics quantified by tensiomyography measures (TMG) or shear wave elastography (SWE) have also been useful to determine the athlete's fatigue status due to its lower cost and faster application ease and could be useful for overload detection and injury prevention (Sadeghi, Newman & Cortes, 2018). These techniques, as do newly developed equipment such as hand-held myometers, aim at analyzing the radial deformation of the muscle belly and the time it takes to happen during contraction caused by an external stimulation (De Paula Simola *et al.*, 2016). This offers information about muscle displacement (Dm), tone, contractile force and response-time, all of which essential muscle mechanical properties involved in contraction. As stated in literature, an increased level of muscle stiffness and tone could interpose technical aspects due to reductions in ROM and increased peak forces (Colomar, Baiget & Corbi, 2020). In the same way, a non-sufficient level could inhibit the capacity to produce fast strokes (Roetert *et al.*, 2009), due to the necessity of a leveled stiffness adjustment of the tendomuscular structure to effectively use elastic energy (Kuitunen *et al.*, 2002). Thus, because of the impact of these factors on tennis player's performance, how these variables are affected by tennis match-play could be of interest. Although some investigations have used TMG to detect exercise-induced fatigue (Wiewelhove *et al.*, 2017), to our knowledge no studies have attempted to focus on stiffness or other muscle mechanical properties affected by competition in youth tennis players.

Moreover, other parameters regarding central activation capacities and neural drive indicators show a progressive activation deficit in prolonged tennis matches, increasing in the latter stages of exhausting competition (Girard & Millet, 2009). Alterations in postural control due to muscular fatigue have been reported in previous studies (Malliou *et al.*,

2010) and seems a valid tool to assess fatigue at the central level (Paillard & Borel, 2013), as the nervous system is responsible of maintaining balance using information from the somatosensory, vestibular and visual inputs (Degache et al., 2014). When any of these channels modify the afferent information provided to the nervous system, balance and stability may be impaired (Ghram et al., 2019). For example, it's well described how vision has a strong effect on postural control as this improves when increased visual information is provided (Ghram et al., 2016). In the same way, local muscle fatigue challenges the postural control system (Ledin, Fransson & Magnusson, 2004), evidencing an adaptive sensory reorganization (Vuillermé, Sporbert & Pinsault, 2009) in response to a given strenuous activity. To the best of our knowledge, few studies (Malliou et al., 2010) have attempted to focus on both, central and peripheric indicators of competition outcome, specifically in young tennis players, making interesting further knowledge around how load may affect performance, taking into account the particular organization models these athletes follow, which can typically lead to playing consecutive matches on the same day or throughout the week. Thus, the goal of this study was to investigate the alterations induced by tennis match-play on postural control and muscle mechanical characteristics.

MATERIALS & METHODS

Subjects

A priori power analysis for a difference between two dependents means was conducted in G-Power (version 3.1.9.5; University of Dusseldorf, Dusseldorf, Germany) to estimate a sufficient sample size. With the alpha level set at 0.05, using a target effect size (ES) of 0.8, a power of 0.80 and two tails, it was determined that a minimum sample size of $n = 15$ was required. Seventeen male junior tennis players (mean \pm SD; age 16.5 ± 1.5 years; height 1.77 ± 0.07 m; body mass 69.3 ± 7.1 kg; BMI 22.2 ± 1.0 kg/m²) with an International Tennis Number (ITN) ranging from 2 to 4 (advanced level) and a weekly training volume of 25 h-week⁻¹ volunteered for this study. Of these 25 h, 5 accounted for physical training, while 20 included technical and tactical sessions. One player performed a one-handed backhand while the remaining 16 players used a two-handed fashion. Also, one player was left-handed, while the remaining participants had a dominant right hand. Inclusion criteria for all subjects required each participant to have a minimum of 1-year experience in strength training and 5-years of tennis training and competition. Participants were excluded from the study if they had any upper body, back or knee pain as well as having surgery or participated in a rehabilitation process in the past 6 months. Before their participation, participants or their legal tutors in the case of being underage, voluntarily signed an informed consent. The study was conducted following the ethical principles for biomedical research with human beings, established in the Declaration of Helsinki of the AMM (2013) and approved by the Catalan Sports Council Institutional Review Board (19/2019/CEICEGC).

Design

A cross-sectional repeated measures experimental design was carried by the same investigator in a static order in groups of two players. Each participant performed a

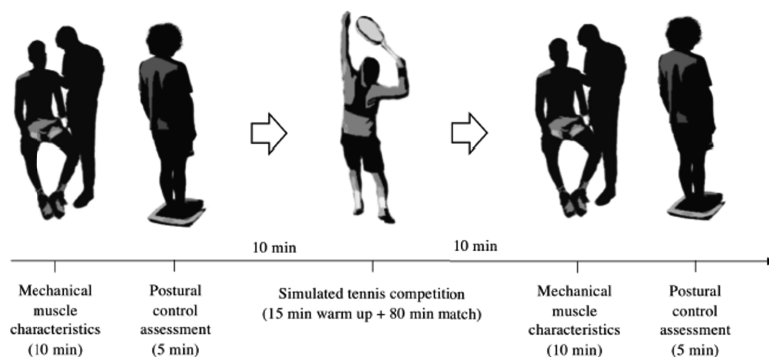


Figure 1 Schematic representation of the experimental procedure.

Full-size DOI: 10.7717/peerj.11445/fig-1

pre-competition experimental trial and, 10 min later, took part in an 80-min simulated tennis match on an outdoor standard clay court following the International Tennis Federation (ITF) rules. After the match, participants immediately performed the post-competition testing session within a 10-min window (Fig. 1). Matches were undertaken by participants playing an opponent with a similar ranking or ITN and with one of the players wearing a GPS unit to register kinematic variables concerning match load. Before the match, players performed a 15-min standardized warm-up routine consisting of 5 min of joint mobilization, light jogging and rallying for an extra 10 min. The use of pain-relieving strategies (e.g., foam rolling, massage, ice baths, etc.) was not allowed in order to avoid interferences with the testing results. Players were allowed to consume water *ad libitum*. Isotonic and energetic drinks were not allowed during the simulated competition. Although only one of the players was wearing a GPS unit due to equipment availability, both participants took place in the pre-post experimental trials. This happened in eight of the simulated matches, while competition number nine was performed with both participants wearing the GPS device. Therefore, 10 participants were included in the match load analysis.

Measurements

Participants were told not to exercise the day before the protocol took place, to maintain their habitual lifestyle during the study, to avoid excitatory substances (i.e., coffee or tea), and to consume their last meal at least 2 h before the scheduled test time.

All measurements were obtained in the morning, approximately from 8 am to 10 am to avoid the influence of biorhythms on balance (Gribble, Tucker & White, 2007).

All registrations were made within the competitive period.

Postural control assessment

Following Association Française de Posturologie standards (Bizzo, 1985), a posturographic platform (Fusyo-Medicapteur, Toulouse, France) at a 40 Hz sampling rate was used to

assess postural control and data was recorded using Fusyo software (V1.2.1 - Mediacpteur, Toulouse, France). The duration of each test was 51.2 s, resulting in a 2048-point time series. Participants were instructed as follows: “stand with your arms at your sides and look straight ahead while trying to maintain your stability the best you can” first with their eyes closed to, after, perform the test with their eyes open. They were instructed to stand double leg with arms at their sides and to look straight ahead. While having their eyes closed, subjects were asked to keep their gaze and to maintain postural stability. Only one postural test was performed in each condition (eyes open and eyes closed). To limit potential recovery time, no familiarization session was conducted.

Mechanical muscle characteristics

Muscle tone (mechanical tension in a relaxed muscle), stiffness (the resistance of the muscle to contraction or an external force that changes muscle’s initial shape), elasticity (recovery of the muscle’s initial shape after contraction or removal of an external force) and time to relaxation (time for the muscle to restore its initial shape after external force) (Ko *et al.*, 2018) were recorded on both extremities using a hand-held myometer (Myoton-Pro®, Myoton AS, Tallinn, Estonia). The MyotonPro® measures the viscoelastic response of the muscle due to a brief (15 ms) mechanical impulse (force, 0.4 N) on the skin surface above the muscle (Julià-Sánchez *et al.*, 2020). The mechanical deformation is delivered by the device testing end ($d = 3$ mm) held perpendicular to the skin surface (Treffel *et al.*, 2016). The device was used in multi scan mode, where the mean value of five measurements was used for the reliability and statistical analysis. The assessment was conducted as in Colomar, Baiget & Corbi (2020). The muscles chosen were those mostly involved in tennis strokes (Correia *et al.*, 2016; Kibler *et al.*, 2007; Knudson & Blackwell, 2000), attending to the whole kinetic chain, measured in a relaxed state and in the following order: pectoralis major, biceps brachii, infraspinatus, deltoids, rectus abdominis, rectus femoris, vastus medialis, biceps femoris and the lateral head of the gastrocnemius.

Tennis match load

Matches were played for 80 min (Hoppe *et al.*, 2014) regardless the score on a standard clay court under stable wind conditions (<2 m·s⁻¹). Match load parameters of one of the players per match were recorded using a GPS unit (WimuPro®, Realtrack Systems, Almería, Spain). Variables included the number of high intensity accelerations (≥ 3 m·s⁻¹) and decelerations (≥ -3 m·s⁻¹), accelerations and decelerations per minute, peak and mean running velocity and distance covered at different running intensities, as recommended in investigations with similar population (Gallo-Salazar *et al.*, 2019; Hoppe *et al.*, 2014). In order to register further data on match load, three heart rate zones were used for analysis. Using a heart rate monitor (Garmin HRM Dual Basic, Garmin, USA) and based on peak heart rate of the match (HR_{max}), zone 1 was determined as low- ($<70\%$ HR_{max}), zone 2, moderate- (75–85% HR_{max}) and zone 3, high-intensity- (>85 HR_{max}), following literature (Gomes *et al.*, 2011). After the match, general fatigue sensation for all participants was measured following the 6 to 20 Borg rate of perceived exertion (RPE) scale (Borg, 1982). Results concerning match load are summarized in Table 2.

Table 1 Reliability of test measurements ($n = 17$).

	Stiffness (N/m^{-1})			Tone (Hz)			Elasticity (Dm)			Relaxation (ms)		
	ICC [95% CI]	CV (%)	SEM	ICC [95% CI]	CV (%)	SEM	ICC [95% CI]	CV (%)	SEM	ICC [95% CI]	CV (%)	SEM
Right BB	0.998 [0.996–0.999]	1.5	3.4	0.998 [0.995–0.999]	0.9	0.17	0.997 [0.994–0.999]	2.1	0.03	0.995 [0.990–0.998]	1.2	0.25
Left BB	0.994 [0.987–0.997]	2.7	3.6	0.996 [0.993–0.999]	0.7	0.06	0.997 [0.993–0.999]	2.5	0.02	0.984 [0.967–0.994]	1.7	0.13
Right BF	0.998 [0.995–0.999]	1.9	7.1	0.998 [0.995–0.999]	1.2	0.13	0.988 [0.975–0.995]	3.5	0.03	0.998 [0.996–0.999]	1.8	0.23
Left BF	0.981 [0.961–0.992]	2.7	11.3	0.996 [0.991–0.998]	1.4	0.29	0.989 [0.978–0.996]	3.1	0.02	0.993 [0.985–0.997]	2.3	0.51
Right D	0.999 [0.998–1.000]	1.4	3.0	0.999 [0.998–1.000]	0.8	0.05	0.995 [0.989–0.998]	2.7	0.02	0.999 [0.998–1.000]	1.2	0.13
Left D	0.994 [0.988–0.998]	2.5	3.2	0.997 [0.994–0.999]	0.8	0.07	0.983 [0.965–0.993]	3.4	0.05	0.998 [0.996–0.999]	1.5	0.27
Right G	0.999 [0.999–1.000]	1.6	2.8	0.999 [0.998–1.000]	0.9	0.11	0.995 [0.991–0.998]	2.2	0.01	1.000 [0.999–1.000]	1.4	0.19
Left G	1.000 [0.999–1.000]	1.2	2.0	1.000 [1.000–1.000]	0.6	0.10	0.998 [0.996–0.999]	2.6	0.02	0.999 [0.998–1.000]	1.0	0.13
Right I	1.000 [0.999–1.000]	2.0	4.5	0.999 [0.999–1.000]	0.8	0.10	0.998 [0.996–0.999]	2.8	0.02	0.998 [0.995–0.999]	1.8	0.15
Left I	0.999 [0.999–1.000]	2.5	2.9	0.999 [0.999–1.000]	0.8	0.05	0.996 [0.992–0.998]	3.2	0.01	0.998 [0.996–0.999]	1.4	0.19
Right PM	0.998 [0.996–0.999]	2.5	4.4	0.999 [0.998–1.000]	1.0	0.21	0.997 [0.994–0.999]	2.5	0.02	0.996 [0.991–0.998]	2.1	0.30
Left PM	0.997 [0.994–0.999]	2.2	2.8	0.998 [0.996–0.999]	0.8	0.15	0.996 [0.992–0.998]	2.5	0.02	0.995 [0.990–0.998]	1.7	0.47
Right RF	0.999 [0.998–1.000]	1.5	5.8	0.999 [0.998–1.000]	0.8	0.13	0.996 [0.992–0.999]	3.5	0.02	0.999 [0.998–1.000]	1.1	0.18
Left RF	0.999 [0.999–1.000]	1.4	4.6	0.999 [0.999–1.000]	0.8	0.18	0.996 [0.992–0.998]	3.9	0.03	0.999 [0.999–1.000]	1.1	0.14
Right RA	0.997 [0.994–0.999]	2.9	5.5	0.997 [0.995–0.999]	1.7	0.24	0.993 [0.986–0.997]	3.8	0.04	0.996 [0.992–0.998]	2.6	0.22
Left RA	0.998 [0.997–0.999]	2.7	6.5	0.998 [0.996–0.999]	1.8	0.24	0.995 [0.990–0.998]	3.5	0.03	0.998 [0.997–0.999]	2.1	0.40
Right VM	0.999 [0.998–1.000]	1.6	1.8	0.999 [0.998–1.000]	0.8	0.03	0.997 [0.994–0.999]	3.5	0.03	0.999 [0.998–1.000]	1.3	0.24
Left VM	0.998 [0.997–0.999]	1.9	5.3	0.999 [0.999–1.000]	0.6	0.09	0.996 [0.991–0.998]	3.2	0.01	0.998 [0.995–0.999]	1.2	0.25

Note:

CV, coefficient of variation; ICC, intraclass correlation coefficient; SEM, standard error of measurement; Dm, decrement; BB, biceps brachii; PM, pectoralis major; D, deltoid; I, infraspinatus; RA, rectus abdominis; BF, biceps femoris; RF, rectus femoris; VM, vastus medialis; G, gastrocnemius.

Statistical analysis

Descriptive data were reported as mean \pm standard deviation (SD). The normality of the distributions and homogeneity of variances were assessed with the Shapiro–Wilk test.

Intrasession reliability of measures was determined using a two-way average measure of the intraclass correlation coefficient (ICC), the standard error of measurements (SEM), and the coefficient of variation (CV) for each variable (Atkinson & Nevill, 1998). ICC, SEM and CV refer to intra-subject variation between 5 measurements. Parametric and non-parametric statistics were used when appropriate. Paired *t*-test were used to discern any significant differences between the mean values of pre- and post-measurements. Because some variables did not have a Gaussian distribution, Wilcoxon paired test was used. Mean differences in absolute and percent values were also used. The magnitude of the differences in mean was quantified as effect size (ES) and interpreted according to the criteria used by Cohen (1988) $<0.2 =$ trivial, $0.2–0.4 =$ small, $0.5–0.7 =$ moderate, $>0.7 =$ large. Seventy-eight preplanned comparisons were considered for this study. Accordingly, correction for multiple comparisons was undertaken using the Bonferroni method with a resulting operational alpha level of 0.0006 ($p = 0.05/78$). All statistical analyses were performed using SPSS 23.0 software (SPSS Inc., Chicago, IL, USA).

RESULTS

All of stiffness, tone, elasticity, time to relaxation and postural control measurements reached an acceptable level of reliability and are presented in Table 1. Mechanical muscle

Table 2 Match load characteristics ($n = 10$).

Variables	Mean \pm SD
Total distance (m)	3961.8 \pm 437.4
Distance at 0 to >1 m·s ⁻¹ (m)	1309.4 \pm 84.2
Distance at 1 to >2 m·s ⁻¹ (m)	2014.5 \pm 404.0
Distance at 2 to >3 m·s ⁻¹ (m)	407.5 \pm 85.9
Distance at 3 to >4 m·s ⁻¹ (m)	155.3 \pm 42.7
Distance at ≥ 4 m·s ⁻¹ (m)	75.2 \pm 23.9
Peak velocity (m·s ⁻¹)	5.95 \pm 0.44
Mean velocity (m·s ⁻¹)	1.05 \pm 0.07
High intensity accelerations (≥ 3 m·s ⁻¹ ; n)	39.7 \pm 10.1
High intensity decelerations (≥ -3 m·s ⁻¹ ; n)	57.9 \pm 14.0
High intensity accelerations (≥ 3 m·s ⁻¹ ; n·min ⁻¹)	0.51 \pm 0.12
High intensity decelerations (≥ -3 m·s ⁻¹ ; n·min ⁻¹)	0.76 \pm 0.18
Peak HR (beats·min ⁻¹)	184.0 \pm 8.4
Mean HR (beats·min ⁻¹)	144.7 \pm 12.5
% time spent at 0–70% of maximum session HR	20.9 \pm 15.2
% time spent at 70–85% of maximum session HR	43.5 \pm 10.3
% time spent at 85–100% of maximum session HR	32.5 \pm 18.0
RPE	15.2 \pm 1.1

Note:

HR, heart rate; n·min⁻¹, number of actions per minute; RPE, rate of perceived exertion.

differences and postural control variations can be found in Tables 3 and 4. Effect sizes (ES) and percentage changes from pre to post match conditions are expressed in Fig. 2.

No significant differences were observed in any of the tested variables. Non-significant moderate-to-large ES for decreased stiffness and tone and greater time to relaxation were found between pre- and post-conditions in the right rectus abdominis (-9.8% , -4.4% and 7.8% ; ES = 0.8, 0.54 and -0.85) (Fig. 2). Also, a decrease in tone was found in the right vastus medialis (-7.1% ; ES = 0.56) (Fig. 2 and Table 3). Total surface area with eyes open showed large ES towards increasing compared to pre-match measurements (55.9% ; ES = 0.56) (Table 4).

DISCUSSION

The main finding of this study was that a single simulated tennis match did not significantly affect mechanical muscle characteristics or postural control in young tennis players. Certain trends and changes could be observed resulting in slightly decreased stiffness and tone and increased time to relaxation in the right rectus abdominis. Also, non-significant decreased tone seemed to appear in the right vastus medialis. Although moderate changes appear in total surface area during a balance test, postural control indicators of fatigue at the central level seem generally unaffected by 80 min of competition.

Previous research has shown the appearance of central and peripheral fatigue indicators following tasks of different duration and intensities (Macgregor *et al.*, 2016; Sadeghi,

Table 3 Pre and post-match mechanical muscle characteristics scores (n=17).

	Stiffness		Tone		Elasticity		Relaxation	
	PRE (N/m ⁻¹)	POST (N/m ⁻¹)	PRE (Hz)	POST (Hz)	PRE (Dm)	POST (Dm)	PRE (ms)	POST (ms)
Right BB	203.3 ± 29.9	195.4 ± 33.6	13.8 ± 1.1	13.6 ± 1.3	1.1 ± 0.2	1.2 ± 0.2	21.7 ± 1.9	22.5 ± 2.3
Left BB	187.5 ± 23.0	181.9 ± 18.6	12.9 ± 0.8	12.6 ± 0.9	1.1 ± 0.2	1.1 ± 0.2	23.4 ± 2.4	23.7 ± 2.0
Right BF	410.0 ± 93.7	402.9 ± 66.9	19.9 ± 2.7	19.6 ± 2.3	0.9 ± 0.2	0.9 ± 0.2	12.7 ± 2.7	12.9 ± 2.3
Left BF	361.5 ± 63	392.1 ± 78.3	18.7 ± 2.0	19.0 ± 2.1	0.9 ± 0.2	0.9 ± 0.2	14.0 ± 2.2	13.3 ± 2.6
Right D	252.8 ± 45.8	232.2 ± 39.0	15.4 ± 1.4	14.7 ± 1.3	0.9 ± 0.1	0.9 ± 0.1	19.3 ± 2.7	20.1 ± 2.7
Left D	234.2 ± 39.1	216.2 ± 42.9	15.1 ± 1.3	14.5 ± 1.2	0.8 ± 0.1	0.8 ± 0.1	18.6 ± 2.7	19.2 ± 2.3
Right G	322.4 ± 52.8	314.0 ± 34.9	18.3 ± 2.0	18.0 ± 1.5	0.9 ± 0.1	0.9 ± 0.1	16.4 ± 2.7	16.5 ± 1.9
Left G	316.6 ± 45.3	314.9 ± 52.5	18.1 ± 2.0	17.9 ± 2.0	0.9 ± 0.1	0.9 ± 0.1	16.7 ± 2.7	17.0 ± 3.0
Right I	209.0 ± 92.8	201.9 ± 69.0	15.4 ± 4.6	13.8 ± 1.9	0.7 ± 0.2	0.7 ± 0.1	19.3 ± 4.3	20.9 ± 3.0
Left I	230.8 ± 61.4	211.5 ± 53.6	16.0 ± 5.2	14.2 ± 1.5	0.7 ± 0.2	0.7 ± 0.1	18.9 ± 3.9	20.8 ± 3.0
Right PM	175.0 ± 28.0	165.7 ± 21.9	12.1 ± 1.1	11.9 ± 0.8	1.1 ± 0.2	1.0 ± 0.1	25.1 ± 2.8	25.3 ± 2.5
Left PM	197.0 ± 33.5	184.7 ± 24.2	13.1 ± 0.9	12.6 ± 1.1	1.0 ± 0.2	1.0 ± 0.2	23.2 ± 2.8	24.2 ± 2.9
Right RF	338.9 ± 70.4	302.3 ± 79.5	17.5 ± 2.2	16.6 ± 2.2	0.9 ± 0.2	0.9 ± 0.2	15.3 ± 3.1	16.1 ± 2.5
Left RF	328.8 ± 77.5	319.8 ± 75.0	17.4 ± 2.7	17.1 ± 2.7	1.0 ± 0.2	0.9 ± 0.2	15.9 ± 3.3	15.9 ± 3.1
Right RA	265.4 ± 59.2	239.3 ± 54.4	14.7 ± 1.8	14.1 ± 1.9	1.2 ± 0.2	1.3 ± 0.4	18.9 ± 3.1	20.4 ± 2.9
Left RA	245.2 ± 60.6	254.4 ± 64.4	14.5 ± 2.0	14.7 ± 1.9	1.1 ± 0.3	1.2 ± 0.3	19.6 ± 2.9	19.2 ± 2.9
Right VM	252.5 ± 79.9	227.3 ± 68.9	15.2 ± 2.4	14.1 ± 2.0	0.8 ± 0.1	0.8 ± 0.2	19.1 ± 3.9	20.3 ± 3.4
Left VM	252.7 ± 60.1	235.2 ± 49.5	15.1 ± 1.6	14.6 ± 1.3	0.8 ± 0.1	0.7 ± 0.1	18.8 ± 3.0	19.2 ± 2.2

Note:

Dm, decrement; BB, biceps brachii; PM, pectoralis major; D, deltoid; I, infraspinatus; Abd, rectus abdominis; BF, biceps femoris; RF, rectus femoris; VM, vastus medialis; G, gastrocnemius. Data are mean ± SD.

Table 4 Postural control differences pre-post-match-play (n = 17).

Variable	PRE	POST	ES	Change (%)
COP Displacement EO (mm)	487.2 ± 227.1	583.1 ± 356.5	-0.47	19.7
COP Displacement EC (mm)	692.1 ± 406.4	752.6 ± 496.9	-0.13	8.7
COP Surface Area EO (mm)	201.3 ± 180.1	314 ± 289.1	-0.56	55.9
COP Surface Area EC (mm)	246.9 ± 183.5	326.2 ± 296.2	-0.44	32.1
Average Speed of COP EO (mm·s ⁻¹)	9.5 ± 4.4	11.3 ± 7	-0.48	18.9
Average Speed of COP EC (mm·s ⁻¹)	13.5 ± 7.9	14.7 ± 9.7	-0.14	8.9

Note:

COP, center of pressure; EO, eyes open; EC, eyes closed; ES, Cohen's effect size. Data are mean ± SD.

Newman & Cortes, 2018; Thomas et al., 2015). Specifically in tennis, it seems clear that isometric strength and ROM around the hip and shoulder complex are negatively affected following match-play (Gallo-Salazar et al., 2017; Gescheit et al., 2015). Thus, although performance seems altered due to fatigue, it would seem these changes should be caused or accompanied by variations in muscle characteristics and therefore alterations in stiffness or other parameters (Macgregor et al., 2016; Sadeghi, Newman & Cortes, 2018). This is given to happen as high-intensity activities might trigger coupling impairment, destruction of cellular structures or membrane integrity due to exercise-induced muscle damage

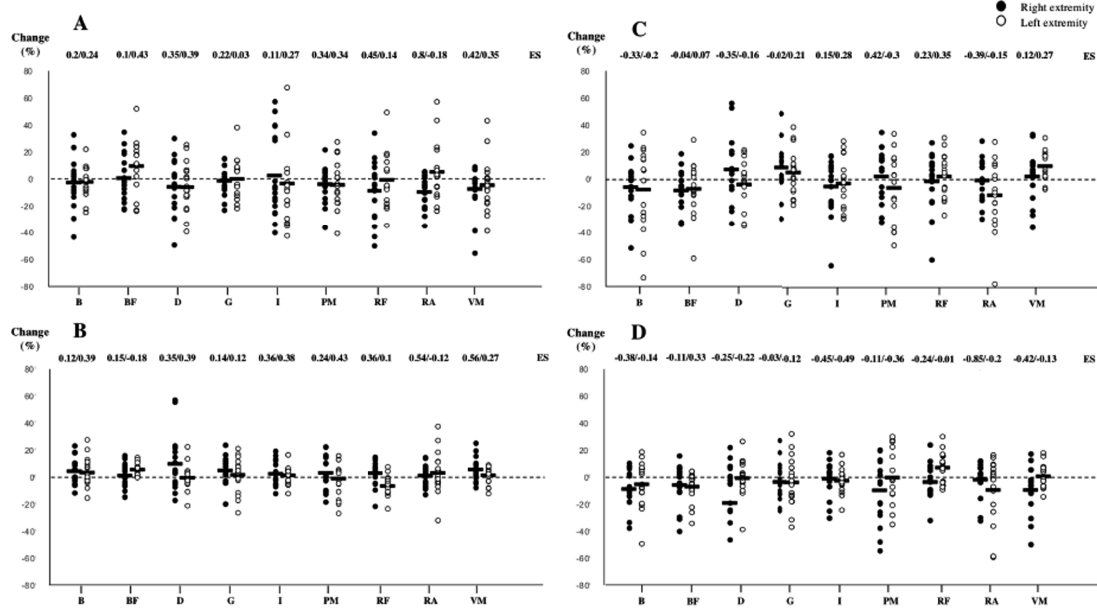


Figure 2 Changes produced in stiffness (A), tone (B), elasticity (C) and time to relaxation (D) from pre to post match measurements. ES, Cohen's effect size; B, biceps brachii; PM, pectoralis major; D, deltoid; I, infraspinatus; RA, rectus abdominis; BF, biceps femoris; RF, rectus femoris; VM, vastus medialis; G, gastrocnemius. Bold line indicates mean value of the tested subjects ($n = 17$). Full-size [DOI: 10.7717/peerj.11445/fig-2](https://doi.org/10.7717/peerj.11445/fig-2)

(Hunter *et al.*, 2012). Nonetheless, no significant changes in mechanical properties of the muscles tested were found in this study. The right rectus abdominis and vastus medialis were the only muscles that showed certain decreases in stiffness and tone and an increase in time to relaxation in post-match measurements. The rectus abdominis is placed in great stress during tennis match-play. Its role is of extreme importance in the kinetic chain present in tennis strokes (Roetert *et al.*, 2009) and activation can be elevated. Specially in the serve or during overhead strokes, eccentric activity is important to support the trunk and avoid excessive spinal stress. Subsequently, during the acceleration phase, a counter rotation occurs, eliciting high concentric activity of the trunk flexors and rotators (Correia *et al.*, 2016). Furthermore, abdominal muscles play a key role as co-contraction muscles in pelvic rotation, leg raising and in cutting maneuvers (Whyte *et al.*, 2018). Also, we should consider the high level of participation of the vastus medialis during the serve, specially at the end of the concentric phase (Girard, Micallef & Millet, 2005). During side-step pivoting and braking patterns it behaves as a stabilizer muscle that could increase fatigue levels (Brown, Brughelli & Hume, 2014). Because of these demands on the mentioned muscles, mechanical characteristics might have been affected and tone and stiffness would follow other usual fatigue responses and suffer alterations. Nevertheless, results can be surprising taking into account that redistribution of sarcomere

lengths, the loss of membrane integrity or the destruction of cellular structures are contributors to enhanced tone and stiffness (Macgregor *et al.*, 2016) and not reductions as happens here. One of the reasons could be that these muscles are eccentrically stimulated repetitively during tennis competition during long periods of time. The high stretch-shortening cycle (SSC) nature of tennis actions can place a certain load on the aforementioned muscles, and an impairment in SSC performance can be associated with a reduced muscle and joint stiffness, due to muscle damage induced by the eccentric phase of the SSC itself (Kuitunen *et al.*, 2002). As seen previously, this might elicit inflammatory responses and edema, which may represent a protective mechanism designed to combat the load associated with long duration activities (Andonian *et al.*, 2016), and decrease stiffness and tone levels in consequence. Nevertheless, the activity pattern and load placed on players here seems rather dissimilar to that presented by Andonian *et al.* (2016). In fact, as presented in Table 2, match-load characteristics, especially those concerning external load measurements, are in accordance to matches of similar duration and population (Gallo-Salazar *et al.*, 2019; Hoppe *et al.*, 2014). While accelerations, decelerations, total distance and velocity indicators are similar to comparable interventions, internal load results (i.e., peak and mean heart rate) seem of a smaller magnitude. Mean values of registered matches indicated 144.7 ± 12.5 beats·min⁻¹ and time spent in zones 1 and 2 (<85% HR_{max}) accounted for approximately 65% of playing time. Therefore, generally non-altered tone and stiffness values might be, in fact, due to low stress or load placed on the subjects. Following this idea, Thomas *et al.* (2015) found that peripheral fatigue indicators presented lower values following longer tasks than in shorter and intense bouts, possibly due to factors other than muscle fatigue playing a larger role in limiting and reducing performance. An 80-min simulated match at a mean HR of 144.7 beats·min⁻¹ and 65% of playing time below 85% of HR_{max} might respond to a moderate intensity task and therefore derive in the observed results. Hence, duration and intensity could be determinants to show changes in the tested variables. Previous research using electromyographic activity as a fatigue indicator observed negative effects on MVC after 180 min of tennis match-play. Although no measurements were performed mid-match for this variable in the mentioned study, maximal joint force reductions seemed to appear at 90 min of play (Martin *et al.*, 2016). In spite of the fact that effective playing time was different in the mentioned investigation and measurements accounted for MVC values, results may indicate that peripheral muscle fatigue indicators might appear with higher loads and that an 80-min simulated match would be insufficient for mechanical property markers to be sensitive to track fatigue, if present. Moreover, RPE registered in Martin *et al.* (2016) accounted for 12.5 ± 1.9 after 90 min of competition whereas 80 min of match-play resulted here in RPE scores of 15.2 ± 1.14 , suggesting further data registered in longer or more strenuous competitions would be of great interest. In this line, some investigations observed how mechanical muscle properties are affected alongside other fatigue indicators. For instance, Wiewelhove *et al.* (2017) found TMG markers not sensitive for monitoring fatigue in youth tennis players following a high-intensity training (HIT) microcycle, although other peripheral fatigue indicators such as counter movement jump (CMJ) performance and muscle soreness (DOMS) were

negatively affected. As the authors point out, the fact that results involving TMG markers did not follow other fatigue indicators could be explained by the fact that younger athletes seem to present a smaller extent of exercise-induced muscle damage than adults due to a strategy of the central nervous system to limit the recruitment of muscle units to prevent any extensive peripheral fatigue (Ratel *et al.*, 2015). Taking this into account and considering the load of the training protocol in Wiewelhove *et al.* (2017) of a greater magnitude than 80 min of match-play presented here, muscle mechanical parameters might have not been sensitive to the load presented as this has to be of a greater magnitude or applied repetitively, especially when referring to adolescents.

Regarding central fatigue indicators, in our study we hypothesized that metabolic and perceptual fatigue caused by a simulated tennis match would negatively influence stability as tennis players must handle both physiological and cognitive loads during match-play (Davranche & Pichon, 2005). As found in similar investigations (Malliou *et al.*, 2010), our results suggest a trend towards worsening, but no significant differences could be observed following the intervention. In general, results regarding the center of pressures (COP), average speed or total displacement of the COP indicate that a competition of these characteristics does not seem to affect the tested parameters. This data should be interpreted with caution because some factors should be taken into consideration. First, fatigue seems to influence the central nervous system differently depending on the duration, type of physical exercise and level of coordination (Tomporowski, 2003). In the same way as in our study, Douchamp-Riboux (1989) did not observe any modification in afferent systems functionality when analyzing a sub-maximum type of physical activity such as a rowing marathon. Meanwhile other studies seem to indicate that incremental exhausting exercises increase the sensory threshold, suggesting an increased cortical arousal as a compensatory pathway (Davranche & Pichon, 2005), as an ability of the central nervous system to tolerate a greater peripheral fatigue. Second, the absence of significant differences in the stability variables does not necessarily mean no effects on the stability pattern in the upright stance, because different strategies for balance control could be active. These strategies could be a different ratio between: i) the activation level of the proximal (hip) and distal (ankle) muscles that will involve different muscle patterns (Henry, Fung & Horak, 2001), ii) the loss or limitation of the information provided by one afferent source could be replaced with the increase of another sensory input from a different source (Tchórzewski, Bujas & Jankowicz-Szymańska, 2013) or iii) key muscular proprioceptive systems are not altered by an activity of these characteristics (Malliou *et al.*, 2010), in accordance to muscle contractile properties found here. Nevertheless, moderate trends showed a reduction in stiffness and tone in the rectus abdominis muscle, which are evidently important due to its influence on balance (Larson & Brown, 2018). Although non-significant, the moderate-to-large increase in the displacement of COP with eyes open found in this study might follow the idea that balance was affected to some extent after a load of these characteristics, but one of the mentioned compensatory pathways might appear in order to maintain balance control. As seen previously, postural control can be recovered in relatively short periods of time following fatiguing exercises, due to the body's capacity to adapt gathering other

somatosensory information to function appropriately (Larson & Brown, 2018). In any case, data suggests that the match induced load could have been moderate and of an insufficient magnitude to show further variations.

This investigation had some limitations. First, the non-inclusion of inter-session reliability measurements and/or a control group could affect results. Second, previously, performance factors have been shown to decrease after competition (Gallo-Salazar et al., 2017; Gescheit et al., 2015), whereas muscle mechanical characteristics seem unaffected by higher intensity activities (Wiewelhoe et al., 2017). The analysis of physical factors alongside other peripheral and central system fatigue indicators would have given insight on the effect of the proposed load in this study on further performance aspects. Also, comparisons with other investigations have to be interpreted with caution due to the fact that the competition here was in simulated conditions and physical and physiological outcomes significantly vary depending on the type of performance. In this line, match load characteristics were registered for 10 subjects only, while the sample size was higher. Last, fatigue at the central level was indirectly assessed using postural control measurements, while directly related methods could have offered different results.

CONCLUSIONS

In conclusion, an 80-min simulated tennis match does not seem to trigger significant changes in muscle characteristics and postural control. Data suggests that physiological responses induced by these match conditions were closer to those following a moderate activity than carrying out a strenuous task.

ACKNOWLEDGEMENTS

The authors thank all the players and coaches for their participation.

ADDITIONAL INFORMATION AND DECLARATIONS

Funding

The authors received no funding for this work.

Competing Interests

The authors declare that they have no competing interests.

Author Contributions

- Joshua Colomar performed the experiments, prepared figures and/or tables, and approved the final draft.
- Francisco Corbi conceived and designed the experiments, authored or reviewed drafts of the paper, and approved the final draft.
- Ernest Baiget conceived and designed the experiments, analyzed the data, prepared figures and/or tables, authored or reviewed drafts of the paper, and approved the final draft.

Human Ethics

The following information was supplied relating to ethical approvals (i.e., approving body and any reference numbers):

Catalan Sports Council Institutional Review Board approved this research (19/2019/ceicegc).

Data Availability

The following information was supplied regarding data availability:

Raw measurements are available in the Supplemental File.

Supplemental Information

Supplemental information for this article can be found online at <http://dx.doi.org/10.7717/peerj.11445#supplemental-information>.

REFERENCES

- Andonian P, Viallon M, Le Goff C, de Bourguignon C, Tourel C, Morel J, Giardini G, Gergel  L, Millet GP, Croisille P. 2016. Shear-wave elastography assessments of quadriceps stiffness changes prior to, during and after prolonged exercise: a longitudinal study during an extreme mountain ultra-marathon. *PLOS ONE* 11(8):e0161855 DOI 10.1371/journal.pone.0161855.
- Atkinson G, Nevill AM. 1998. Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine. *Sports Medicine* 26(4):217–238 DOI 10.2165/00007256-199826040-00002.
- Bizzo G. 1985. Specifications for building a vertical force platform designed for clinical stabilometry. *Medicine & Biology Engineering & Computer* 23(5):474–476 DOI 10.1007/BF02448937.
- Borg GA. 1982. Psychophysical bases of perceived exertion. *Medicine and Science in Sports and Exercise* 14:377–381.
- Brown SR, Brughelli M, Hume PA. 2014. Knee mechanics during planned and unplanned sidestepping: a systematic review and meta-analysis. *Sports Medicine* 44(11):1573–1588 DOI 10.1007/s40279-014-0225-3.
- Cohen J. 1988. *Statistical power analysis for the behavioral sciences*. Mahwah: Lawrence Erlbaum Associates.
- Colomar J, Baiget E, Corbi F. 2020. Influence of strength, power, and muscular stiffness on Stroke velocity in junior tennis players. *Frontiers in Physiology* 11:196 DOI 10.3389/fphys.2020.00196.
- Correia JP, Oliveira R, Vaz JR, Silva L, Pezarat-Correia P. 2016. Trunk muscle activation, fatigue and low back pain in tennis players. *Journal of Science and Medicine in Sport* 19(4):311–316 DOI 10.1016/j.jsams.2015.04.002.
- Davranche K, Pichon A. 2005. Critical flicker frequency threshold increment after an exhausting exercise. *Journal of Sport and Exercise Psychology* 27(4):515–520 DOI 10.1123/jsep.27.4.515.
- De Paula Simola R , Raeder C, Wiewelhove T, Kellmann M, Meyer T, Pfeiffer M, Ferrauti A. 2016. Muscle mechanical properties of strength and endurance athletes and changes after one week of intensive training. *Journal of Electromyography and Kinesiology* 30:73–80 DOI 10.1016/j.jelekin.2016.05.005.
- Degache F, Van Zaen J, Oehen L, Guex K, Trabucchi P, Millet G. 2014. Alterations in postural control during the world’s most challenging mountain ultra-marathon. *PLOS ONE* 9(1):e84554 DOI 10.1371/journal.pone.0084554.

- Douchamp-Riboux F. 1989. Arousal as a tridimensional variable: an exploratory study of behavioural changes in rowers following a marathon race. *Journal of Sport Psychology* 20:31–41.
- Gallo-Salazar C, Del Coso J, Barbado D, Lopez-Valenciano A, Santos-Rosa FJ, Sanz-Rivas D, Moya M, Fernandez-Fernandez J. 2017. Impact of a competition with two consecutive matches in a day on physical performance in young tennis players. *Applied Physiology, Nutrition, and Metabolism* 42(7):750–756 DOI 10.1139/apnm-2016-0540.
- Gallo-Salazar C, Del Coso J, Sanz-Rivas D, Fernandez-Fernandez J. 2019. Game activity and physiological responses of young tennis players in a competition with 2 consecutive matches in a day. *International Journal of Sports Physiology and Performance* 14(7):887–893 DOI 10.1123/ijsp.2018-0234.
- Gescheit DT, Cormack SJ, Reid M, Duffield R. 2015. Consecutive days of prolonged tennis match play: performance, physical, and perceptual responses in trained players. *International Journal of Sports Physiology and Performance* 10(7):913–920 DOI 10.1123/ijsp.2014-0329.
- Ghrum A, Damak M, Rhibi F, Marchetti PH. 2016. The contract-relax proprioceptive neuromuscular facilitation (PNF) stretching can affect the dynamic balance in healthy men. *Medical Express (Sao Paulo, Online)* 3(4):M160404 DOI 10.5935/MedicalExpress.2016.04.04.
- Ghrum A, Young JD, Soori R, Behm DG. 2019. Unilateral knee and ankle joint fatigue induce similar impairment to bipedal balance in judo athletes. *Journal of Human Kinetics* 66(1):7–18 DOI 10.2478/hukin-2018-0063.
- Girard O, Micallef J-P, Millet GP. 2005. Lower-limb activity during the power serve in tennis: effects of performance level. *Medicine & Science in Sport & Exercise* 37(6):1021–1029.
- Girard O, Millet GP. 2009. Neuromuscular fatigue in racquet sports. *Physical Medicine and Rehabilitation Clinics of North America* 20(1):161–173 DOI 10.1016/j.pmr.2008.10.008.
- Gomes RV, Coutts AJ, Viveiros L, Aoki MS. 2011. Physiological demands of match-play in elite tennis: a case study. *European Journal of Sport Science* 11(2):105–109 DOI 10.1080/17461391.2010.487118.
- Gribble PA, Tucker SM, White P. 2007. Time-of-day influences on static and dynamic postural control. *Journal of Athletic Training* 42(1):35–41.
- Henry SM, Fung J, Horak FB. 2001. Effect of stance width on multidirectional postural responses. *Journal of Neurophysiology* 85(2):559–570 DOI 10.1152/jn.2001.85.2.559.
- Hoppe MW, Baumgart C, Bornefeld J, Sperlich B, Freiwald J, Holmberg H-C. 2014. Running activity profile of adolescent tennis players during match play. *Pediatric Exercise Science* 26(3):281–290 DOI 10.1123/pes.2013-0195.
- Hunter AM, Galloway SD, Smith IJ, Tallent J, Ditroilo M, Fairweather MM, Howatson G. 2012. Assessment of eccentric exercise-induced muscle damage of the elbow flexors by tensiomyography. *Journal of Electromyography and Kinesiology* 22(3):334–341 DOI 10.1016/j.jelekin.2012.01.009.
- Julià-Sánchez S, Álvarez-Herms J, Cirer-Sastre R, Corbi F, Burtscher M. 2020. The influence of dental occlusion on dynamic balance and muscular tone. *Frontiers in Physiology* 10:1626 DOI 10.3389/fphys.2019.01626.
- Kibler WB, Chandler TJ, Shapiro R, Conuel M. 2007. Muscle activation in coupled scapulohumeral motions in the high performance tennis serve. *British Journal of Sports Medicine* 41(11):745–749 DOI 10.1136/bjism.2007.037333.
- Knudson D, Blackwell J. 2000. Trunk muscle activation in open stance and square stance tennis forehands. *International Journal of Sports Medicine* 21(5):321–324 DOI 10.1055/s-2000-3776.
- Ko C-Y, Choi H-J, Ryu J, Kim G. 2018. Between-day reliability of MyotonPRO for the non-invasive measurement of muscle material properties in the lower extremities of patients

- with a chronic spinal cord injury. *Journal of Biomechanics* 73:60–65
DOI 10.1016/j.jbiomech.2018.03.026.
- Kuitunen S, Avela J, Kyrolainen H, Nicol C, Komi P. 2002. Acute and prolonged reduction in joint stiffness in humans after exhausting stretch-shortening cycle exercise. *European Journal of Applied Physiology* 88(1–2):107–116 DOI 10.1007/s00421-002-0669-2.
- Larson DJ, Brown SHM. 2018. The effects of trunk extensor and abdominal muscle fatigue on postural control and trunk proprioception in young, healthy individuals. *Human Movement Science* 57(6):13–20 DOI 10.1016/j.humov.2017.10.019.
- Ledin T, Fransson PA, Magnusson M. 2004. Effects of postural disturbances with fatigued triceps surae muscles or with 20% additional body weight. *Gait & Posture* 19(2):184–193
DOI 10.1016/S0966-6362(03)00061-4.
- Macgregor LJ, Ditroilo M, Smith IJ, Fairweather MM, Hunter AM. 2016. Reduced radial displacement of the gastrocnemius medialis muscle after electrically elicited fatigue. *Journal of Sport Rehabilitation* 25(3):241–247 DOI 10.1123/jsr.2014-0325.
- Malliou VJ, Beneka AG, Gioftsidou AF, Malliou PK, Kallistratos E, Pafis GK, Katsikas CA, Douvis S. 2010. Young tennis players and balance performance. *Journal of Strength and Conditioning Research* 24(2):389–393 DOI 10.1519/JSC.0b013e3181c068f0.
- Martin C, Bideau B, Delamarche P, Kulpa R. 2016. Influence of a prolonged tennis match play on serve biomechanics. *PLOS ONE* 11(8):e0159979 DOI 10.1371/journal.pone.0159979.
- Paillard T, Borel L. 2013. Unilateral and bilateral fatiguing contractions similarly alter postural stability but differently modify postural position on bipedal stance. *Human Movement Science* 32(2):353–362 DOI 10.1016/j.humov.2012.12.001.
- Ratel S, Kluka V, Vicencio SG, Jegu A-G, Cardenoux C, Morio C, Coudeyre E, Martin V. 2015. Insights into the mechanisms of neuromuscular fatigue in boys and men. *Medicine & Science in Sports & Exercise* 47(11):2319–2328 DOI 10.1249/MSS.0000000000000697.
- Roetert EP, Kovacs M, Knudson D, Groppe JL. 2009. Biomechanics of the tennis groundstrokes: implications for strength training. *Strength and Conditioning Journal* 31(4):41–49
DOI 10.1519/SSC.0b013e3181aff0c3.
- Sadeghi S, Newman C, Cortes DH. 2018. Change in skeletal muscle stiffness after running competition is dependent on both running distance and recovery time: a pilot study. *PeerJ* 6(9):e4469 DOI 10.7717/peerj.4469.
- Schwellnus M, Soligard T, Alonso J-M, Bahr R, Clarsen B, Dijkstra HP, Gabbett TJ, Gleeson M, Hägglund M, Hutchinson MR, Janse Van Rensburg C, Meeusen R, Orchard JW, Pluim BM, Raftery M, Budgett R, Engebretsen L. 2016. How much is too much? (Part 2) International Olympic Committee consensus statement on load in sport and risk of illness. *British Journal of Sports Medicine* 50(17):1043–1052 DOI 10.1136/bjsports-2016-096572.
- Tchórzewski D, Bujas P, Jankowicz-Szymańska A. 2013. Body posture stability in ski boots under conditions of unstable supporting surface. *Journal of Human Kinetics* 38:33–44
DOI 10.2478/hukin-2013-0043.
- Thomas K, Goodall S, Stone M, Howatson G, Gibson ASC, Ansley L. 2015. Central and peripheral fatigue in male cyclists after 4-, 20-, and 40-km time trials. *Medicine & Science in Sports & Exercise* 47(3):537–546 DOI 10.1249/MSS.0000000000000448.
- Tomporowski PD. 2003. Effects of acute bouts of exercise on cognition. *Acta Psychologica* 112(3):297–324 DOI 10.1016/S0001-6918(02)00134-8.
- Treffel L, Dmitrieva L, Gauquelin-Koch G, Custaud M-A, Blanc S, Gharib C, Millet C. 2016. Craniomandibular system and postural balance after 3-day dry immersion. *PLOS ONE* 11(2):e0150052 DOI 10.1371/journal.pone.0150052.

- Vuillerme N, Sporbert C, Pinsault N. 2009.** Postural adaptation to unilateral hip muscle fatigue during human bipedal standing. *Gait & Posture* 30(1):122–125
DOI 10.1016/j.gaitpost.2009.03.004.
- Whyte EF, Richter C, O'Connor S, Moran KA. 2018.** Effects of a dynamic core stability program on the biomechanics of cutting maneuvers: a randomized controlled trial. *Scandinavian Journal of Medicine & Science in Sports* 28(2):452–462 DOI 10.1111/sms.12931.
- Wiewelhove T, Raeder C, De Paula Simola RA, Schneider C, Döweling A, Ferrauti A. 2017.** Tensiomyographic markers are not sensitive for monitoring muscle fatigue in elite youth athletes: a pilot study. *Frontiers in Physiology* 8:406 DOI 10.3389/fphys.2017.00406.



STUDY 4

Inter-limb muscle property differences in junior tennis players.

Citation: Colomar J, Corbi F, Baiget E. 2022. Inter-limb muscle property differences in junior tennis players. Journal of Human Kinetics [published in press].

doi: 10.2478/hukin-2022-0026

Journal information:

Journal of Human Kinetics

ISSN: 1640-5544

Category: Sport Sciences

Impact Factor: 2.193

Quartile: Q3

Inter-limb muscle property differences in junior tennis players

Joshua Colomar^{1,2,3}, Francisco Corbi⁴, Ernest Baiget¹

¹ National Institute of Physical Education of Catalonia (INEFC), University of Barcelona (UB), Barcelona, Spain.

² Sport Performance Analysis Research Group (SPARC), University of Vic – Central University of Catalonia, Barcelona, Spain.

³ Emilio Sánchez Academy Barcelona, Sports Science Department, Barcelona, Spain.

⁴ National Institute of Physical Education of Catalonia (INEFC), University of Lleida (UdL), Lleida, Spain.

Corresponding author information:

Name: Joshua Colomar

Postal Address: Avinguda de l'Estadi 14, 08038, Barcelona, Spain.

Email: joshuacolomar@gmail.com

Phone: +34 679260619

Acknowledgements:

The authors thank all the players and coaches for their enthusiastic participation.

Abstract

The goal of this study was to investigate side-to-side differences and asymmetries regarding muscle characteristics in young tennis players. Thirty-four participants performed contractile property measurements (stiffness, tone, elasticity and time to relaxation) on the dominant and non-dominant extremities including nine muscle groups involved in the kinetic chain of main tennis strokes. Significant differences ($p \leq 0.05$) and small-to-moderate effect sizes for greater stiffness and tone were found for the dominant biceps femoris (-11.1% and -5.6%; ES = 0.53 and 0.54) and the non-dominant vastus medialis (5.4% and 3.2%; ES = -0.33 and -0.41), while greater tone was present in the non-dominant pectoralis major (4.0%; ES = -0.56). Time to relaxation was increased in the dominant biceps femoris (10.3%; ES = -0.58), the non-dominant pectoralis major (5.1%; ES = -0.56) and the gastrocnemius (9.1%; ES = -0.5). The non-dominant infraspinatus and dominant rectus abdominis showed greater elasticity than contralateral muscles (9.9% and -8.0%; ES = -0.58 and 0.6, respectively). These results reflect the existence of small-to-moderate differences when comparing side-to-side values of contractile characteristics in a small amount of the muscle groups tested. However, passive measurements of a relaxed muscle do not seem to fully reflect possible adaptation and changes derived from gameplay in young tennis players.

Key words: asymmetries, stiffness, tone, elasticity, relaxation.

Introduction

Tennis is widely considered as an asymmetrical sport with great unilateral predominance (Cools et al., 2014; Sanchis-Moysi et al., 2009, 2010, 2011). Because of the way it is played, functional and morphological differences appear as a consequence of prolonged exposure. Structurally, bone mineral density, hypertrophy and fiber type distribution can report

significantly greater values in one side of the body when compared to the opposite (Sanchis-Moysi et al., 2009, 2010, 2011, 2017). In the same way, these differences also appear when comparing neuromuscular performance, strength values (Fernandez-Fernandez et al., 2019; Sanchis-Moysi et al., 2009) and range of motion (ROM) (Fernandez-Fernandez et al., 2019; Moreno-Pérez et al., 2016) outcomes. When assessing strength values specifically, asymmetries appear clearly around the shoulder (Cools et al., 2014; Fernandez-Fernandez et al., 2019; Gillet et al., 2017; Moreno-Pérez et al., 2015), the hip (Moreno-Pérez et al., 2017) and lumbo-pelvic muscles (Sanchis-Moysi et al., 2010, 2017). These differences have often been associated to an increased risk of injury prevalence. For example, considering the shoulder complex, a deficit in glenohumeral internal rotation ROM with respect to the contralateral side of the body (GIRD) increases likelihood of shoulder or elbow pathologies (Moreno-Pérez et al., 2015; Shanley et al., 2011). Opposite to this, bilateral differences could not be observed in lower body structures such as the hip, expressing compromised mobility around the joint, but no significant variances in side-to-side values (Moreno-Pérez et al., 2016; Young et al., 2014). Moreover, strength imbalances present at the rectus abdominis seem to be relevant regarding lower back pain and muscle tears (Sanchis-Moysi et al., 2010, 2017), establishing the importance of contralateral ROM, strength ratios and differences.

In the same way, muscle mechanical characteristics, especially stiffness, have previously been studied in relation to their importance regarding performance and the link to injury in a wide range of sports (Brazier et al., 2019; Pickering Rodriguez et al., 2017; Pruyn et al., 2012, 2015). Concerning effects on performance, specifically in tennis, a certain level of stiffness may interpose or aid in velocity production of strokes, depending on the structure analyzed (Colomar et al., 2020). Interestingly, this idea follows previous statements on how stiffness may be an important factor benefiting performance and associating greater values to enhanced sprinting or jumping (Brughelli and Cronin, 2008). Counterproductively, an increased level of these capacities could also result unfavorable and contribute to increased shock peak forces, reduced ROM (Brazier et al., 2019) and a high level of muscle tightness (Marcondes et al., 2013), which, as seen in overhead athletes (Moreno-Pérez et al., 2015), can generally lead to pathologies or injury. Furthermore, it seems that a high level of asymmetry of stiffness values when comparing limbs could also be directly associated to injury risk and worsen the performance outcome (Pruyn et al., 2012). As pointed out in previous works in other sports (Pickering Rodriguez et al., 2017), an optimal stiffness zone that benefits performance variables and does not interfere or increases injury likelihood is yet to be further investigated, but the importance of side-to-side ratios seems clearly relevant regarding performance and injuries. Due to the aforementioned characteristics, the hypothesis tested here was that the dominant upper extremity of tennis players would show significantly greater values of stiffness, tone and time to relaxation compared to the contralateral side of the body, as chronic adaptation to high volumes of tennis practice.

No studies to our knowledge have assessed interlimb asymmetries regarding mechanical muscle characteristics in young tennis players. Therefore, and because of the aforementioned asymmetric nature of tennis and its possible negative outcome or implications for training, it seems interesting to value side-to-side differences concerning muscle mechanical characteristics. Thus, the goal of this study was to assess interlimb asymmetries regarding tone, stiffness, elasticity and time to relaxation in young tennis players.

Methods

Participants

Thirty-four male tennis players (mean \pm SD; age, 16.7 ± 1.2 years; body height, 1.78 ± 0.07 m; body mass, 70.3 ± 6.4 kg; BMI, 22.1 ± 1.3 kg/m²) with an International Tennis Number (ITN) ranging from 2 to 4 (advanced level) participated in this study. This sample size was justified by *a priori* power analysis conducted in G*power using a target effect size (ES) of 0.5, alpha level of 0.05, power of 0.80 and two tails, which determined that 34 subjects would be needed for participation (G-Power software version 3.1.9.5, University of Dusseldorf, Dusseldorf, Germany).

The player's ITN was established by the consensus of three coaches accredited with RPT (Professional Tennis Registry) level 3, following the ITN Description of Standards (www.internationaltennisnumber.com). Thirty-one of 34 (91.2%) subjects performed a two-handed backhand and 8.8% of participants were left-handed. Players had a training volume of 25 h·week⁻¹ of which 5 h accounted for fitness training and 20 h for technical and tactical sessions. The mean training background of players was 7.8 ± 1.8 years, which focused on tennis-specific training (i.e., technical and tactical skills), aerobic and anaerobic training (i.e., on- and off-court exercises), and strength training (which included prevention strategies in the form of foam rolling, static stretching and posterior shoulder capsule muscle strengthening exercises). Inclusion criteria for all subjects required each participant to have a minimum of 1-year experience in strength training and 5 years of tennis training and competition. Participants were excluded from the study if they had a history of upper or lower extremity surgery, shoulder, back or knee pain and/or rehabilitation for the past 12 months. All subjects were informed in advance about the objectives of the study and, before participation, players or their legal tutors voluntarily signed an informed consent form. The study was conducted following the ethical principles for biomedical research with human beings, established in the Declaration of Helsinki of the AMM (2013) and approved by an accredited Ethics Committee.

Design and procedures

This was a cross-sectional laboratory study with uninjured participants. The collection of data took place in March and April during normal in-season training weeks in groups of 4 or 5 players, executed from 8:00 to 8:30 am, before players' normal technical-tactical training and prior to any physical activity or warm up routines. Participants had not trained for at least 16 h before the testing procedure. During testing, participants were assessed for mechanical muscle characteristics via muscle natural oscillation (Dm) using a hand-held myometer. The use of pain-relieving strategies (e.g., foam rolling or massage) or energy techniques was not allowed during tests as well as stretching exercises on the same day in order to avoid interferences with the results.

Measures

Contractile properties measurement

Muscle properties, which involved tone (mechanical tension in a relaxed muscle), stiffness (the resistance of the muscle to an external force that changes its initial shape), elasticity (recovery of the muscle's initial shape after contraction or removal of an external force) and time to relaxation (time for the muscle to restore its initial shape after external force) (Ko et al., 2018) were measured on both the dominant and the non-dominant side of the body using a hand-held myometer (Myoton-Pro, Myoton AS, Tallinn, Estonia) following previous similar protocols (Colomar et al., 2020) and approximately in positions marked in Figure 1. The dominant extremity or side of the body was established based on upper body dominance (i.e., extremity used to hit strokes). Although this may not match when referring to the lower body, for this study, a right-handed player would have a dominant right leg and vice versa, since leg dominance does not seem relevant in specific tennis actions. Before the assessment, body marks were established for nine measurement points using the SENIAM electrode placement guidelines (Hermens et al., 2000). The muscle groups chosen were those mostly involved in tennis strokes (Chow et al., 2009; Girard et al., 2005; Kibler et al., 2007; Rogowski et al., 2011) attending to the whole kinetic chain, i.e., the pectoralis major (PM), biceps brachii (B), infraspinatus (I), deltoids (D), rectus abdominis (RA), the rectus femoris (RF), vastus medialis (VM), biceps femoris (BF) and the lateral head of the gastrocnemius (G). Since the goal of this study was to assess chronic adaptation in the form of variations of muscle mechanical characteristics, measurements were performed with a state of muscle relaxation and participants lying down (RA), seated (PM, B, I, D) or in an anatomical position (RF, VM, BF, G), depending on the test point. The tip of the Myoton-Pro was placed perpendicular to all measurement zones sampling at 15 ms with a force of 0.58 N and measured the damped natural oscillations caused by the probe impact. The device's

accelerometers operated at 3200 Hz, offering an average value of 5 consecutive measurements. The Myoton-Pro reliability shows excellent test-retest values as shown previously in other investigations (Colomar et al., 2020).

Statistical analysis

Descriptive data were reported as mean \pm standard deviation (SD). The normality of the distributions and homogeneity of variances were assessed with the Shapiro-Wilk test. Parametric and non-parametric statistics were used when appropriate. The differences between group mean values of the dominant and the non-dominant side were tested by a paired *t*-test, in cases of non-normality the nonparametric Wilcoxon paired test was used to assess differences. The magnitude of the differences in mean was quantified as effect size (ES) and interpreted according to the criteria used by Cohen (1988); <0.2 = trivial, $0.2-0.4$ = small, $0.5-0.7$ = moderate, >0.7 = large. The level of significance was set at $p < 0.05$. All statistical analyses were performed using SPSS 26.0 software (SPSS Inc., Chicago, IL, USA).

Results

Inter-limb differences for stiffness, tone, elasticity, and time to relaxation are presented in Figure 2, while values for assessing the magnitude of changes and effect sizes are shown in Table 1. Significant differences and small-to-moderate effect sizes for greater stiffness and tone were found for the dominant biceps femoris (-11.1% and -5.6%; ES = 0.53 and 0.54) and the non-dominant vastus medialis (5.4% and 3.2%; ES = -0.33 and -0.41), while greater tone was present in the non-dominant pectoralis major (4.0%; ES = -0.56). Time to relaxation was increased in the dominant biceps femoris (10.3%; ES = -0.58), the non-dominant pectoralis major (5.1%; ES = -0.56) and the gastrocnemius (9.1%; ES = -0.5). The non-dominant infraspinatus and the dominant rectus abdominis showed greater elasticity than contralateral muscles (9.9% and -8.0%; ES = -0.58 and 0.6, respectively).

Discussion

The main finding of this study was that although certain differences regarding muscle mechanical characteristics existed when comparing side-to-side values in youth tennis players, these did not seem to present a consistent outcome or happen in more muscle groups. Regarding the lower body, significant ($p < 0.05$) moderate differences towards increased stiffness, tone and time to relaxation (-11.1%, -5.6% and 10.3%; ES = 0.53, 0.54 and -0.58, respectively) could be observed in the dominant biceps femoris. Besides this, only small variations towards increased stiffness and tone in the vastus medialis (5.4% and 3.2%; ES = -0.33 and -0.41) and the time to relaxation of the gastrocnemius (9.1%; ES = -0.5), both on the non-dominant side, were registered. Upper body assessment followed this line and small differences towards greater values in tone and elasticity were observed only in few muscle groups such as the non-dominant pectoralis major (5.1%; ES = -0.56) and infraspinatus (9.9%; ES = 0.58) and the dominant rectus abdominis (8.0%; ES = 0.6). Although previous investigations have well established the existence of stiffness asymmetries among athletes, even with significant relations to soft-tissue injury risk (Pruyn et al., 2012), these differences account for lower body musculature and have typically measured active stiffness levels via hopping tests (i.e., vertical stiffness). When assessing passive measurements as in this study, investigations have found certain asymmetries in some muscle groups, although conclusions were drawn indicating that these indexes may not be as indicative or present the same differences (Pruyn et al., 2015). Elevated levels of stiffness have been thoroughly related to enhanced performance indicators such as strength, the rate of force development and jumping values (Pruyn et al., 2012, 2015), all of which are relevant to tennis performance, but also represent dynamic actions that may be better addressed using measurements which assess an active state of the muscle. It could be that, as increased levels of stiffness and derivative muscle properties (i.e., tone, time to relaxation and elasticity) are related to a faster release of elastic energy and are therefore advantageous for highly dynamic explosive actions, adaptation is not evident when analyzing the muscle in a relaxed state. Nevertheless, changes and asymmetries derived from high volumes of tennis training and match-play have

previously been observed in the form of morphological (Sanchis-Moysi et al., 2009, 2010, 2011, 2017) and neuromuscular (Madruza-Parera et al., 2019) chronic adaptation. A possible explanation to rather small differences between side-to-side muscles could be that more evident asymmetries appear as age, level and consequent training volumes increase. Differences have previously been observed in players at prepubescent ages (Sanchis-Moysi et al., 2017), although greater differences when comparing muscle volumes appear when analyzing professional subjects (Sanchis-Moysi et al., 2009, 2010) with similar weekly loads, but greater training experience than participants in this study. Therefore, years of competitive training and competition could be a determining factor affecting side-to-side asymmetries.

Regarding results registered for the lower body, significantly greater values and small-to-moderate changes for stiffness, tone and time to relaxation could be observed for the dominant biceps femoris. In tennis, a great deal of short sprints are performed during play, covering short distances that average 5 to 15 m per point and 20% of these tending to follow horizontal displacement (Galé-Ansodi et al., 2017). In the acceleration phase of sprinting, the biceps femoris shows high electromyographic (EMG) activation, especially in the swing phase (Morin et al., 2015), and thus it would be reasonable to assume this musculature would show trends towards increased levels of stiffness, tone and consequently time to relaxation, even in resting conditions as chronic adaptation. Nevertheless, results here indicate differences within the contralateral side of the body rather than an increased level of activation. Coordinatively, when accelerating to sprint, athletes tend to perform a step back movement in order to accelerate and move forward as fast as possible, taking advantage of the stretch shortening cycle (SSC) and ground reaction forces (Frost and Cronin, 2011). This step back is normally repeatedly performed with the same leading leg, simply due to the convenience and the habit of the player. The combination of repetitive short forward accelerations added to the high activation of the biceps femoris when swinging the leg forward in sprinting could explain higher values observed. Regarding the vastus medialis and gastrocnemius, the importance of these muscles is evident during the serve, especially in the forward leg (i.e., non-dominant here) at the end of the concentric (Girard et al., 2005) or the landing phase, respectively. Although with caution and being speculative, the high volume of serving during practice and match-play (Perri et al., 2018) could place a higher degree of stress over both muscle groups of the non-dominant leg and increase stiffness and tone differences when compared to the contralateral side. Also, side-step acceleration patterns are preceded usually by players performing split steps, which generate high levels of activation of the gastrocnemius on the opposite direction of movement before and after landing (Uzu et al., 2009). This contributes to stiffness regulation during the subsequent jump, producing an effective and quick lateral first step (Uzu et al., 2009). Moreover, the vastus medialis behaves as a stabilizer muscle (Brown et al., 2014) in side breaking and accelerating movements. These actions account for 70% of total volume during tennis match-play (Galé-Ansodi et al., 2017), in many occasions in order to hit a baseline forehand, as it seems to be the most repeated stroke, especially when referring to male junior tennis (Kovalchik and Reid, 2017). This is important due to the laterality of these specific tennis actions. To hit a forehand, players typically have to side-shuffle towards the doubles isle, which is at the same side of their dominant extremity. This means the outer leg (i.e., non-dominant here) performs the push off motion in order to move towards the hitting position. In any case, this is speculative, and results seem to indicate small differences in few muscles tested and active measurements may be a better option to assess side-to-side asymmetries.

Regarding trunk and upper body values, side-to-side differences were found regarding tone of the pectoralis major, with a greater value in the non-dominant extremity when compared to the playing arm. Results here are surprising regarding the repetitive internal rotation, horizontal adduction and scapula protraction motion of the dominant extremity, especially when playing serves and forehands (Cools et al., 2014). Typically, players present adaptation due to these actions in the form of posterior capsular tightness, rotator cuff strength imbalances and

scapular dyskinesis (Cools et al., 2014), preceded by alterations in length in muscles such as the pectoralis minor (Cools et al., 2010). It would be expected that, contrary to the results, higher values of stiffness and/or tone, even in resting conditions, would be found in the dominant pectoralis major as adaptation to its high activity during strokes (Rogowski et al., 2011) and response to fatigue (Macgregor et al., 2016). The greater level of tone in the non-dominant muscle found here may have two reasons. First, due to the aforementioned increased activation of the pectoralis major during main strokes, fatigue appears sooner and the central nervous system triggers adaptation performing different neuromuscular adjustments and compensatory strategies to overcome fatigue and conserve performance (Rota et al., 2014), resulting in significant differences when compared to the contralateral side of the body. Second, fitness training interventions of the participants tested here included a great deal of stretching and foam rolling exercises. These programs were performed daily, especially in the dominant extremity, and aimed to decrease injury likelihood reducing shoulder capsule tightness using strategies such as self-myofascial release. As stated in the literature, these techniques can achieve progressive reduction in muscle stiffness and tone, being of greater magnitude when observed after a certain period of time (Behm and Wilke, 2019). Training programs including self-myofascial release and performed regularly by players mainly on the dominant extremities may explain side-to-side differences in this matter and limit findings as this variable was not registered. Concluding, the non-dominant abdominal and dominant infraspinatus presented lower elasticity values, or capacity of the muscle to recover its initial shape (Ko et al., 2018). Elasticity is measured via an oscillation decrement (Dm), which is inversely proportional to elasticity, meaning a greater Dm results in a lower capacity of the muscle to return to its original form. Due to the tennis serve motion, the rectus abdominis presents greater hypertrophy on the non-dominant side of the athlete's body (Sanchis-Moysi et al., 2010). Because of repetitive contractions, this muscle activates asymmetrically and is therefore responsible for this adaptation (Sanchis-Moysi et al., 2010). Unilateral repetitions most likely predispose to greater stress and could present greater Dm values, meaning that fatigue, repetitive loading and stress inhibit effective recovery of the muscle. In the same manner, the dominant infraspinatus could be affected by match-play and competition, especially during the follow-through phase of the serve to help control humeral deceleration (Kibler et al., 2007). As a possible reason no differences could be observed in further upper body contractile variables, the fact that the majority of players played a two-handed backhand (91.2%) could affect results. EMG activity of the deltoids, pectoralis major, biceps and triceps brachii muscles during the two-handed backhand is higher in both limbs than executing in the one-handed fashion (Genevois et al., 2015). Due to this, differences would be diminished as muscle participation is similar on both sides when performing this specific stroke.

As a perspective for future investigations, although this study found slight asymmetries in some muscle groups as adaptation to tennis practice and match-play, the analysis of data regarding musculature in an active state could be of great interest. Studies such as that of Pruyn et al. (2016) state correlations between the use of myometry and active stiffness measurement methods such as vertical hopping tests, indicating the possibility of using these methods for further insights into the matter. This study had some limitations. Although only two participants (8.8% of total) performed a one-handed backhand while playing, effects on muscle characteristics could differ highly when compared to the two-handed fashion. As stated in previous research (Genevois et al., 2015), disparities regarding muscle activation and kinematic differences between both styles may affect mechanical muscle adaptation and outcomes, hence affecting to some extent results of this study. Last, the periodic use of self-myofascial release techniques by players involved in the investigation could somewhat affect results.

In conclusion, moderate differences regarding muscle properties can be observed in the dominant biceps femoris of young tennis players. Also, small differences towards an increased level of stiffness and tone seem to appear in the non-dominant vastus medialis and pectoralis major, while greater time to relaxation and elasticity values are present in the non-dominant

gastrocnemius, infraspinatus and dominant rectus abdominis, respectively. These measurements reflect to some extent the existence of differences when comparing side-to-side values in young tennis players, however, passive measurements of a relaxed muscle using a hand-held myometer do not seem to fully represent possible adaptation and changes derived from training and gameplay.

References

- Behm, D. G., & Wilke, J. (2019). Do self-myofascial release devices release myofascia? rolling mechanisms: a narrative review. *Sports Medicine*, 49(8), 1173–1181. <https://doi.org/10.1007/s40279-019-01149-y>
- Brazier, J., Maloney, S., Bishop, C., Read, P. J., & Turner, A. N. (2019). Lower extremity stiffness: considerations for testing, performance enhancement, and injury risk. *Journal of Strength and Conditioning Research*, 33(4), 1156–1166. <https://doi.org/10.1519/JSC.0000000000002283>
- Brown, S. R., Brughelli, M., & Hume, P. A. (2014). Knee mechanics during planned and unplanned sidestepping: A systematic review and meta-analysis. *Sports Medicine*, 44(11), 1573–1588. <https://doi.org/10.1007/s40279-014-0225-3>
- Brughelli, M., & Cronin, J. (2008). A review of research on the mechanical stiffness in running and jumping: Methodology and implications. *Scandinavian Journal of Medicine & Science in Sports*, 18(4), 417–426. <https://doi.org/10.1111/j.1600-0838.2008.00769.x>
- Chow, J. W., Park, S.-A., & Tillman, M. D. (2009). Lower trunk kinematics and muscle activity during different types of tennis serves. *BMC Sports Science, Medicine and Rehabilitation*, 1(1), 24. <https://doi.org/10.1186/1758-2555-1-24>
- Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed). Lawrence Erlbaum Associates.
- Colomar, J., Baiget, E., & Corbi, F. (2020). Influence of strength, power, and muscular stiffness on stroke velocity in junior tennis players. *Frontiers in Physiology*, 11, 196. <https://doi.org/10.3389/fphys.2020.00196>
- Cools, A. M., Johansson, F. R., Cambier, D. C., Velde, A. V., Palmans, T., & Witvrouw, E. E. (2010). Descriptive profile of scapulothoracic position, strength and flexibility variables in adolescent elite tennis players. *British Journal of Sports Medicine*, 44(9), 678–684. <https://doi.org/10.1136/bjsm.2009.070128>
- Cools, A. M., Palmans, T., & Johansson, F. R. (2014). Age-related, sport-specific adaptations of the shoulder girdle in elite adolescent tennis players. *Journal of Athletic Training*, 49(5), 647–653. <https://doi.org/10.4085/1062-6050-49.3.02>
- Fernandez-Fernandez, J., Nakamura, F. Y., Moreno-Perez, V., Lopez-Valenciano, A., Del Coso, J., Gallo-Salazar, C., Barbado, D., Ruiz-Perez, I., & Sanz-Rivas, D. (2019). Age and sex-related upper body performance differences in competitive young tennis players. *PLOS ONE*, 14(9), e0221761. <https://doi.org/10.1371/journal.pone.0221761>
- Frost, D. M., & Cronin, J. B. (2011). Stepping back to improve sprint performance: a kinetic analysis of the first step forwards. *Journal of Strength and Conditioning Research*, 25(10), 2721–2728. <https://doi.org/10.1519/JSC.0b013e31820d9ff6>
- Galé-Ansodi, C., Castellano, J., & Usabiaga, O. (2017). Physical profile of young tennis players in the tennis match-play using global positioning systems. *Journal of Physical Education and Sport*, 17(2), 826–832.
- Genevois, C., Reid, M., Rogowski, I., & Crespo, M. (2015). Performance factors related to the different tennis backhand groundstrokes: A Review. *Journal of Sports Science and Medicine*, 14(1), 194–202.
- Gillet, B., Begon, M., Sevrez, V., Berger-Vachon, C., & Rogowski, I. (2017). Adaptive alterations in shoulder range of motion and strength in young tennis players. *Journal of Athletic Training*, 52(2), 137–144. <https://doi.org/10.4085/1062-6050.52.1.10>

- Girard, O., Micallef, J. P., & Millet, G. P. (2005). Lower-limb activity during the power serve in tennis: Effects of performance level. *Medicine & Science in Sports & Exercise*, 37(6), 1021–1029.
- Hermens, H. J., Freriks, B., Disselhorst-Klug, C., & Rau, G. (2000). Development of recommendations for SEMG sensors and sensor placement procedures. *Journal of Electromyography and Kinesiology*, 10(5), 361–374. [https://doi.org/10.1016/S1050-6411\(00\)00027-4](https://doi.org/10.1016/S1050-6411(00)00027-4)
- Kibler, W. B., Chandler, T. J., Shapiro, R., & Conuel, M. (2007). Muscle activation in coupled scapulohumeral motions in the high performance tennis serve. *British Journal of Sports Medicine*, 41(11), 745–749. <https://doi.org/10.1136/bjsm.2007.037333>
- Ko, C. Y., Choi, H. J., Ryu, J., & Kim, G. (2018). Between-day reliability of MyotonPRO for the non-invasive measurement of muscle material properties in the lower extremities of patients with a chronic spinal cord injury. *Journal of Biomechanics*, 73, 60–65. <https://doi.org/10.1016/j.jbiomech.2018.03.026>
- Kovalchik, S. A., & Reid, M. (2017). Comparing matchplay characteristics and physical demands of junior and professional tennis athletes in the era of big data. *Journal Sports Science and Medicine*, 16(4), 489–497.
- Macgregor, L. J., Ditroilo, M., Smith, I. J., Fairweather, M. M., & Hunter, A. M. (2016). Reduced radial displacement of the gastrocnemius medialis muscle after electrically elicited fatigue. *Journal of Sport Rehabilitation*, 25(3), 241–247. <https://doi.org/10.1123/jsr.2014-0325>
- Madruga-Parera, M., Romero-Rodríguez, D., Bishop, C., Beltran-Valls, M. R., Latinjak, A. T., Beato, M., & Fort-Vanmeerhaeghe, A. (2019). Effects of maturation on lower limb neuromuscular asymmetries in elite youth tennis players. *Sports*, 7(5), 106. <https://doi.org/10.3390/sports7050106>
- Marcondes, F. B., Jesus, J. F. de, Bryk, F. F., Vasconcelos, R. A. de, & Fukuda, T. Y. (2013). Posterior shoulder tightness and rotator cuff strength assessments in painful shoulders of amateur tennis players. *Brazilian Journal of Physical Therapy*, 17(2), 185–193. <https://doi.org/10.1590/S1413-35552012005000079>
- Moreno-Pérez, V., Ayala, F., Fernandez-Fernandez, J., & Vera-Garcia, F. J. (2016). Descriptive profile of hip range of motion in elite tennis players. *Physical Therapy in Sport*, 19, 43–48. <https://doi.org/10.1016/j.ptsp.2015.10.005>
- Moreno-Pérez, V., Lopez-Valenciano, A., Barbado, D., Moreside, J., Elvira, J. L. L., & Vera-Garcia, F. J. (2017). Comparisons of hip strength and countermovement jump height in elite tennis players with and without acute history of groin injuries. *Musculoskeletal Science and Practice*, 29, 144–149. <https://doi.org/10.1016/j.msksp.2017.04.006>
- Moreno-Pérez, V., Moreside, J., Barbado, D., & Vera-Garcia, F. J. (2015). Comparison of shoulder rotation range of motion in professional tennis players with and without history of shoulder pain. *Manual Therapy*, 20(2), 313–318. <https://doi.org/10.1016/j.math.2014.10.008>
- Morin, J. B., Gimenez, P., Edouard, P., Arnal, P., Jiménez-Reyes, P., Samozino, P., Brughelli, M., & Mendiguchia, J. (2015). Sprint acceleration mechanics: The major role of hamstrings in horizontal force production. *Frontiers in Physiology*, 6. <https://doi.org/10.3389/fphys.2015.00404>
- Perri, T., Norton, K. L., Bellenger, C. R., & Murphy, A. P. (2018). Training loads in typical junior-elite tennis training and competition: Implications for transition periods in a high-performance pathway. *International Journal of Performance Analysis in Sport*, 18(2), 327–338. <https://doi.org/10.1080/24748668.2018.1475198>
- Pickering Rodriguez, E. C., Watsford, M. L., Bower, R. G., & Murphy, A. J. (2017). The relationship between lower body stiffness and injury incidence in female netballers. *Sports Biomechanics*, 16(3), 361–373. <https://doi.org/10.1080/14763141.2017.1319970>

- Pruyn, E. C., Watsford, M. L., & Murphy, A. J. (2015). Differences in lower-body stiffness between levels of netball competition: *Journal of Strength and Conditioning Research*, 29(5), 1197–1202. <https://doi.org/10.1519/JSC.0000000000000418>
- Pruyn, E. C., Watsford, M. L., & Murphy, A. J. (2016). Validity and reliability of three methods of stiffness assessment. *Journal of Sport and Health Science*, 5(4), 476–483. <https://doi.org/10.1016/j.jshs.2015.12.001>
- Pruyn, E. C., Watsford, M. L., Murphy, A. J., Pine, M. J., Spurrs, R. W., Cameron, M. L., & Johnston, R. J. (2012). Relationship between leg stiffness and lower body injuries in professional Australian football. *Journal of Sports Sciences*, 30(1), 71–78. <https://doi.org/10.1080/02640414.2011.624540>
- Rogowski, I., Rouffet, D., Lambalot, F., Brosseau, O., & Hautier, C. (2011). Trunk and upper limb muscle activation during flat and topspin forehand drives in young tennis players. *Journal of Applied Biomechanics*, 27(1), 15–21. <https://doi.org/10.1123/jab.27.1.15>
- Rota, S., Morel, B., Saboul, D., Rogowski, I., & Hautier, C. (2014). Influence of fatigue on upper limb muscle activity and performance in tennis. *Journal of Electromyography and Kinesiology*, 24(1), 90–97. <https://doi.org/10.1016/j.jelekin.2013.10.007>
- Sanchis-Moysi, J., Idoate, F., Álamo-Arce, D., Calbet, J. A. L., & Dorado, C. (2017). The core musculature in male prepubescent tennis players and untrained counterparts: A volumetric MRI study. *Journal of Sports Sciences*, 35(8), 791–797. <https://doi.org/10.1080/02640414.2016.1189589>
- Sanchis-Moysi, J., Idoate, F., Dorado, C., Alayón, S., & Calbet, J. A. L. (2010). Large asymmetric hypertrophy of rectus abdominis muscle in professional tennis players. *PLoS ONE*, 5(12), e15858. <https://doi.org/10.1371/journal.pone.0015858>
- Sanchis-Moysi, J., Idoate, F., Izquierdo, M., Calbet, J. A. L., & Dorado, C. (2011). Iliopsoas and gluteal muscles are asymmetric in tennis players but not in soccer players. *PLoS ONE*, 6(7), e22858. <https://doi.org/10.1371/journal.pone.0022858>
- Sanchis-Moysi, J., Idoate, F., Olmedillas, H., Guadalupe-Grau, A., Alayón, S., Carreras, A., Dorado, C., & Calbet, J. A. L. (2009). The upper extremity of the professional tennis player: Muscle volumes, fiber-type distribution and muscle strength: The tennis player upper extremity. *Scandinavian Journal of Medicine & Science in Sports*, 20(3), 524–534. <https://doi.org/10.1111/j.1600-0838.2009.00969.x>
- Shanley, E., Rauh, M. J., Michener, L. A., Ellenbecker, T. S., Garrison, J. C., & Thigpen, C. A. (2011). Shoulder range of motion measures as risk factors for shoulder and elbow injuries in high school softball and baseball players. *The American Journal of Sports Medicine*, 39(9), 1997–2006. <https://doi.org/10.1177/0363546511408876>
- Uzu, R., Shinya, M., & Oda, S. (2009). A split-step shortens the time to perform a choice reaction step-and-reach movement in a simulated tennis task. *Journal of Sports Sciences*, 27(12), 1233–1240. <https://doi.org/10.1080/02640410903233222>
- Young, S. W., Dakic, J., Stroia, K., Nguyen, M. L., Harris, A. H. S., & Safran, M. R. (2014). Hip range of motion and association with injury in female professional tennis players. *The American Journal of Sports Medicine*, 42(11), 2654–2658. <https://doi.org/10.1177/0363546514548852>

Table 1. Dominant and non-dominant stiffness, tone, elasticity, and time to relaxation differences (n = 34).

	Stiffness				Tone				Elasticity				Time to relaxation			
	<i>p</i>	ES	Desc.	%	<i>p</i>	ES	Descr	%	<i>p</i>	ES	Desc	%	<i>p</i>	ES	Desc	%
B	.667	-0.08	Trivial	1.2	.437	-0.03	Trivial	2.2	.203	0.23	Small	-5.6	.706	-0.07	Trivial	0.8
BF	.004†	0.53	Moderate	-11.1	.004†	0.54	Moderate	-5.6	.117	0.31	Small	-3.3	.002†	-0.58	Moderate	10.3
D	.431	0.23	Small	-4.3	.321	0.20	Small	-1.9	.549	-0.13	Trivial	1.3	.773	-0.04	Trivial	0.7
G	.043	0.35	Small	-7.6	.022	0.42	Small	-4.8	.737	-0.07	Trivial	1.2	.006†	-0.5	Moderate	9.1
I	.018	-0.37	Small	7.8	.132	-0.19	Trivial	2.5	.002†	-0.58	Small	9.9	.186	0.22	Small	-2.9
PM	.124	-0.25	Small	3.6	.004†	-0.56	Moderate	4.0	.055	0.33	Small	-5.9	.003†	-0.56	Moderate	5.1
RF	.050	-0.39	Small	3.0	.115	-0.27	Small	1.8	.873	-0.06	Trivial	1.0	.196	0.23	Small	-2.3
RA	.804	0.04	Trivial	-0.7	.570	-0.1	Trivial	0.9	.002†	0.6	Moderate	-8.0	.864	-0.03	Trivial	0.4
VM	.004†	-0.33	Small	5.4	.003†	-0.41	Small	3.2	.201	-0.27	Small	3.7	.017	0.37	Small	-3.8

B = biceps brachii; I = infraspinatus; D = deltoid; PM = pectoralis major; RA = rectus abdominis; RF = rectus femoris; VM = vastus medialis; BF = biceps femoris; G = gastrocnemius ES = Cohen's Effect Size; Descr = Descriptor; % = percentage of change; † = significant differences.

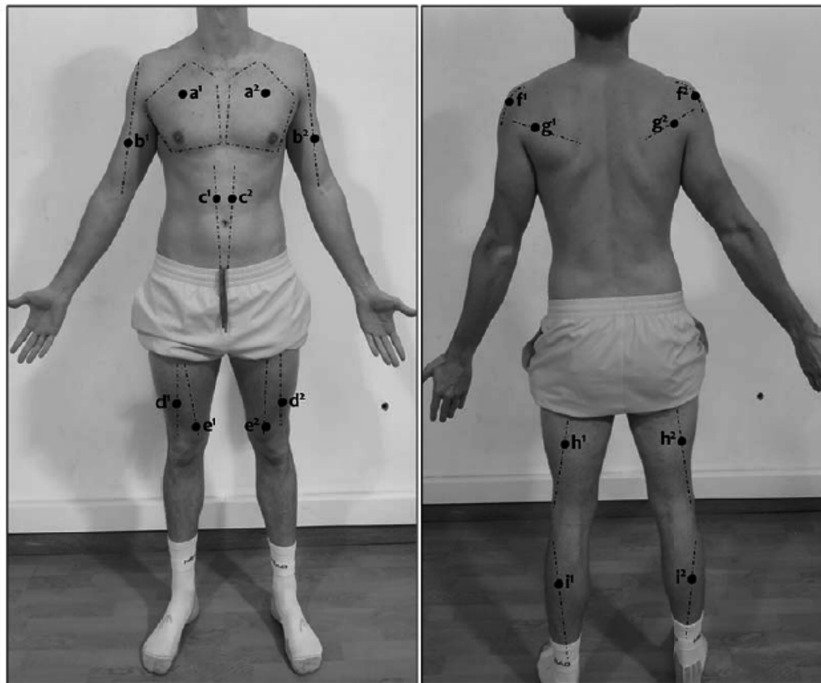


Figure 1. Approximate anatomic points for Myoton-Pro tip positioning.

¹ = dominant; ² = non-dominant; a = pectoralis major; b = biceps brachii; c = rectus abdominis; d = rectus femoris; e = vastus medialis; f = deltoids; g = infraspinatus; h = biceps femoris; i = gastrocnemius

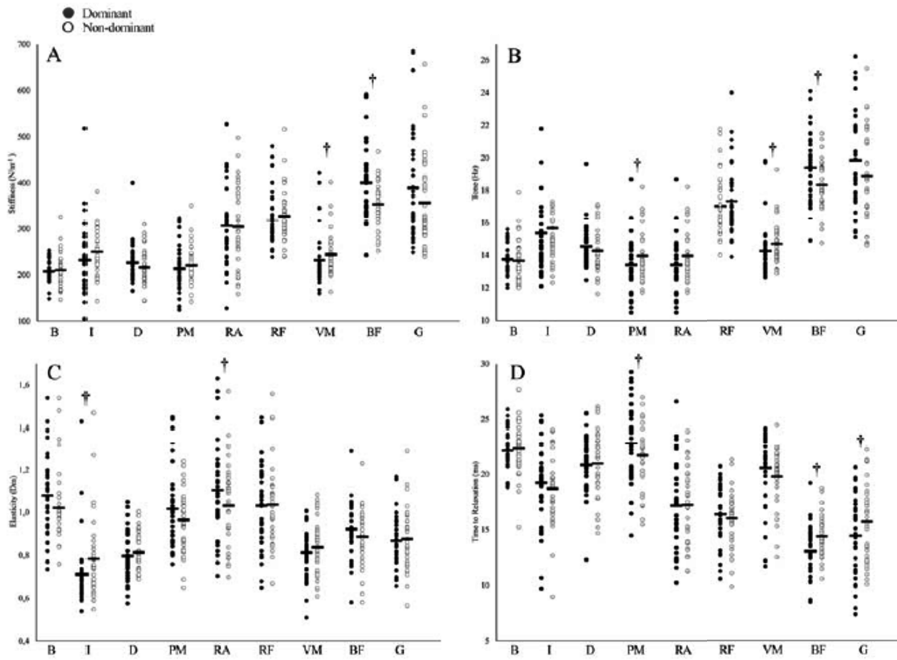


Figure 2. Dominant and non-dominant differences regarding stiffness (A), tone (B), elasticity (C) and time to relaxation (D).

B = biceps brachii; I = infraspinatus; D = deltoid; PM = pectoralis major; RA = rectus abdominis; RF = rectus femoris; VM = vastus medialis; BF = biceps femoris; G = gastrocnemius; † = significant differences from the dominant limb at $p < 0.05$.



STUDY 5

Force-time curve variable outcomes following a simulated tennis match in junior players.

Citation:

Colomar J, Baiget E, Corbi F. 2022. Force-time curve variable outcomes following a simulated tennis match in junior players. *Journal of Sports Science and Medicine*. [Under review].

doi: -

Journal information:

ISSN: -

Category: -

Impact Factor: -

Quartile: -

FORCE-TIME CURVE VARIABLE OUTCOMES FOLLOWING A SIMULATED TENNIS MATCH IN JUNIOR PLAYERS

ABSTRACT

Objectives: This study examined the alterations induced by a simulated tennis competition on maximal isometric voluntary contraction (MVC), peak rate of force development (PRFD) and rate of force development (RFD) at different stages of contraction.

Methods: Twenty junior tennis players performed an 80-minute simulated tennis match and two (pre and post) muscular performance tests. Variables tested included MVC, PRFD and RFD at 50, 100, 150 and 200 ms while performing a 90° shoulder internal rotation (IR90), 90° shoulder external rotation (ER90), shoulder horizontal adduction (ADD), shoulder horizontal abduction (ABD) and isometric mid-thigh pull (IMTP). Serve velocity (SV) was also registered.

Results: No significant changes were found regarding MVC, PRFD or SV. Non-significant moderate effect size (ES) towards a decrease in the IR90 RFD at 50 ms could be observed (16%; ES = 0.5) alongside an increase in the ADD and IMTP RFD at 150 ms (-15.8%, -8.2%; ES = -0.53, -0.54) and IMTP RFD at 200 ms (-13%; ES = -0.54).

Conclusions: Results indicate that MVC, PRFD, RFD at different time intervals and SV are unaltered following an 80-minute simulated match, possibly due to insufficient alterations triggered on key factors affecting the tested variables.

Key words: power, serve, fatigue, effects, strength

INTRODUCTION

Tennis has evolved into a fast-paced sport in which the ability to generate explosive actions and movements such as strokes, sprints and changes of direction is essential towards a greater performance (Kovacs, 2006). These actions rely, among other qualities, on certain fitness traits that are considered determinant for the sport and can be observed in higher ranked players. These include an enhanced level of speed over short distances, upper and lower body strength and power alongside a greater serve velocity (SV) (Ulbricht et al., 2016). Research has related force-time characteristics around the shoulder complex (Cools et al., 2014; Baiget et al., 2016; Baiget et al., 2021; Hayes et al., 2021) and upper body power levels (Ulbricht et al., 2016), to SV. Positive correlations have also been found between lower body isometric strength measurements and sprint and serve performance (Ulbricht et al., 2016; Hayes et al., 2021). These main actions normally involve one or more stretch-shortening cycles (SSC) throughout the kinetic chain (Kibler et al., 2007), and force production is to happen in a short period of time. For instance, the acceleration phase of tennis serve is due to happen in intervals as short as 80 ms approximately (Kibler et al., 2007), and other repetitive burst of fast movements such as jumping or 0-5 m accelerations and changes of direction require contraction times around 50-250 ms. (Aagaard et al., 2002). This reaffirms force production in determinant tennis actions would typically appear in what is considered as the early phase of explosive contraction (Maffiuletti, 2016; Baiget et al., 2021). This highlights the importance of generating high forces in brief or rapid intervals (i.e., rate of force development (RFD)) during the duration of a match or in consecutive days of play for an enhanced tennis performance (Girard et al., 2014; Baiget et al., 2021; Hayes et al., 2021). Therefore, how these aspects are affected by competition seems essential towards

effective recovery and training organization.

Prior investigations have stated significant impairments following match-play or competitive events, including the previously mentioned strength and power qualities. These changes derived from competition include increased muscle soreness (DOMS) (Gescheit et al., 2015), reductions in maximal isometric voluntary contraction (MVC) (Girard, 2006; Girard et al., 2008, 2011, 2014), decreased range of motion (ROM) (Martin et al., 2016; Gallo-Salazar et al., 2017; Moreno-Pérez et al., 2019) and SV (Gescheit et al., 2015). The appearance of fatigue due to muscle damage following inflammation, serum creatin kinase (CK) concentration and muscle function impairment would result in a reduction in performance in the mentioned variables (Girard, 2006; Mendez-Villanueva et al., 2007). Nevertheless, few studies to our knowledge have explored how competition-induced fatigue affects MVC and RFD at different time intervals in young tennis players. Previous works (Girard, 2006; Girard et al., 2008, 2011, 2014; Ojala and Häkkinen, 2013; Gescheit et al., 2015) have observed negative changes in these variables following prolonged tennis playing or simulated competitions, although testing typically included few selected leg or shoulder muscles or were performed including male professional or highly competitive participants.

Young players can perform an average of 10 to 21 competitive events and 65 matches year-round (Kovalchik and Reid, 2017; Johansson et al., 2022). Added to this, they also perform an accumulated 15 hours per week of tennis or fitness training. How physical qualities vary from pre to post playing conditions seems of great importance for junior competitors towards effective recovery strategies and load

management. Moreover, as stated previously and given the importance of developing force rapidly in tennis and the significance of MVC and RFD in determinant actions, knowledge around RFD within different phases of contraction could provide insights on how mechanisms underpinning explosive force production are affected by match-play. Thus, the goal of this study was to investigate the alterations induced by tennis match-play on MVC and RFD at different stages of contraction (i.e., <250 ms), in specific joint positions observed in tennis actions and in junior competitors. Based on previous literature (Girard, 2006; Girard et al., 2008, 2011, 2014), we hypothesized that upper and lower body measures of MVC, PRFD and RFD at different time intervals would be negatively affected by fatigue. Accordingly, SV reductions would be observed.

METHODS

Participants

G-Power statistical software (version 3.1.9.5; University of Dusseldorf, Dusseldorf, Germany) was used to determine that a minimum sample size of $n = 19$ was required for statistical power ≥ 0.8 at an alpha level of $p \leq 0.05$. Twenty (12 male and 8 female) junior tennis players (mean \pm SD; age, 16.9 ± 1.7 years; height, 1.76 ± 0.07 m; body mass, 64.4 ± 7.9 kg; BMI 20.7 ± 1.8 kg/m²) with an International Tennis Number (ITN) between 2 and 4 (advanced level) and a tennis training experience of 8.4 ± 1.9 years participated in this study. ITN was established by the consensus of two coaches accredited with RPT (Professional Tennis Registry) level 3, following the ITN Description of Standards (www.internationaltennisnumber.com). Participants had a weekly training volume of 20 h-week⁻¹ consisting of 3h of technical and tactical on-court tennis training and 1h of fitness training per day from Monday to Friday.

Seventeen participants (85% of total) performed a two-handed backhand, while the remaining 15% executed a one-handed fashion. One subject (5% of total) was left-handed while all other participants had a dominant right extremity. Inclusion criteria required each participant to have at least 1-year of participation in a structured physical training program and 5-years of tennis training and competition. Participants were excluded from the study if they had any back, upper or lower extremity pain or undergone surgery or rehabilitation in the past 3 months. All participants were informed in advance about the characteristics of the study and voluntarily signed an informed consent. In the case of being underage, their legal tutors signed the consent. The study was conducted following the ethical principles for biomedical research with human beings, established in the Declaration of Helsinki of the AMM (2013) and approved by an accredited Ethics Committee (15/CEICGC/2020).

Design

The experimental design was conducted as summarized in Figure 1. A cross-sectional repeated measures experimental design was performed on two testing sessions in a static order. Each player participated in two sessions (pre- and post-simulated match) separated approximately by 120 minutes under similar atmospheric, experimental conditions (wind < 2 m·s⁻¹) and by the same researcher. Between trials, participants played an 80-minute simulated tennis match on an outdoor standard hard court following the International Tennis Federation (ITF) rules and using new tennis balls (Head ATP Pro, Spain). Matches were undertaken by participants playing an opponent with a similar ITN level. In a 15-minute window after the match, participants performed the post-competition testing session. The use of recovery strategies (e.g., self-myofascial release, massage, stretching, etc.) was not

allowed in order to avoid interferences with the results. Players were allowed to consume water ad libitum. Energetic drinks were not allowed during the trials.

Insert Figure 1 around here

Procedures

Participants did not exercise for at least 18h before the protocol took place and they were encouraged to maintain their habitual lifestyle, to avoid excitatory substances (i.e., coffee or tea) and strenuous exercise during the previous day to the test. All measurements were registered in the morning, approximately from 7:30 am to 10 am. Testing sessions were performed in May and June during competition period.

Maximum isometric voluntary contraction (MVC) and rate of force development (RFD)

Participants were asked to perform five maximum isometric tests. The different positions assessed were (a) external shoulder rotation with the elbow and shoulder flexed 90° (ER90), (b) internal shoulder rotation with the elbow and shoulder flexed 90° (IR90), (c) horizontal shoulder adduction (ADD), (d) horizontal shoulder abduction (ABD) and (e) mid-thigh pull (IMTP) as summarized in Figure 1. As a warm up and prior to testing, participants performed five minutes of dynamic mobility exercises and two submaximal trials of 3 seconds of all tested positions at approximately 50% and 75% maximal effort, separated by 60 seconds each (Comfort et al., 2019). Tests concerning upper body were performed in a similar manner as Baiget et al., (2016), sitting on an Ercolina machine (Technogym Company, Cesena, Italy). The participants sat in a position with a 90° hip flexion and the back resting on a bench.

Participants were then fastened with a harness on the chest to avoid additional movement of other body segments. Only the dominant extremity was registered. For lower body assessment, tests were performed using a portable alternative to a force plate using a strength gauge (Chronojump, Boscosystem, Barcelona, Spain) attached to a heavy metal base or plate in a very similar fashion to that offered by James et al., (2017). Participants stood over the plate and the mid-thigh position was determined for each participant before testing by marking the midpoint distance between the knee and hip joints. This mid-point was established halfway between the iliac crest and the patella, as it seems athletes adopt their preferred hip and knee angles for the test (Comfort et al., 2015). The height of the bar was adjusted up or down to make sure it was in contact with the mid-thigh. Participants were allowed to use either overhand or hook grip. For all tests, participants were instructed to perform 1 second of quiet standing followed by a maximal effort for 5 seconds (as fast and hard as possible) (Comfort et al., 2019). The force-time curve for each trial was recorded using a strain gauge sampling at 80 Hz and the subsequent analysis software (Chronojump, Boscosystem, Barcelona, Spain). MVC and PRFD were defined as the highest value achieved during the 5 seconds. Additionally, force outputs at 50, 100, 150 and 200 ms from the initiation of the pull were determined for each trial (Comfort et al., 2015). RFD was then calculated as the segment between time points and following the equation: $RFD = \Delta Force / \Delta Time$ (Baiget et al., 2021). Precision and reproducibility were addressed using a test-retest design for which participants performed two trials spaced by 2 min rest between attempts. To avoid that the order of the evaluations could influence fatigue, tests were randomized. The reliability of test measurements showed good intervals of confidence in all variables (Table 2), as seen in similar investigations (Baiget et al., 2021)

Serve speed

Data collection was executed on a standard tennis hard court with stable wind conditions ($< 2 \text{ m}\cdot\text{s}^{-1}$) using new tennis balls (Head ATP Pro, Spain). Before the measurements, participants performed a standardized warm-up that included mobility exercises, 5 minutes of free rallies and 10 progressive serves. Each subject executed 8 serves (2 sets of 4 serves on each side of the court) with 2 minutes of rest between sets and 10 seconds between serves) before and after the simulated tennis match. Only the serves that landed in the serve box were registered. Maximum SV was determined using a hand-held radar gun (Stalker ATS II, USA, frequency: 34.7 GHz [Ka-Band] ± 50 MHz). The radar was positioned in the center of the baseline, 2 m behind the line and at an approximate height of 2 m following the trajectory of the ball. Players were asked to hit as hard as possible to the T and immediate feedback was provided to the participants to encourage maximum effort.

Tennis match load

Match load was recorded using a GPS unit (WimuPro[®], Realtrack Systems, Almería, Spain). Both players involved in the simulated match wore an adjusted vest with the attached device and diverse data was recorded for posterior descriptive information on match load (Table 1). Registered data included variables previously used in similar participants (Hoppe et al., 2014; Galé-Ansodi et al., 2017; Perri et al., 2018) such as total distance, number of accelerations, decelerations, distance at different running speeds, mean and peak velocity. Added to this, three heart rate (HR) zones were used for analysis. Using a HR monitor (Garmin HRM Dual Basic, Garmin, USA) and based on peak HR of the match (HR_{max}), zone 1 was determined as low- ($<70\%$ HR_{max}), zone 2, moderate- (70-85% HR_{max}) and zone 3, high-intensity-

(>85% HRmax). Time spent in different HR zones included play and changeover intervals. The same warm-up performed before the SV assessment was considered appropriate for the simulated match. Matches were played for 80 minutes regardless the score on a standard tennis hard court under stable wind conditions (<2 m·s⁻¹). Posterior to competition, fatigue perception was measured following the 6 to 20 Borg Scale Test (RPE).

Insert Table 1 around here

Statistical Analysis

Data are reported as mean ± standard deviation (SD). Normality of distributions and homogeneity of variances were assessed with the Shapiro-Wilk test. The reliabilities of test measurements were assessed using intraclass correlation coefficients (ICCs) and the coefficient of variation (CV) (Table 2). Parametric and non-parametric statistics were used when appropriate. Paired t-test were used to discern any significant differences between the mean values of pre- and post-measurements. Because some variables did not have a Gaussian distribution (all excluding SV, ER90° 200 ms, ABD 100 ms and ABD 150 ms) Wilcoxon paired test was used. Mean differences in absolute and percent values were also used. The magnitude of the differences in mean was quantified as effect size (ES) and interpreted according to the criteria used by (Cohen, 1988) <0.2 = trivial, 0.2–0.4 = small, 0.5– 0.7 = moderate, >0.7 = large. Thirty-one preplanned comparisons were considered for this study. Accordingly, correction for multiple comparisons was undertaken using the Bonferroni method with a resulting operational alpha level of 0.0016 ($p = 0.05/31$). All statistical analyses were performed using SPSS 23.0 software (SPSS Inc., Chicago,

IL, USA).

Insert Table 2 around here

RESULTS

Match-load characteristics are expressed in Table 1. Pre- and post-match SV, MVC and PRFD differences are summarized in Table 3, while data concerning RFD at different times is plotted in Figure 2. No significant differences were found between pre- and post-match measurements in any of the tested conditions. Moderate effect sizes (ES) towards a decreased IR90 RFD at 50 ms and an increased RFD in the IMTP at 150 ms and 200 ms in post-match conditions could be observed (-16%, 8.2% and 13%; ES = 0.5, -0.54 and -0.54), respectively. Also, a moderate increase in the post-match measurements in ADD RFD at 150 ms was noted (15.8%; ES = -0.53). No statistically significant differences could be observed concerning MVC values, PRFD or SV.

Insert Table 3 around here

Insert Figure 2 around here

DISCUSSION

The main finding of this investigation was that MVC, PRFD, RFD at different time intervals and SV remain unaltered following an 80-minute simulated tennis match in young players. Yet, after following this specific load, RFD at different time points while performing a MVC in certain joint positions (i.e., IR90, ADD and IMTP) seemed moderately affected.

Previous works have established alterations in certain physical aspects following tennis match-play, involving reductions in shoulder internal rotation ROM (Martin et al., 2016; Gallo-Salazar et al., 2017; Moreno-Pérez et al., 2019), DOMS and increased CK values (Gescheit et al., 2015). More specifically related to strength measurements, results here differ from those present in other investigations. MVC resulted in reductions in the majority of previous studies following tennis competitions or match-play (Girard, 2006; Girard et al., 2008, 2011, 2014; Gescheit et al., 2015; Gallo-Salazar et al., 2017; Moreno-Pérez et al., 2019). Nevertheless, significant reductions in this variable are noted only after performing a considerably greater competitive load compared to the one proposed here, especially regarding match-duration. In Girard et al., (2006, 2008), MVC of knee extensors suffered progressive reductions starting as soon as 30 minutes into match-play, but only being significant ($p < 0.05$) compared to pre-match conditions at 150 minutes of play, while plantar flexor and leg extensor muscles accounted similar decreases following 120 minutes of competition in further works (Girard et al., 2011, 2014; Ojala and Häkkinen, 2013), indicating that match duration could be an essential aspect inducing MVC reductions. More recent studies have also registered decreases in MVC around the shoulder joint in internal and external rotation gestures. Moreno-Pérez et al., (2019) observed significant changes towards lower strength levels in the shoulder external rotation motion following 80 minutes of match-play. As match duration is similar to that performed in this study, differences may be explained by the population analyzed or match-load differences. Reductions in MVC following a tennis match can be determined by fatigue induced in response to high and repetitive loads performed during serves, groundstrokes, short sprints and changes of direction (Mendez-Villanueva et al., 2007). Nevertheless, external match loads concerning number of

strokes, running distance and high-intensity bouts may be considerably different when comparing adolescents, professional players and male or female participants (Hoppe et al., 2014; Kovalchik and Reid, 2017; Perri et al., 2018). Analyzed population differences could be one of the reasons of dissimilar results, as participants in Moreno et al., (2019) represent professional male players of greater age and level that could achieve a higher number of strokes and high intensity bouts during competition, although performing similar match durations (Hoppe et al., 2014; Kovalchik and Reid, 2017; Perri et al., 2018). In investigations focusing on populations with a similar age (Gallo-Salazar et al., 2017), reductions in MVC have been observed in shoulder internal and external rotation values following two consecutive matches of approximately 80 minutes in one day, which in absolute numbers accounted for roughly two-times the competition duration than that performed in this study. This reinforces the idea that duration here might be of an insufficient magnitude to evoke changes, especially in players with a significantly high volume of training (20h-week-1). Added, although match duration responded to typical matches of youth populations, internal load indicators such as mean and maximal HR slightly differ from those seen in similar studies (Hoppe et al., 2014). In short, reductions in MVC in lower and upper body values seem to appear following tennis match-play of longer duration, especially in male players of greater level, while results here indicate that 80 minutes of competition seems an insufficient load to negatively affect these values in junior players.

In the same way, no decreases in PRFD of the analysed motions were noted. Gescheit et al., (2015) observed how consecutive days of prolonged tennis match-play negatively affected this variable in the IMTP test. However, in a similar way to

data concerning MVC discussed previously, RFD values diminished only after day two of competition, when accumulated volume of play was at least of two matches of 240 minutes. Similarly, Ojala and Hakkinen (2013) observed a decrease in RFD in a bilateral leg press following the first match (i.e., 120 minutes duration and 13.2 RPE values) of a three-day tennis tournament while Girard et al., (2014) found similar reductions in knee extensors after a 120-minute match in hot temperature conditions ($-22 \pm 10.9\%$). Added to this, participants analysed in the aforementioned studies highly differed in age (23 ± 3.8 vs. 16.9 ± 1.7) and level (elite vs. competitive) (Ojala and Häkkinen, 2013; Girard et al., 2014) from players present in this investigation, restating that differences regarding match load and volume alongside age and level of play are important factors affecting MVC and PRFD outcomes following competition.

RFD at different stages of contraction was unaffected by 80 minutes of match-play. Investigations in other sports such as handball reported reductions in RFD as early as 50 ms in knee extensors and at 200 ms in both knee extensors and flexors (Thorlund et al., 2007). Specifically in tennis, Girard et al., (2014) observed significant decreases following 120 minutes of competition in knee extensors at 200 ms of contraction in experimented players. Unaffected variables here are surprising as tennis match-play characteristics certainly seem to have the potential to affect rates of muscle force production due to repetitive accelerations, decelerations, changes of direction and high velocity strokes (Mendez-Villanueva et al., 2007). Nevertheless, results should be analysed with caution and generally unaltered values could have a various number of reasons. First, comparing studies becomes challenging as methods to detect force production at different time intervals during a MVC bout are

not fully agreed on (Thompson, 2012). Additionally, within-participant variability (see Figure 2), especially during initial phases of contraction (<50ms) could reduce the capacity of detecting changes, requiring larger sample sizes to do so (Buckthorpe et al., 2012). More specifically regarding strength values observed here, RFD would seem unaffected as MVC remained unchanged following the simulated tennis match. As literature points out, diverse mechanisms affect explosive force production and maximal strength seems increasingly dependent on MVC, especially in intervals later than 90 ms (Maffiuletti, 2016). Following this idea, inexistent reductions in MVC would result in similar RFD outcomes in the tested contraction times. Moreover, other key factors identified as mechanisms affecting earlier and later phases of RFD such as motor unit discharge rate, fibre type composition, stiffness of the muscle-tendon unit and shifts in muscle length and torque production produced by eccentric damage (Maffiuletti, 2016) may have been unaffected due to insufficient competitive load. In the same way as mentioned regarding MVC and PRFD, 80-minutes of simulated competition may have been insufficient to elicit the fatigue mechanisms that would progressively affect explosive force production, at any stage of contraction whatsoever. Although this study reproduced typical match durations and loads regarding junior tennis competition (Galé-Ansodi et al., 2017; Perri et al., 2018), the fact that the intervention consisted of a simulated tennis match with lower demands than competitive bouts (Murphy et al., 2016) and participants typically performing high training volumes throughout their program (20h·week⁻¹) could reinforce the idea that the load was not as demanding for participants. This added to age and sex differences may result in such different results. In any case, this is speculative, and changes remained generally unaffected in all variables, including on-court functional performance measurements such as SV.

This study had some limitations. Participants were slightly heterogenous regarding age, although not in training experience and level. Added, sample size and the fact that mixed male and female participants were included in the study may have affected results to some extent. Also, the strain gauge used sampled at 200 Hz which might be a low frequency for early contraction time measurements such as the 50 ms. Furthermore, as a recommendation for future investigations, ensuring interventions of longer duration and in competitive conditions could seem essential to observe changes in the analysed variables.

Tennis is a sport characterized by high training volume that are sometimes distorted in several training sessions that take place on the same day with strength and conditioning programs following on-court drills and competition or vice versa. This study shows that key physical factors such as MVC, PRFD or SV do not seem to be negatively affected by relatively low loads of match-play, specifically in simulated conditions in junior players with a high training volume background. Various significant aspects affecting tennis performance rely on the aforementioned tested variables, making knowledge around how training and competition influence their outcome of high importance. Therefore, including programs that incorporate exercises focused on speed, power and velocity production following simulated matches, far from being counterproductive, could be a valid option towards effective use of training time. On the other hand, performing these interventions performing after matches of longer duration in competitive contexts and especially of greater match-load, may not be recommended and coaches should address training in consequence.

In conclusion, MVC, PRFD, RFD at different time intervals and SV are unaltered following an 80-minute simulated match in young tennis competitors, possibly due to an insufficient load and subsequent alterations of key factors and mechanisms affecting the variables tested. However, RFD values while performing a MVC in the IR90, ADD and IMTP positions seem to moderately change following an intervention of these characteristics, suggesting that performing a load of greater duration, magnitude or with more experimented players with a greater level could result in significant changes.

ACKNOWLEDGEMENTS

The authors would like to thank the participants for their enthusiastic participation.

REFERENCES

- Aagaard, P., Simonsen, E.B., Andersen, J.L., Magnusson, P. and Dyhre-Poulsen, P. (2002) Increased rate of force development and neural drive of human skeletal muscle following resistance training. *Journal of Applied Physiology* 93, 1318–1326.
- Baiget, E., Colomar, J. and Corbi, F. (2021) Upper-Limb Force–Time Characteristics Determine Serve Velocity in Competition Tennis Players. *International Journal of Sports Physiology and Performance* Ahead of print, 1–9.
- Baiget, E., Corbi, F., Fuentes, J.P. and Fernández-Fernández, J. (2016) The Relationship Between Maximum Isometric Strength and Ball Velocity in the Tennis Serve. *Journal of Human Kinetics* 53, 63–71.
- Buckthorpe, M.W., Hannah, R., Pain, T.G. and Folland, J.P. (2012) Reliability of neuromuscular measurements during explosive isometric contractions, with special reference to electromyography normalization techniques: Reliability of Explosive

Neuromuscular Measurements. *Muscle & Nerve* 46, 566–576.

Cohen, J. (1988) *Statistical Power Analysis for the Behavioral Sciences*. , 2nd ed. Hillsdale, N.J: L. Erlbaum Associates.

Comfort, P., Dos'Santos, T., Beckham, G.K., Stone, M.H., Guppy, S.N. and Haff, G.G. (2019) Standardization and Methodological Considerations for the Isometric Midthigh Pull: *Strength and Conditioning Journal* 41, 57–79.

Comfort, P., Jones, Paul.A., McMahon, J.J. and Newton, R. (2015) Effect of Knee and Trunk Angle on Kinetic Variables During the Isometric Midthigh Pull: Test–Retest Reliability. *International Journal of Sports Physiology and Performance* 10, 58–63.

Cools, A.M., Palmans, T. and Johansson, F.R. (2014) Age-Related, Sport-Specific Adaptions of the Shoulder Girdle in Elite Adolescent Tennis Players. *Journal of Athletic Training* 49, 647–653.

Galé-Ansodi, C., Castellano, J. and Usabiaga, O. (2017) Physical profile of young tennis players in the tennis match-play using global positioning systems. *Journal of Physical Education and Sport* 17, 826–832.

Gallo-Salazar, C., Del Coso, J., Barbado, D., Lopez-Valenciano, A., Santos-Rosa, F.J., Sanz-Rivas, D., et al. (2017) Impact of a competition with two consecutive matches in a day on physical performance in young tennis players. *Applied Physiology, Nutrition, and Metabolism* 42, 750–756.

Gescheit, D.T., Cormack, S.J., Reid, M. and Duffield, R. (2015) Consecutive Days of Prolonged Tennis Match Play: Performance, Physical, and Perceptual Responses in Trained Players. *International Journal of Sports Physiology and Performance* 10, 913–920.

Girard, O. (2006) Changes in exercise characteristics, maximal voluntary contraction, and explosive strength during prolonged tennis playing. *British Journal of Sports*

Medicine 40, 521–526.

Girard, O., Lattier, G., Maffiuletti, N.A., Micallef, J.-P. and Millet, G.P. (2008) Neuromuscular fatigue during a prolonged intermittent exercise: Application to tennis. *Journal of Electromyography and Kinesiology* 18, 1038–1046.

Girard, O., Racinais, S., Micallef, J.-P. and Millet, G.P. (2011) Spinal modulations accompany peripheral fatigue during prolonged tennis playing: Spinal reflexes in tennis. *Scandinavian Journal of Medicine & Science in Sports* 21, 455–464.

Girard, O., Racinais, S. and Périard, J.D. (2014) Tennis in hot and cool conditions decreases the rapid muscle torque production capacity of the knee extensors but not of the plantar flexors. *British Journal of Sports Medicine* 48, i52–i58.

Hayes, M.J., Spits, D.R., Watts, D.G. and Kelly, V.G. (2021) Relationship Between Tennis Serve Velocity and Select Performance Measures. *Journal of Strength and Conditioning Research* 35, 190–197.

Hoppe, M.W., Baumgart, C., Bornefeld, J., Sperlich, B., Freiwald, J. and Holmberg, H.-C. (2014) Running Activity Profile of Adolescent Tennis Players During Match Play. *Pediatric Exercise Science* 26, 281–290.

James, L.P., Roberts, L.A., Haff, G.G., Kelly, V.G. and Beckman, E.M. (2017) Validity and Reliability of a Portable Isometric Mid-Thigh Clean Pull: *Journal of Strength and Conditioning Research* 31, 1378–1386.

Johansson, F., Gabbett, T., Svedmark, P. and Skillgate, E. (2022) External Training Load and the Association With Back Pain in Competitive Adolescent Tennis Players: Results From the SMASH Cohort Study. *Sports Health: A Multidisciplinary Approach* 14, 111–118.

Kibler, W.B., Chandler, T.J., Shapiro, R. and Conuel, M. (2007) Muscle activation in coupled scapulohumeral motions in the high performance tennis serve. *British*

Journal of Sports Medicine 41, 745–749.

Kovacs, M.S. (2006) Applied physiology of tennis performance. *British Journal of Sports Medicine* 40, 381–386.

Kovalchik, S.A. and Reid, M. (2017) Comparing Matchplay Characteristics and Physical Demands of Junior and Professional Tennis Athletes in the Era of Big Data. *Journal of Sports Science and Medicine* 16, 489–497.

Maffiuletti, N.A. (2016) Rate of force development: physiological and methodological considerations. *Eur J Appl Physiol*, 26.

Martin, C., Bideau, B., Delamarche, P. and Kulpa, R. (2016a) Influence of a Prolonged Tennis Match Play on Serve Biomechanics. *PLOS ONE* 11, e0159979.

Martin, C., Kulpa, R., Ezanno, F., Delamarche, P. and Bideau, B. (2016b) Influence of Playing a Prolonged Tennis Match on Shoulder Internal Range of Motion. *The American Journal of Sports Medicine* 44, 2147–2151.

Mendez-Villanueva, A., Fernandez-Fernandez, J. and Bishop, D. (2007) Exercise-induced homeostatic perturbations provoked by singles tennis match play with reference to development of fatigue. *British Journal of Sports Medicine* 41, 717–722.

Moreno-Pérez, V., López-Samanes, Á., Domínguez, R., Fernández-Elías, V.E., González-Frutos, P., Fernández-Ruiz, V., et al. (2019) Acute effects of a single tennis match on passive shoulder rotation range of motion, isometric strength and serve speed in professional tennis players. *PLOS ONE* 14, e0215015.

Murphy, A.P., Duffield, R., Kellett, A. and Reid, M. (2016) A Comparison of the Perceptual and Technical Demands of Tennis Training, Simulated Match Play, and Competitive Tournaments. *International Journal of Sports Physiology and Performance* 11, 40–47.

Ojala, T. and Häkkinen, K. (2013) Effects of the Tennis Tournament on Players'

Physical Performance, Hormonal Responses, Muscle Damage and Recovery. *Journal of Sports Science and Medicine* 12, 240–248.

Perri, T., Norton, K.I., Bellenger, C.R. and Murphy, A.P. (2018) Training loads in typical junior-elite tennis training and competition: implications for transition periods in a high-performance pathway. *International Journal of Performance Analysis in Sport* 18, 327–338.

Thompson, B.J. (2012) Consistency of rapid muscle force characteristics: Influence of muscle contraction onset detection methodology. *Journal of Electromyography and Kinesiology*, 8.

Thorlund, J.B., Michalsik, L.B., Madsen, K. and Aagaard, P. (2007) Acute fatigue-induced changes in muscle mechanical properties and neuromuscular activity in elite handball players following a handball match: Neuromuscular fatigue in elite handball. *Scandinavian Journal of Medicine & Science in Sports* 18, 462–472.

Ulbricht, A., Fernandez-Fernandez, J., Mendez-Villanueva, A. and Ferrauti, A. (2016) Impact of Fitness Characteristics on Tennis Performance in Elite Junior Tennis Players: *Journal of Strength and Conditioning Research* 30, 989–998.

STUDY 5 FIGURES AND TABLES

TABLES

Table 1. Match load characteristics (n = 20).

Variables	Mean ± SD
Games per match	15.7 ± 2.72
Total distance (m)	3184.6 ± 601.2
Distance at 0 to > 1 m·s ⁻¹ (m)	1260.3 ± 203.5
Distance at 1 to > 2 m·s ⁻¹ (m)	1532.0 ± 386.2
Distance at 2 to > 3 m·s ⁻¹ (m)	267.8 ± 95.5
Distance at 3 to > 4 m·s ⁻¹ (m)	88.8 ± 48.7
Distance at ≥ 4 m·s ⁻¹ (m)	35.6 ± 29.0
Peak velocity (m·s ⁻¹)	5.37 ± 0.73
Mean velocity (m·s ⁻¹)	0.96 ± 0.07
High intensity accelerations (≥ 3 m·s ⁻¹ ; n)	19.7 ± 10.2
High intensity decelerations (≥ -3 m·s ⁻¹ ; n)	34.1 ± 19.3
High intensity accelerations (≥ 3 m·s ⁻¹ ; n·min ⁻¹)	0.29 ± 0.15
High intensity decelerations (≥ -3 m·s ⁻¹ ; n·min ⁻¹)	0.49 ± 0.25
HRmax (beats·min ⁻¹)	172.1 ± 19.2
Mean HR (beats·min ⁻¹)	135.0 ± 18.8
Time spent at <70% HRmax (%)	45.8 ± 32.9
Time spent at 70-85% HRmax (%)	29.6 ± 16.8
Time spent at >85% HRmax (%)	20.2 ± 19.9
RPE	12.4 ± 1.2

HRmax = match peak heart rate; RPE = rate of perceived exertion.

Table 2. Reliability of test measurements (n = 20)

	ICC (95% CI)	CV (%)
SV	0.970 (0.946 - 0.986)	4.0
MVC IR90°	0.897 (0.618 – 0.972)	11.1
MVC ER90°	0.990 (0.958 – 0.997)	6.0
MVC ADD	0.981 (0.937 – 0.994)	6.0
MVC ABD	0.923 (0.747 – 0.976)	16.6
MVC IMTP	0.982 (0.950 – 0.993)	6.7
PRFD IR90°	0.933 (0.666 – 0.987)	19.3
PRFD ER90°	0.953 (0.728 – 0.992)	15.3
PRFD ADD	0.969 (0.884 – 0.992)	19.1
PRFD ABD	0.937 (0.720 – 0.986)	20.8
PRFD IMTP	0.844 (0.307 – 0.965)	16.4
IR 90° 50 ms	0.932 (0.764 – 0.980)	19.2
IR90° 100 ms	0.965 (0.885 – 0.989)	12.1
IR90° 150 ms	0.973 (0.911 – 0.992)	13.6
IR90° 200 ms	0.920 (0.646 – 0.982)	14.9
ER 90° 50 ms	0.904 (0.615 – 0.976)	18.3
ER90° 100 ms	0.957 (0.849 – 0.987)	14.1
ER90° 150 ms	0.907 (0.677 – 0.973)	12.4
ER90° 200 ms	0.872 (0.486 – 0.968)	11.8
ADD 50 ms	0.960 (0.862 – 0.989)	14.4
ADD 100 ms	0.987 (0.959 – 0.996)	7.8
ADD 150 ms	0.860 (0.514 – 0.960)	14.0
ADD 200 ms	0.910 (0.689 – 0.974)	16.8
ABD 50 ms	0.984 (0.941 – 0.996)	11.3
ABD 100 ms	0.959 (0.848 – 0.989)	13.3
ABD 150 ms	0.890 (0.558 – 0.973)	14.8
ABD 200 ms	0.880 (0.399 – 0.976)	16.3
IMTP 50 ms	0.910 (0.622 – 0.980)	7.2
IMTP 100 ms	0.915 (0.623 – 0.981)	5.3
IMTP 150 ms	0.823 (0.286 – 0.956)	14.7
IMTP 200 ms	0.879 (0.548 – 0.967)	9.1

CV = coefficient of variation; ICC = intraclass correlation coefficient; SV = serve velocity; MVC = maximal voluntary contraction; PRFD = peak rate of force development; IR = shoulder internal rotation; ER = shoulder external rotation; ADD = horizontal shoulder adduction; ABD = horizontal shoulder abduction; IMTP = isometric mid-thigh pull.

Table 3. Pre- and post-match serve velocity (SV), maximal isometric voluntary contraction (MVC) and peak rate of force development (PRFD) changes.

Variable	PRE	POST	ES	Change (%)	p
SV (km·h⁻¹)	140.4 ± 11.8	141.1 ± 12.4	-0.14	0.4	.543
MVC IR90° (N)	125.8 ± 49.2	125.4 ± 54.7	0.19	- 0.3	.475
MVC ER90° (N)	95.4 ± 35.5	93.4 ± 38.5	0.09	- 2.1	.756
MVC ADD (N)	85.2 ± 36.7	83.6 ± 31.4	0.23	- 1.9	.388
MVC ABD (N)	115.4 ± 51.4	114.1 ± 49.6	0.24	- 1.1	.368
MVC IMTP (N)	938.8 ± 365.8	967.9 ± 402.2	-0.25	3.0	.41
PRFD IR90° (N·s⁻¹)	954.3 ± 555.6	794.5 ± 391.4	0.33	- 20.1	.202
PRFD ER90° (N·s⁻¹)	992.4 ± 799.2	1202.5 ± 800.3	0.04	17.5	.898
PRFD ADD (N·s⁻¹)	935.7 ± 892.9	940.3 ± 683.5	0.07	0.5	.812
PRFD ABD (N·s⁻¹)	969.9 ± 619.3	976.7 ± 709.8	0.1	0.7	.729
PRFD IMTP (N·s⁻¹)	5768.6 ± 2222.1	5059.8 ± 2715.8	0.47	- 14.0	.27

ES = Cohen's effect size; SV = serve velocity; MVC = maximal isometric voluntary contraction; PRFD = peak rate of force development; IR = shoulder internal rotation; ER = shoulder external rotation; ADD = horizontal shoulder adduction; ABD = horizontal shoulder abduction; IMTP = isometric mid-thigh pull.

FIGURES

Figure 1. Experimental design. a) external shoulder rotation with the elbow and shoulder flexed 90° (ER90); b) internal shoulder rotation with the elbow and shoulder flexed 90° (IR90); c) horizontal shoulder adduction (ADD); d) horizontal shoulder abduction (ABD); e) isometric mid-thigh pull (IMTP).

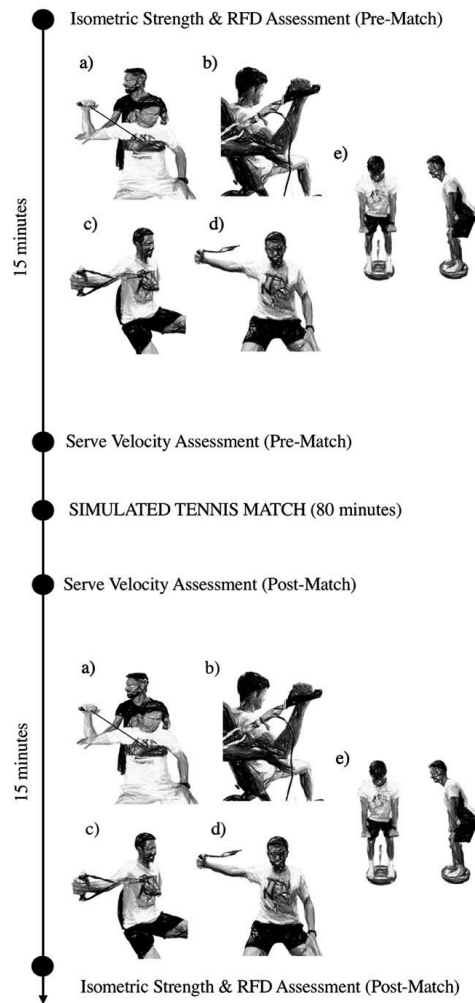
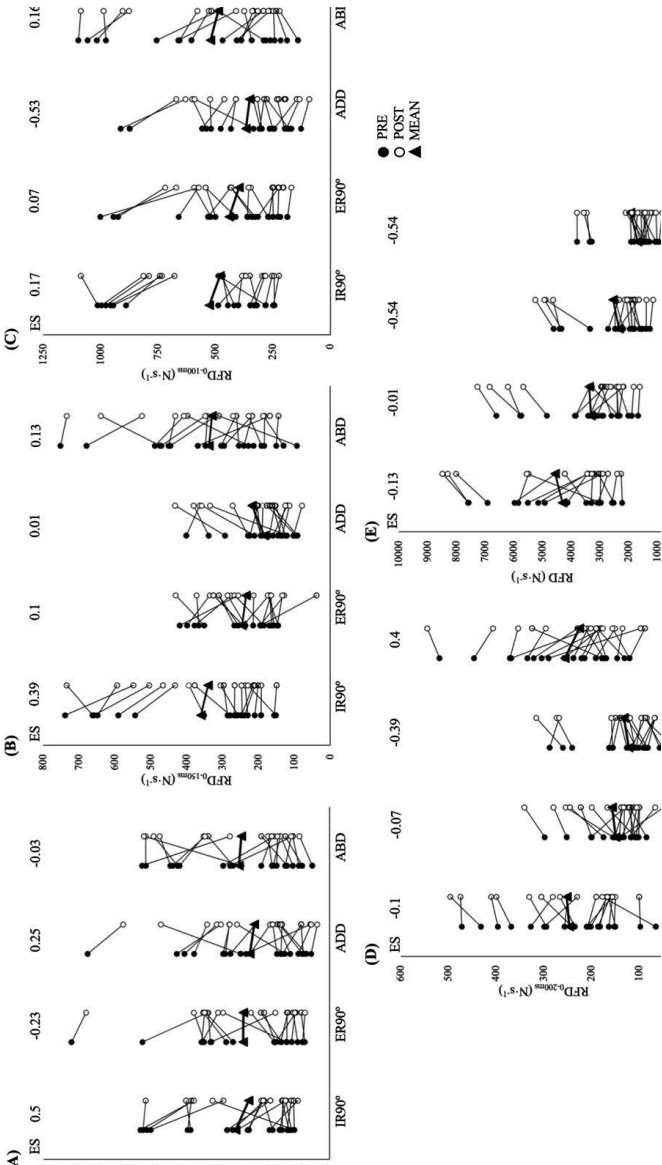


Figure 2. Pre- and post-match rate of force development (RFD) at (A) 50 ms, (B) 100 ms, (C) 150 ms, (D) 200 ms and (E) during the isometric mid-thigh pull test (IMTP) at all stages of contraction (50 ms, 100 ms, 150ms and 200 ms).

Data are mean \pm SD. ES = Cohen's effect size; IR90° = shoulder internal rotation; ER90° = shoulder external rotation; ADD = horizontal shoulder adduction; ABD = horizontal shoulder abduction; IMTP = isometric mid-thigh pull.



STUDY 6

Acute effects of in-step and wrist weights on change of direction speed, accuracy, and stroke velocity in junior tennis players.

Citation:

Colomar J, Baiget E, Corbi F, Muñoz J (2020) Acute effects of in-step and wrist weights on change of direction speed, accuracy, and stroke velocity in junior tennis players. PLOS ONE 15(3): e0230631.

doi: 10.1371/journal.pone.0230631

Journal information:

PLoS One

ISSN: 1932-6203

Category: Multidisciplinary sciences

Impact Factor: 3.240

Quartile: Q2

RESEARCH ARTICLE

Acute effects of in-step and wrist weights on change of direction speed, accuracy and stroke velocity in junior tennis players

Joshua Colomar^{1,2*}, Ernest Baiget³, Francisco Corbi⁴, Joshua Muñoz^{1,2}

1 National Institute of Sport and Physical Education (INEFC), University of Barcelona, Barcelona, Spain, 2 Sports Science Department, Academia Sánchez-Casal, Barcelona, Spain, 3 Sport Performance Analysis Research Group (SPARG), University of Vic—Central University of Catalonia, Vic, Spain, 4 National Institute of Sport and Physical Education (INEFC), University of Lleida, Lleida, Spain

* joshuacolomar@gmail.com

Abstract

The main aim of this study was to investigate the acute effects of the use of a weighting set (Powerinstep®) on measures of stroke velocity (StV), accuracy and change of direction speed (CODS) in junior tennis players. A within-subjects design was used to evaluate seventeen (6 female and 11 male) tennis players (mean \pm SD; 16.5 \pm 1.3 years old; 1.75 \pm 8.4 m; 67.0 \pm 8.1 kg; 22.04 \pm 1.8 kg/m²) on StV of three specific tennis actions (serve, forehand and backhand) and CODS for the following conditions: wearing a 50, 100, 150, 200 g weight or no weight at all (baseline). No significant differences were found between conditions for forehand ($F = 0.412$; $p = 0.799$), backhand ($F = 0.269$; $p = 0.897$) and serve ($F = 0.541$; $p = 0.706$) velocity and forehand ($F = 1.688$; $p = 0.161$), backhand ($F = 0.567$; $p = 0.687$) and serve ($F = 2.382$; $p = 0.059$) accuracy and CODS ($F = 0.416$; $p = 0.797$). Small-to-moderate effect sizes (ES) negatively affecting StV when using 200 g compared to the baseline (ES = 0.48, 0.35 and 0.45) could be observed. Moderate (ES = -0.49) and trivial (ES = -0.14 and -0.16) ES for a higher accuracy score were noticed in serve, forehand and backhand 100 g compared to the baseline. Moreover, small ES (ES = 0.41) for improvement in 200 g CODS comparing to baseline conditions were found. These results indicate that the use of a weighting set does not significantly affect StV or CODS respectively. Notwithstanding, small-to-moderate changes show impact in accuracy and no variance in velocity production when using 100 g alongside faster execution in CODS when using 200 g.

OPEN ACCESS

Citation: Colomar J, Baiget E, Corbi F, Muñoz J (2020) Acute effects of in-step and wrist weights on change of direction speed, accuracy and stroke velocity in junior tennis players. *PLoS ONE* 15(3): e0230631. <https://doi.org/10.1371/journal.pone.0230631>

Editor: Caroline Sunderland, Nottingham Trent University, UNITED KINGDOM

Received: November 6, 2019

Accepted: March 4, 2020

Published: March 23, 2020

Peer Review History: PLOS recognizes the benefits of transparency in the peer review process; therefore, we enable the publication of all of the content of peer review and author responses alongside final, published articles. The editorial history of this article is available here: <https://doi.org/10.1371/journal.pone.0230631>

Copyright: © 2020 Colomar et al. This is an open access article distributed under the terms of the [Creative Commons Attribution License](https://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

Data Availability Statement: All relevant data are within the manuscript.

Funding: The research leading to these results has been conducted using funds from the agreement

Introduction

The development of hitting or throwing velocity in overhead sports has often involved improving movement patterns, enhancement of conditioning or modifying implement such as racquets or baseballs [1]. As speed, power and stroke velocity (StV) have become determinant factors of tennis [2,3], it may become interesting to observe specific strategies to improve velocity production that practitioners can use to manage and plan new training methods. Concerning modification of implement, and focusing on tennis, customizing racquets in order to alter their weight, balance point and swing weight is an extended practice performed by players

between the Universitat de Vic – Universitat Central de Catalunya and Powerinstep, SL. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Competing interests: The authors declare that there is no conflict of interest between the participants, the materials and equipment used, or any other procedure undertaken during the experiments and the researchers of this investigation.

and coaches [4]. This practice, in addition to other reasons, intends to use the transfer of momentum created by the mass of the racquet to hit the ball faster. In this line, heavier racquets will produce faster balls but consequently be swung slower than lighter versions [5]. Nevertheless, current literature is scarce about the effects of these variations and also offers doubts on how different customizing techniques (i.e., how the mass is distributed throughout the racquet) may affect speed [1,4] or accuracy. Moreover, intervention programs have suggested that the use of overweight implements or balls could be an effective way of improving throwing velocity in overhead sports [6,7] including tennis [8]. Although in this case tendencies have generally aimed to vary weight on the frame of the racquet, no investigations are available on how StV may be affected by the use of extra loading on extremities, raising uncertainty on how this may affect ball speed alongside kinetics and kinematics. Taking into account that the International Tennis Federation (ITF) does not prohibit the use of materials that modify the shape or physical properties of the racquet, the appearance of new equipment and training techniques may offer other ways of modifying momentum and consequently StV without modifying the racquet's features, giving insight on new ways of affecting velocity production. As a starting point, further knowledge on how StV and accuracy are affected when modifying swing weight could be interesting for developing specific intervention programs that seek to maximize the mechanical power output using light loads [9].

Added to this, around four changes of direction per point and as many as 1000 per match are produced during tennis match-play and cover on average a distance of 8–15 m per point [10,11], highlighting the importance of short distance sprinting, change of direction speed (CODS) and agility for competitive tennis players [3]. Following the aforementioned use of wearable resistance training systems in order to improve physical aspects in predominantly upper body actions, literature shows some interesting performance adaptations when using this kind of equipment. Aspects such as oxygen consumption or energy cost are increased when running using certain external light loads on the lower limbs [12]. Furthermore, the use of wearable devices on the trunk and limbs may also affect sporting aspects such as jumping and sprinting, decreasing or increasing performance [13,14]. The use of light loads that can easily be attached and don't interfere in the athlete's movement could enable higher execution velocities that performed in a sport-specific context may further optimize training adaptations [15]. However, literature seems to be limited when speaking of the effects of these wearables in over-the-ground sprinting or acyclic sporting actions such as agility or CODS [13], which would more appropriately fit those actions present in tennis match-play.

A mobile weighting set with the name of Powerinstep®[®], consisting of various weight capsules (50, 100, 150, 200 g) and a wristband or plastic pieces to place them on the player's wrist or instep could be one of the aforementioned systems that practitioners may be interested in using in order to develop velocity production on both, specific tennis strokes and change of direction performance. Therefore, the purpose of this study was to investigate the acute effects of the use of a weighting set (Powerinstep®) on the tennis player's wrist or shoe on measures of StV, accuracy and CODS in comparison with 5 different conditions (i.e., wearing 50, 100, 150, 200 g weights or no weights at all) in young competitive tennis players. It is hypothesized that the use of certain weights that increase the momentum of the swing without altering speed (i.e., 100 g and 150 g) and that do not exceed a certain weight and interfere in velocity production (i.e., 200 g) will improve StV without affecting accuracy. On the other hand, CODS will be negatively affected exponentially as weight increases.

Materials and methods

Subjects

Seventeen (6 female and 11 male) competitive tennis players (mean \pm SD; age, 16.5 ± 1.3 years; height, 1.75 ± 8.4 m; weight, 67.0 ± 8.1 kg; BMI 22.04 ± 1.8 kg/m²) with an International Tennis Number (ITN) ranging from 2 to 4 participated in this study. Based on the repeated-measures design and an anticipated statistical power of 0.80 with an effect size 1.2, it was determined that a minimal sample size of $n = 15$ subjects would be necessary (G-Power software version 3.1.9.5, University of Dusseldorf, Dusseldorf, Germany). The player's ITN was established by the consensus of three coaches accredited with RPT (Registry of Tennis Professionals) level 3, following the ITN Description of Standards. Out of the seventeen players, just one of them used a one-handed backhand style while the remaining subjects played two-handed. Participants had a weekly volume of training of $25\text{h}/\text{week}^{-1}$, and were required to have a minimum of 1 year of experience in tennis and strength training. Also, they should not have experienced any pain in the trunk/upper body or other musculoskeletal discomfort in the six previous months.

Ethics statement

All subjects were informed in advance about the characteristics of the study and, before their participation, the participants and their legal tutors, in the case of being underage, voluntarily signed an informed consent. The study was conducted following the ethical principles for biomedical research with human beings, established in the Declaration of Helsinki of the AMM (2013) and approved by the Ethics Committee of the Catalan Sports Council (01/2019/CEICEGC).

Experimental design

A randomized, repeated measures within study design were assessed to compare the acute effects of wearing a set of weights (50, 100, 150, 200 g. Powerinstep®) with respect of not wearing them on StV, accuracy and CODS in young competitive tennis players. All weight sets were provided by Powerinstep® and consisted of one weight attached to a wristband for StV testing and two weights with instep plastic pieces for attachment to assess CODS (Fig 1). A familiarization session was carried out to inform on how to place the weights to avoid discomfort and possible inconveniences. Conditions were randomly distributed to avoid the influence of fatigue and test-learning effects. Subjects weren't familiarized with in-step or wrist weights. As dependent variables, StV (in km·h⁻¹), accuracy points and CODS (in seconds) were recorded to compare between 4 different conditions (50, 100, 150, 200 g) and baseline conditions (0 g). The comparison between these situations aimed to investigate the effects of using light weight loads on StV, accuracy and CODS.

Measurements

The collection of data took place in March during a normal in-season training week in groups of 4 players and on 2 separate testing sessions, performed in the morning and executed at least 48h apart. Participants hadn't trained in the previous 24h to any of the testing sessions and received all information regarding the risks and benefits of the study to obtain the informed consent in advance. Players were allowed to consume water ad libitum. Isotonic, energetic and caffeinated drinks were not allowed before or during the testing sessions. The first session consisted of performing the CODS test while the second session was scheduled to obtain StV and accuracy parameters.



Fig 1. Powerinstep® wristband and in-step weight attachment.

<https://doi.org/10.1371/journal.pone.0230631.g001>

Maximum stroke velocity and accuracy. Data collection was executed on a tennis hard court with stable wind conditions ($< 2 \text{ m}\cdot\text{s}^{-1}$) using new tennis balls (Head ATP Pro, Spain). Before the test, subjects performed a standardized warm-up that included mobility exercises, 5 minutes of free rallies and 5 to 10 progressive serves. Each subject randomly executed 5 series of 8 serves (4 on each side of the court) with 2 minutes of rest between sets for each one of the analyzed conditions (i.e., wearing a 50, 100, 150, 200 g or no weight set on the dominant wrist as shown in Fig 1). Following the serves, and after a 5-minute rest, participants performed 5 random series of 8 forehands and 8 backhands (crossed-court) without alternating strokes following each testing condition and following the same resting periods, as explained in Fig 2. Participants wore one of the weight sets exclusively attached to the dominant extremity. Only the serves that were in the serve box and the groundstrokes that landed in the singles court were registered. Maximum StV was determined using a hand-held radar gun (Stalker ATS II, USA, frequency: 34.7 GHz [Ka-Band] ± 50 MHz). The radar was positioned in the center of the baseline, 2 m behind the line and at an approximate height of 2 m for the serves and behind the player following the trajectory of the ball. Hitting as hard and precise as possible was indicated and immediate feedback was provided to the subjects to encourage maximum effort. To avoid variability performing groundstrokes, balls were fed by a ball-throwing machine (Pop-

<i>Set 1</i>	<i>Rest</i>	<i>Set 2</i>	<i>Rest</i>	<i>Set 3</i>	<i>Rest</i>	<i>Set 4</i>	<i>Rest</i>	<i>Set 5</i>
x8 Serves	2min	x8 Serves	2min	x8 Serves	2min	x8 Serves	2min	x8 Serves
<i>Rest = 5min</i>								
x8 Forehands	2min	x8 Forehands	2min	x8 Forehands	2min	x8 Forehands	2min	x8 Forehands
<i>Rest = 5min</i>								
x8 Backhands	2min	x8 Backhands	2min	x8 Backhands	2min	x8 Backhands	2min	x8 Backhands

Fig 2. StV and accuracy experimental design.

<https://doi.org/10.1371/journal.pone.0230631.g002>

Lob Airmatic 104, France) at a constant speed ($68.6 \pm 1.9 \text{ km}\cdot\text{h}^{-1}$). Also, accuracy of the strokes was registered for further analysis using a similar approach to Pialoux et al., 2015 [16] as explained in Fig 3. To assess serve accuracy, a ball that landed in the S1 area ($1 \times 1 \text{ m}$) accounted for 5 points; S2 ($2 \times 2 \text{ m}$), 3 points and S3 (remaining area of the serve box), 1 point. To assess groundstrokes, a ball that landed in the area FH1 or BH1 ($2 \times 2 \text{ m}$) accounted for 5 points; FH2 or BH2 ($3 \times 3 \text{ m}$), 3 points and FH3 or BH3 (rest of the tennis court besides doubles alleys), 1 point. All other ball placements resulted in zero points. Accuracy was defined by the sum of all points, with a higher score corresponding to a higher accuracy. StV assessment measurements showed good to excellent test-retest reliability (ICCs 0.73 to 0.96) with a coefficient of variation (CV) ranging from 4.6 to 5.9%. Accuracy showed poor to moderate test-retest reliability (ICCs < 0.2 to 0.550), similar to previous investigations [17] but contrary to studies that found good reliability in similar assessments [18].

CODS assessment. To assess the ability to perform a single change of direction (CODS), the 505-agility test was performed on a tennis hard court [19]. Participants executed a standardized warm-up prior to the commencement of the test, consisting of a series of mobility exercises, a 5-minute jog and 3 progressive sprints. The 505-agility test consisted of sprinting from a standing position for 15 m (through the timing gates at 10 m) and executing a 180° change of direction on their preferred foot to further sprint through the timing gates [20]. Players assumed a preferred foot behind the starting position and started the test voluntarily. Results were registered using timing gates (Chronojump®, Barcelona, Spain), as they offer higher degrees of accuracy than stopwatch-recorded times [21]. All subjects executed the test two times with each one of the analyzed conditions (i.e., wearing a 50, 100, 150, 200 g on both feet (Fig 1) or no weight set in a randomized order. After every attempt, subjects were asked to rest for 1 minute prior to performing again. All measurements demonstrated a good to excellent test-retest reliability (ICCs 0.79 to 0.91) with CV ranging from 1.6 to 3.3%.

Statistical analyses

Descriptive data were expressed as mean \pm standard deviation (SD). The normality of the distributions and homogeneity of variances were assessed with the Shapiro–Wilk and Levene tests, respectively. The reliabilities of test measurements were assessed using intraclass correlation coefficients (ICCs), all of agility, serve, forehand and backhand velocity measurements reached an acceptable level of reliability (ICC > 0.73). The typical error of measurement (TEM) was calculated for the intraindividual test–retest strokes (i.e., forehand, backhand and service) and CODS variables and expressed as a mean CV. Differences between the StV and accuracy and CODS 0 g (baseline) and the scores at 4 conditions (50, 100, 150 and 200 g) were evaluated using a one-way analysis of variance (ANOVA) with repeated-measures with Bonferroni-corrected post hoc analysis. Mean differences in absolute and percent values were also used. The magnitude of the differences in mean was quantified as effect size (ES) and interpreted according to the criteria used by Cohen [22] (< 0.2 = trivial, 0.2 – 0.5 = small, 0.5 – 0.8 = moderate, > 0.8 = large). Because forehand velocity 0 g and 150 g data were not normally distributed, Friedman’s test was used to examine the differences between baseline and different weights in forehand velocity. The level of significance was set at $p \leq 0.05$. All statistical analyses were performed using SPSS 23.0 software (SPSS Inc., Chicago, IL, USA).

Results

No significant differences were found between conditions for forehand ($F = 0.412$; $p = 0.799$), backhand ($F = 0.269$; $p = 0.897$) and serve ($F = 0.541$; $p = 0.706$) velocity and forehand

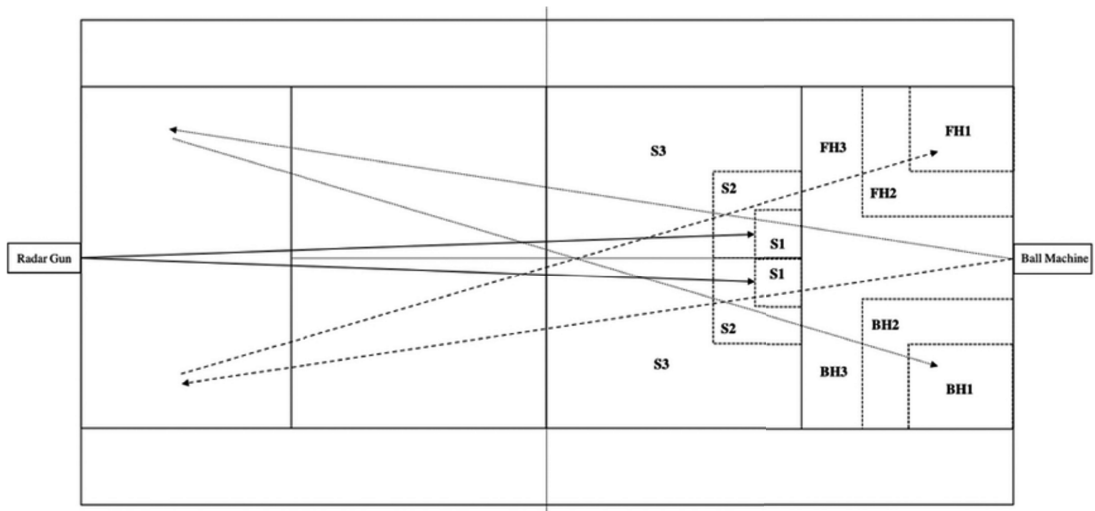


Fig 3. Tennis court layout for stroke velocity and accuracy assessment. S1, S2 and S3, the target areas for the serve; FH1, FH2 and FH3, the target areas for forehand drives; BH1, BH2 and BH3, the target areas for backhand drives. The full arrows indicate the ball trajectories for the serve, the dotted arrows indicate the ball trajectories for backhand drive, and the dash arrows the ball trajectories for forehand drive.

<https://doi.org/10.1371/journal.pone.0230631.g003>

($F = 1.688$; $p = 0.161$), backhand ($F = 0.567$; $p = 0.687$) and serve ($F = 2.382$; $p = 0.059$) accuracy and CODS ($F = 0.416$; $p = 0.797$).

There were no significant decreases and small-to-moderate effect sizes of StV in serve, forehand and backhand 200 g compared to the baseline (-4.5, -2.91 and -2.99%; $ES = 0.48, 0.35$ and 0.45) (Table 1). Moderate (23.04%; $ES = -0.49$) and trivial (6.06 and 7.33%; $ES = -0.14$ and -0.16) effect sizes for higher accuracy were found in serve, forehand and backhand 100 g compared to the baseline (Fig 4). A non-significant small effect size (-2.35%; $ES = 0.41$) for improvement in 200 g CODS comparing to the baseline conditions was observed (Fig 5).

Table 1. Magnitude and percentage changes from baseline (0 g) in serve, forehand and backhand velocity and accuracy and change of direction speed (CODS) between 4 conditions (50, 100, 150 and 200 g).

	50 g		100 g		150 g		200g	
	ES	%	ES	%	ES	%	ES	%
Serve								
Velocity ($\text{km}\cdot\text{h}^{-1}$)	0.06	-0.61	0.08	-0.76	0.29	-0.31	0.48	-4.50
Accuracy (points)	-0.08	4.30	-0.49	23.04	0.55	-29.58	0.11	-5.42
Forehand								
Velocity ($\text{km}\cdot\text{h}^{-1}$)	-0.06	0.52	0.06	-0.50	-0.01	0.10	0.35	-2.91
Accuracy (points)	0.48	-23.40	-0.14	6.06	0.25	-10.94	0.53	-21.47
Backhand								
Velocity ($\text{km}\cdot\text{h}^{-1}$)	-0.05	0.36	0.13	-0.96	0.02	-0.14	0.45	-2.99
Accuracy (points)	0.00	0.00	-0.16	7.33	-0.01	0.44	0.31	-12.09
CODS								
Time (s)	0.13	-0.60	0.13	-0.64	0.11	-0.48	0.41	-2.35

ES, Cohen's effect size; CODS, change of direction speed.

<https://doi.org/10.1371/journal.pone.0230631.t001>

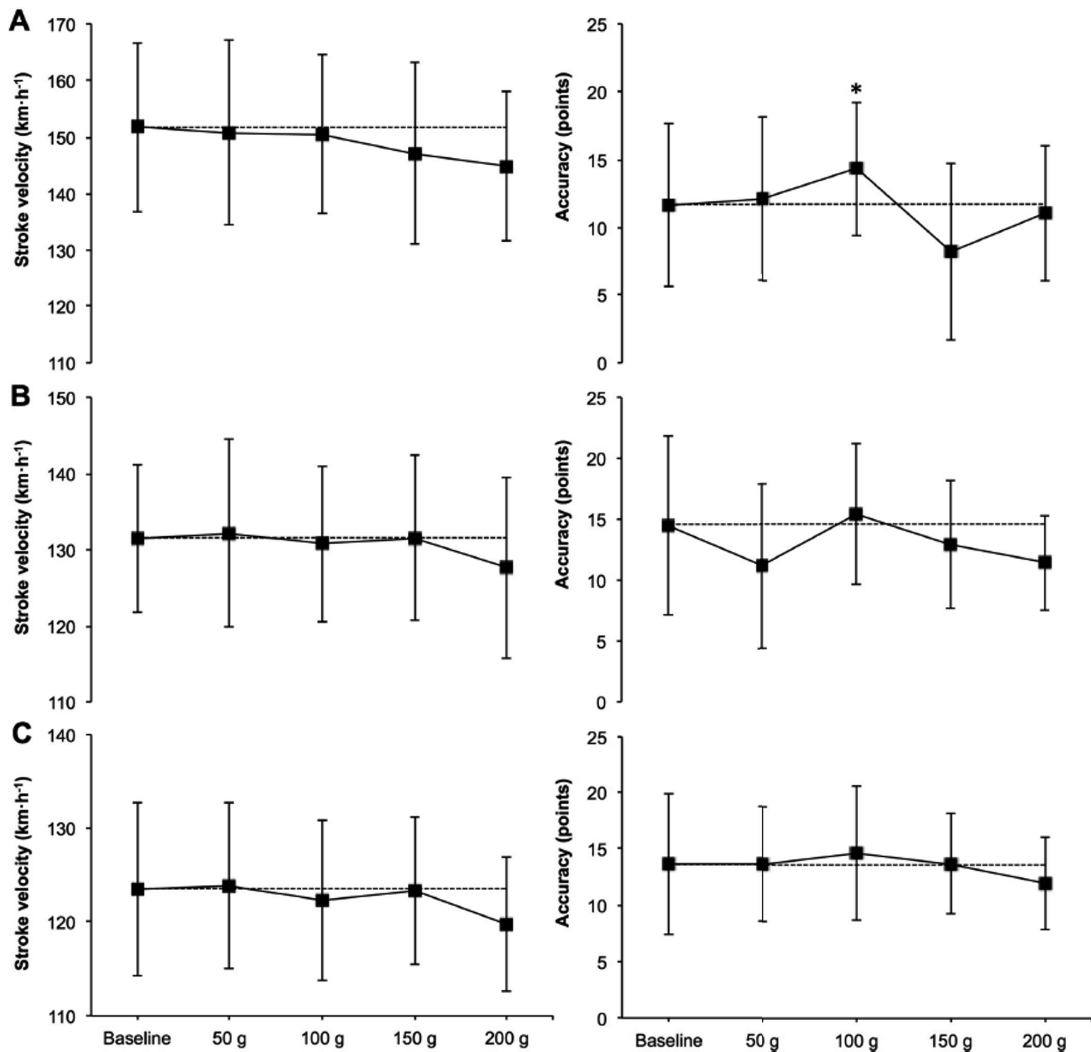


Fig 4. Comparisons of serve (A), forehand (B) and backhand (C) velocity and accuracy between 4 conditions (50, 100, 150 and 200 g). *Significant change from 150 g at $p \leq 0.05$.

<https://doi.org/10.1371/journal.pone.0230631.g004>

Discussion

The main findings of this investigation were that the use of external light loads on upper and lower extremities do not seem to have significant effects on StV or CODS in junior tennis players. However, certain negative small-to-moderate changes were observed regarding StV when using heavier loads (200 g) and a higher accuracy without affecting velocity when using moderate loads (100 g). Regarding the use of weights on lower limbs, similar changes indicated that the use of heavier loads (200 g) could affect CODS in a positive way. Although no significant

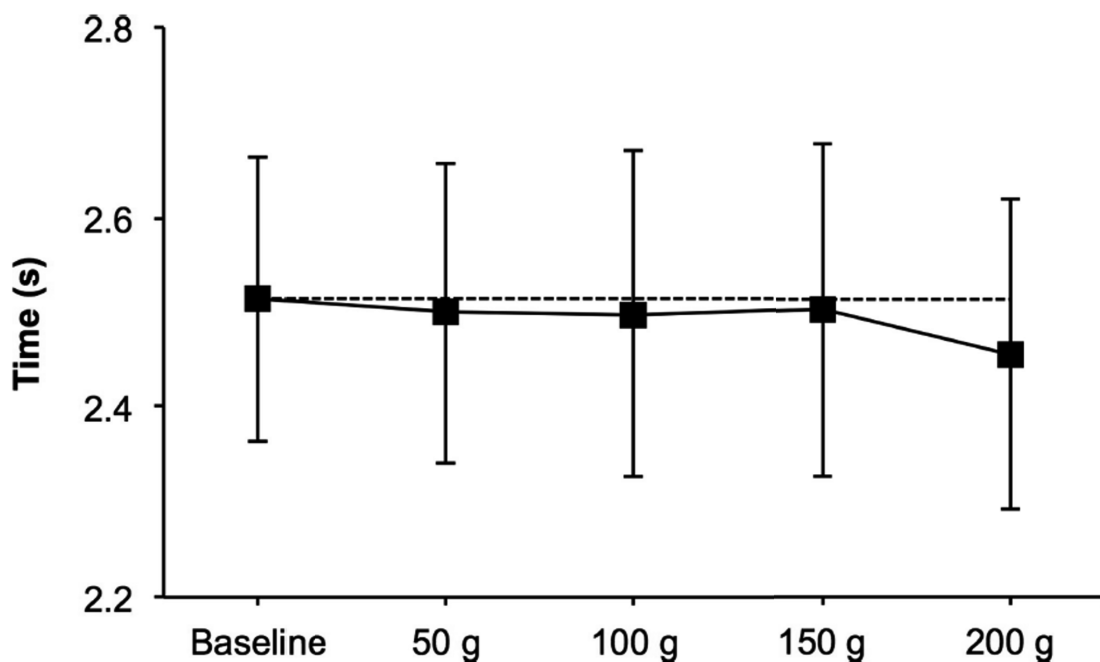


Fig 5. Comparisons of change of direction speed (CODS) between 5 conditions (0, 50, 100, 150 and 200 g).

<https://doi.org/10.1371/journal.pone.0230631.g005>

increases in performance were observed by using a weighting set, no variables were diminished either.

More specifically, the lack of significant positive results regarding higher StV when using certain weights matches findings in other similar studies [1,4]. While literature has mainly focused on the acute effects of serve speed when adding weight to the racquet rather than the extremity as in this study, results did not find significant increases in velocity either. Even though a higher momentum caused by a heavier extremity could result in greater StV, the need of maintaining an optimal speed of the swing is necessary to benefit from this principle. As suggested by other authors, an increment in weight might cause deceleration in key determinant contributors to velocity production as internal rotation speed of the arm in the case of the serve [1,4,23]. Moreover, heavier loads placed on the extremity instead of the implement could reduce the speed of the racquet head due to a decreased linear and angular speed of the wrist, which is an important contributor to velocity production [23]. Precisely this issue may be the causative of no increases in speed in any of the weights used in this investigation and the greater loss of velocity that seems to happen when using 200 g weights (Fig 4). Interestingly, and focusing on groundstrokes, similar changes towards a decrease in StV occurred in players with a 2-handed backhand and the single subject that performed a 1-handed backhand with the weight and wrist band on his dominant extremity (2.99 and 1.12%; ES = 0.45 and ES = 0.49 respectively). Differences in both types of strokes rely on aspects such as a greater trunk rotation in the 2-handed backhand and a more rotated shoulder complex when playing with one hand [24]. In any case, as literature points out, players with either technique are able to produce similar horizontal racquet speed relying on a higher linear velocity in the 1-handed

fashion or angular velocity in the 2-handed style [24]. The fact that two strokes that build speed around different kinematic aspects but obtain similar results when performing with extra light loading as in this study, may reinforce the idea that certain weights affect key factors that influence the player's ability to provide speed to the stroke. Added to this, investigations have found important kinematic and physical differences between elite and competitive players, concluding that those of a greater level rely on certain variables to produce speed. Aspects such as a more efficient use of elastic energy in leg extensors [2] or horizontal shoulder and racquet velocities [25], among others, contribute to enhancing StV, highlighting the importance of specific strength and kinematic parameters. As stated previously, the use of weights on the player's extremity may affect some of the mentioned key factors. Moreover, only players of a certain age and level may be able to maintain arm and racquet swing speed invariable and benefit from a higher momentum at impact on both, groundstrokes and serves. As a limitation of this study and aspects further investigations could focus on, the analysis of kinematic differences between the use of different weights and maturity/age status differences of the players could be registered to offer a further approach to the results obtained. Regarding the differences observed in the use of moderate weights (100 g), results seem to indicate slight changes towards an increased accuracy with unaffected velocity. It may appear that this could be a suitable load to observe positive longitudinal effects on StV or accuracy. Unlike non-significant immediate results observed in investigations that focused on acute effects [1,4], longitudinal studies that proposed the use of extra light loading around the implement or mobile offered positive increases in other overhead sports [6,7] besides tennis [8]. As literature suggests, the use of these kinds of strength training programs seem to be a good way of enhancing velocity production [26], benefiting from the principle of overload. On the other hand, this approach could compromise other factors such as kinematics and kinetics of the sporting action or injury rates [7]. Following suggestions presented by other authors, these interventions could be a way of improving velocity production after achieving a certain strength level in previous programs to, after, transfer these gains into specific tennis actions such as the serve and groundstrokes [4]. Concerning accuracy, as results seem to show small-to-moderate differences for greater scores with velocity unaffected, the use of this approach to training may offer players and coaches some beneficial technical outcomes regarding skill acquisition based on variability during the training of the stroke itself, following modern coaching practices [27]. In any case, to our knowledge, this is the first study to examine the acute effects of increasing weight on extremities) on StV or accuracy, manifesting the need of further investigations to expose such statements. As a limitation, and regarding accuracy reliability, the test was probably limited by asking subjects to hit the ball at maximum speed, causing greater variability in accuracy and consequently decreasing it. This issue has previously been observed in tennis [17] and is frequent when testing accuracy.

Regarding the use of light weights on lower limbs, no studies, to our knowledge, have attempted to investigate the effects on agility aspects or, more specifically, on CODS. Linear sprinting has received attention from literature both on treadmill and over-the-ground conditions [13,28], showing no changes in running or sprinting technique but decreases in performance (maximum sprint running), especially in the acceleration phase due to a reduction in stride frequency [29]. Contrary to results noticed when analyzing StV, the differences observed in this study showed a small decrease in time when using the heavier load (200 g), unlike the mentioned researches. These contrary results could be due to the differences in the weight used in previous investigations. The loads presented ranged from 1–5% of bodyweight in the mentioned studies whereas the higher load in this investigation (i.e., 200 g) accounted for around 0.335% of bodyweight. Loads of a certain magnitude may interpose stride frequency and consequently sprinting velocity. Although little literature is available on this matter,

presumably we will find differences when analyzing linear sprinting and change of direction or agility parameters such as the present here. In fact, some authors have analyzed kinematic factors affecting CODS and found better performances in those groups that had an increased stride frequency [30]. The use of wearable weights may cause greater stride rate triggered by the enhanced gravitational forces [31] and consequently result beneficial for agility-based tasks as the 505-agility test analyzed in this study. At any rate, further studies should focus on investigating longitudinally the effects of in-step weights on change of direction and agility and examine how loads may affect essential kinematic aspects such as stride length or frequency that are key determinants of CODS [13] performance before being able to state this.

In conclusion, the use of a weighting set on both wrists and in-steps does not significantly affect StV or CODS respectively. Although differences are not observed, the use of these light weights do not affect negatively velocity production or accuracy scores in junior tennis players either. Taking into account that further investigation is needed, small-to-moderate differences show an interesting improvement in accuracy and no variance in velocity production when using some of the weights tested (i.e., 100 g), suggesting that the use of this kind of apparel as a training tool could result in some way useful. This study also shows certain small changes for an increased performance in CODS when using 200 g in-step weights, suggesting that gear of these characteristics may affect change of direction or agility aspects to some extent. In any case, further investigations on the effects of the use of weighting sets on StV and CODS would be of great interest.

Practical applications

Taking into account that using certain external light loads on the upper limbs in the form of a weight set does not seem to affect negatively velocity production or accuracy scores in young competitive tennis players, the use of this kind of apparel as a training tool could result in improvements on StV in the mid-long term, as suggested in similar literature [8]. Most likely, it would be preferable that strength training preceded wearable weight interventions, being this type of protocols more adequate for in-season programs where the goal is to transfer strength gains into specific tennis actions. Furthermore, programs should be applied with caution and not be maintained during long periods of training or competition since some studies suggest compromised kinematics and kinetics of the sporting action or increases in injury rates when analyzing light-weight interventions [7]. Moreover, variability of practice may be induced by the use of this piece of equipment and offer coaches and players new insights in emergent methods of training [27]. Regarding the use of in-step weights and their effects on CODS, further studies are needed to examine how loads may affect essential kinematic aspects such as stride length or frequency that are key determinants of CODS performance.

Acknowledgments

The authors thank all the players and coaches for their enthusiastic participation. They would like to thank Academia Sánchez-Casal Barcelona. The research leading to these results has been conducted using funds from the agreement between the Universitat de Vic–Universitat Central de Catalunya and Powerinstep, SL. The authors declare that there is no conflict of interest between the participants, the materials and equipment used, or any other procedure undertaken during the experiments and the researchers of this investigation.

Author Contributions

Conceptualization: Joshua Colomar, Ernest Baiget, Francisco Corbi.

Data curation: Ernest Baiget.
Formal analysis: Ernest Baiget.
Funding acquisition: Ernest Baiget.
Investigation: Joshua Colomar, Joshua Muñoz.
Resources: Joshua Muñoz.
Supervision: Francisco Corbi.
Validation: Joshua Colomar, Ernest Baiget, Francisco Corbi.
Visualization: Joshua Colomar.
Writing – original draft: Joshua Colomar.

References

1. Whiteside D, Elliott B, Lay B, Reid M. The effect of racquet swing weight on serve kinematics in elite adolescent female tennis players. *Journal of Science and Medicine in Sport*. 2014; 17(1):124–8. <https://doi.org/10.1016/j.jsams.2013.03.001> PMID: 23587536
2. Girard O, Micallef JP, Millet GP. Lower-limb activity during the power serve in tennis: Effects of performance level. *Medicine and Science in Sports and Exercise*. 2005; 37(6):1021–9. PMID: 15947729
3. Girard O. Physical determinants of tennis performance in competitive teenage players. *Journal of Strength and Conditioning Research*. 2009; 23(6):1867–72. <https://doi.org/10.1519/JSC.0b013e3181b3df89> PMID: 19675471
4. Söğüt M. Acute effects of customizing a tennis racket on serve speed. *Baltic Journal of Sports Health and Science*. 2017; 1(104):44–6.
5. Miller S. Modern tennis rackets, balls, and surfaces. *British Journal of Sports Medicine*. 2006; 40(5):400–5.
6. DeRenne C, Szymanski DJ. Effects of Baseball Weighted Implement Training: A Brief Review. *Strength and Conditioning Journal*. 2009; 31(2):30–7.
7. Reinold MM, Macrina LC, Fleisig GS, Aune K, Andrews JR. Effect of a 6-week weighted baseball throwing program on pitch velocity, pitching arm biomechanics, passive range of motion, and injury rates. *Sports Health*. 2018; 10(4):327–33. <https://doi.org/10.1177/1941738118779909> PMID: 29882722
8. Genevois C, Frican B, Creveaux T, Hautier C, Rogowski I. Effects of two training protocols on the forehand drive performance in tennis. *Journal of Strength and Conditioning Research*. 2013; 27(8):677–82.
9. Wilson GJ, Newton RU, Murphy AJ et al. The optimal training load for the development of dynamic athletic performance. *Med Sci Sports Exerc* 1993; 25:1279–86. PMID: 8289617
10. Kovacs MS. Applied physiology of tennis performance. *British Journal of Sports Medicine*. 2006; 40:381–386. <https://doi.org/10.1136/bjism.2005.023309> PMID: 16632565
11. Fernandez J, Sanz D, Mendez-Villanueva A. A review of the activity profile and physiological demands of tennis match play. *Strength and Conditioning Journal*. 2009; 31(4):15–26.
12. Martin PE. Mechanical and physiological responses to lower extremity loading during running. *Medicine and Science in Sports and Exercise*. 1985; 18(4):415–9.
13. Macadam P, Cronin JB, Simperingham KD. The effects of wearable resistance Training on metabolic, kinematic and kinetic variables during walking, running, sprint running and jumping: A Systematic Review. *Sports Medicine*. 2017; 47(5):887–906. <https://doi.org/10.1007/s40279-016-0622-x> PMID: 27638041
14. Macadam P, Simperingham KD, Cronin JB. Acute kinematic and kinetic adaptations to wearable resistance during sprint acceleration. *Journal of Strength and Conditioning Research*. 2017; 31(5):1297–304. <https://doi.org/10.1519/JSC.0000000000001596> PMID: 27548784
15. Hrysomallis C. The effectiveness of resisted movement training on sprinting and jumping performance. *Journal of Strength and Conditioning Research*. 2012; 26(1):299–306. <https://doi.org/10.1519/JSC.0b013e3182185186> PMID: 22158137
16. Pialoux V, Genevois C, Capoen A, Forbes SC, Thomas J, Rogowski I. Playing vs. nonplaying aerobic training in tennis: Physiological and performance outcomes. *PLoS One*. 2015; 10(3):1–10.

17. Menayo R, Moreno FJ, Fuentes JP, Reina R, Damas J. Relationship between motor variability, accuracy, and ball speed in the tennis serve. *Journal of Human Kinetics*. 2012; 33(1):45–53.
18. Guillot A, Di Renzo F, Pialoux V, Simon G, Skinner S, Rogowski I. Implementation of motor imagery during specific aerobic training session in young tennis players. *PLoS One*. 2015; 10(11):e014331.
19. Stewart PF, Turner AN, Miller SC. Reliability, factorial validity, and interrelationships of five commonly used change of direction speed tests. *Scandinavian Journal of Medicine and Science in Sport*. 2014; 24(3):500–6.
20. Draper JA, Lancaster MG. The 505 test: A test for agility in the horizontal plane. *Australian Journal of Science and Medicine in Sport*. 1985; 17(1):15–18.
21. Hetzler FK, Stickley CD, Lundquist KM, Kimura IF. Reliability and accuracy of handheld stopwatches compared with electronic timing in measuring sprint performance. *Journal of Strength and Conditioning Research*. 2008; 22(6):1969–76. <https://doi.org/10.1519/JSC.0b013e318185f36c> PMID: 18978613
22. Cohen J. *Statistical Power Analysis for the Behavioral Sciences*. 1988. United States of America: Lawrence Erlbaum Associates.
23. Elliot BC, Marshall RM, Noffal GJ. Contributors of upper limb segment rotations during the power serve in tennis. *Journal of Applied Biomechanics*. 1995; 11:433–442.
24. Reid M, Elliot BC. The one- and two-handed backhands in tennis. *Sports Biomechanics*. 2002; 1(1):47–68. <https://doi.org/10.1080/14763140208522786> PMID: 14658135
25. Landlinger J, Lindlinger S, Stöggl T, Wagner H, Müller E. Kinematic differences of elite and high-performance tennis players in the cross court and down the line forehand. *Sport Biomechanics*. 2010; 9(4):280–95.
26. Van den Tillaar R. Effect of different training programs on the velocity of overarm throwing: a brief review. *Journal of Strength and Conditioning Research*. 2004; 18(2):388–96. <https://doi.org/10.1519/R-12792.1> PMID: 15142008
27. Reid M, Crespo M, Lay B, Berry J. Skill acquisition in tennis: Research and current practice. *Journal of Science and Medicine in Sport*. 2007; 10(1): 1–10. <https://doi.org/10.1016/j.jsams.2006.05.011> PMID: 16809063
28. Simperingham KD, Cronin JB. Changes in sprint kinematics and kinetics with upper body loading and lower body loading using exogen Exoskeletons: a pilot study. *Journal of Australian Strength and Conditioning*. 2014; 22(5):69–72.
29. Ropret R, Kukulj M, Ugarkovic D, Matavulj D, Jaric S. Effects of arm and leg loading on sprint performance. *European Journal of Applied Physiology and Occupational Physiology*. 1998; 77(6):547–50. <https://doi.org/10.1007/s004210050374> PMID: 9650741
30. Hewit JK, Cronin JB, Hume PA. Kinematic factors affecting fast and slow straight and change-of-direction acceleration times. *Journal of Strength and Conditioning Research*. 2013; 27(1):69–75. <https://doi.org/10.1519/JSC.0b013e31824f202d> PMID: 22362087
31. Rusko H, Bosco C. Metabolic response of endurance athletes to training with added load. *European Journal of Applied Physiology and Occupational Physiology*. 1987; 56(4):412–8. <https://doi.org/10.1007/bf00417768> PMID: 3622484



STUDY 7

Improving serve velocity in the young tennis player. Program design and training.

Citation:

Colomar J, Baiget E, Corbi F. 2022. Improving serve velocity in the young tennis player. program design and training. Strength and Conditioning Journal. [Under review].

doi: -

Journal information:

ISSN: -

Category: -

Impact Factor: -

Quartile: -

IMPROVING SERVE VELOCITY IN THE YOUNG TENNIS PLAYER.

PROGRAM DESIGN AND TRAINING

ABSTRACT

Serve velocity (SV) is an essential component to success in junior tennis players. Coaches and practitioners aim at increasing this determinant physical factor to maximize efficiency and efficacy towards greater performance and results. Concentrically or eccentrically predominant conventional resistance training programs have been used to rise SV, obtaining moderate increases. Nevertheless, indirect improvements in other components such as asymmetry reductions and increased neural adaptations could be of interest following these designs. Other methodologies such as medicine ball throws and explosive or power-based programs that mimic the serve kinetic chain seem to obtain greater gains in young players, as the implication and body structures involved seem more specific to the action. More recent methodologies such as flywheel based training or weighted implements or limbs also could be of interest, although further studies are needed to confirm the effectiveness of these programs and specific load prescriptions. However, data suggests including exercises of heavier or lighter loads seem valid options to improve SV if maximal intended velocity of execution is performed by the athlete. Added to the available literature revision on training methods to increase SV, exercise prescription examples are provided to help the strength and conditioning coach to increase this key variable.

Key words: resistance training, flywheel, medicine ball throw, rate of force development

INTRODUCTION

Improving velocity production in overhead athletes and serve velocity (SV) in tennis players particularly has been of paramount importance for strength and conditioning coaches. Being a determinant functional factor directly affecting performance in all age groups (19,21,27), any practitioner aiming at improving an athlete's game or providing the best tools towards success will eventually design and implement programs towards faster serves. Key points influencing SV have been thoroughly studied in literature and it seems four main pillars have been identified as determinant physical factors affecting the speed of a serve. Technique or biomechanics of the stroke (11,22,27,40), specific anthropometric traits (19), range of motion (38,52) and strength, power, or neuromuscular characteristics (2,3,7,19) seem to shape the final result of a serve. These factors seem to influence the outcome in a different way depending on the players age and level (7,19,25,30). As a highly complex motor skill, youth, pre-puberal and unexperienced players with favorable anthropometric characteristics or a greater technical proficiency may take advantage of these abilities to generate faster serves than their peers and rivals, therefore increasing performance differences (19). On the other hand, when speaking of older, adolescent and more experienced competitors, technique and anthropometrics seem to stabilize and differences may appear because of disparities in strength and power values (25,30). In this line, literature has found that the capacity of producing high levels of strength in short periods of time in movements present in the serve kinetic chain is positively related to an increased SV (2,26). Because of this, it has been recommended to implement training programs that develop power in forceful and rapid rotational movements that include multiple body segments present in the totality of the motion (2). Medicine ball throws (MBT) have

been established as a valid method to achieve these training recommendations and have previously been found to effectively improve SV (14) in young competitors. However, other training options and equipment could offer similar benefits or should be considered. Investigations have tested improvements in SV following isokinetic designs (35), flywheel or machine-based interventions (6), elastic tubing and plyometrics (4,13,39), or conventional resistance training tasks (4,28,29). Nevertheless, which methodology achieves greater developments or more thoroughly adjusts to those determinant factors that shape the young tennis players serve may remain unclear. Therefore, this study aims at reviewing studies testing training methods towards improving SV, alongside providing the strength coach with interesting options considered to be as useful to positively affect SV, directly or indirectly, in the junior competitor.

CONVENTIONAL RESISTANCE TRAINING

Programs focusing on improving strength levels around the shoulder joint, as it seems the most important during tennis strokes, have resulted in positive outcomes regarding SV improvements (Table 1A). Mont et al., (35) tested the effectiveness of a concentric or eccentric based resistance program using an isokinetic dynamometer three times a week during six weeks. Both programs seemed to be useful tools to improve SV increasing values around 11%. Treiber et al., (50) also found that following a program based on TheraBand® and lightweight dumbbell training was sufficient to increment torque in shoulder internal (23.8%) and external (17.8%) rotations, alongside SV (6 – 7.9%). The mentioned studies identified improvements in experienced populations of a certain age and level. Canós et al., (6) observed that 8 weeks of training using traditional machines enhanced upper body power levels (i.e.,

MBT velocity) but SV remained unaltered in junior participants. In this same line, Behringer et al., (4) did not find the same outcome when testing a resistance training program (around 65 – 85% 1 repetition maximum (RM)) compared to a plyometric setting during 8 weeks in young competitors. Contrary, only the plyometric group improved SV. Authors hypothesize the necessity of having a certain technical level to obtain improvements following conventional resistance training, and although they may be moderately beneficial for improving velocity production, this seems to occur as factors such as muscle balance, motor control, neural drive or motor unit discharge rate are affected by these types of programs. Absolute dynamic strength values do not seem to have a strong relationship with SV (28), nevertheless, some indirect positive effects may result from implementing resistance training layouts, aiming at an increased maximum strength output. Although the serve is a fast executed explosive action performed with a rather light implement of around 200-300 g, long term adaptations derived from heavy weighted maximal strength designs may appear if well implemented (27), as an increase in these values is associated with an enhanced relative strength and derived power abilities (17). Previously, literature has found that following resistance training (4 to 10 RM) programs for long periods resulted in moderately enhanced SV (28,29). The use of heavy loads seemed to achieve neural adaptations that benefited SV in the long term. Regardless tennis abilities seem to be directly influenced by muscular power, this potential is promoted by the increase of the force component of the power equation (41). If the intended velocity of movement is maximal, increases in muscle size and type II muscle fibers will appear as an adaptation to heavy-loaded training (41).

In this line, these programs have also been considered useful to reduce fat

percentages and increase muscle mass indexes (28,29). As investigated previously, it seems that a more favorable fat-free body mass index and an increased muscle percentage could have a positive relationship to faster serves, especially in female populations (16,19). Last, considering that tennis is a high asymmetrical sport with several muscle imbalances (42–44), resistance training programs aiming at increasing overall strength values could be beneficial to reduce these sport-specific adaptations. An increased load of unilateral predominant actions such as the serve has been associated with glenohumeral internal rotation deficits (GIRD), imbalances at the abdominal and lower back level and an increased injury likelihood (37,42). In a highly specialized context as youth tennis, programs that aim at optimizing performance should include training contents towards minimizing negative early sport-specialization adaptations (31). Following this line, resistance training exercises have proven to be effective in reducing side-to-side asymmetries (5), which could be important not to directly increase SV but to minimize non-desired effects of training and match-play, that may compromise the youth athlete's long-term development.

In short, conventional resistance training seems to moderately improve SV, especially in the long term as a part of a structured program and in older more experienced competitors. Nevertheless, indirect benefits may be more thoroughly achieved by these training options in the form of increased motor unit discharge, neural drive, fat free body mass ratios and reduced muscle imbalances. Therefore, exercises are presented to provide examples of tasks that intend to assess the desired improvements in overall strength gains and reductions in side-to-side imbalances in the main body structures involved in the serve (Figure 1). Load prescription will follow that recommended by the international consensus and position

statement on youth resistance training for improving strength levels in advanced level adolescents (32). Exercise selection will intend to include in the program single and multi-jointed exercises with an eccentric and concentric predominance at moderate to high intensities (70-85% 1RM) for ≥ 3 sets of 6 to 10 repetitions. To achieve the previously reviewed positive neural adaptations of resistance training, intended velocity regardless the external load will be maximal and rest intervals should be sufficient to guarantee maximal exertion in posterior sets (2-3 minutes). The SV enhancement program should include a weekly frequency of 2 to 3 sessions per week and coaches should ensure technical integrity throughout the program (12,32).

PLYOMETRICS, STRETCH SHORTENING CYCLE (SSC) ENHANCED AND SERVE SPECIFIC TRAINING

Exercises that mimic throwing or striking actions that have a marked SSC nature seem to have a greater transfer to functional tennis actions than methods that demand movements at constant velocities and resistance throughout the totality of motion (54). Fernández-Fernández et al., (14) tested the improvements in SV after following an elastic tube and MBT program resulting in significant increases (4.9%) after just 6 weeks of training. Also, in further studies including upper and lower body plyometric exercises, investigations found notable increases in junior tennis players ranging from 1.18% to 7.68% (4,13,15,23,39) (Table 1B). Comparatively, these exercises seem to obtain greater benefits than conventional or traditional resistance exercises including machine-based layouts or free weight designs with a concentric phase predominance (4). It seems MBT based programs or upper body plyometric exercises obtain the benefits of applying high levels of force in short periods of time involving several body structures present in the serve kinetic chain. Performing these

exercises in full range of motion, high-velocity rotations and involving multiple joints (i.e., especially around the shoulder complex) seem to reproduce those key physical aspects determinant for a fast serve (2). Moreover, the fact that these exercises involve a great deal of coordinative skill, benefits may be superior because of the technical resemblance to the serve. As suggested previously, investigations seem to find a greater strength of associations between strength and power levels and serve performance in older more experienced players, while anthropometric traits and technical differences may be more important in pre-adolescent or lower ranked players (7,19,25,30). Following this idea, programs including MBT involving whole-body movements with a certain technical similarity seem a valid option for coaches to implement in velocity production enhancement programs for the young tennis player. Nevertheless, multiple variations of MBT can be found across exercise prescriptions, while high-velocity rotational movements may also be achieved using other equipment and devices. These specific exercise requirements seem essential towards effective improvements in determinant strength factors affecting SV as it stimulates the player's rate of force development (RFD) capacity. Being able to produce high levels of strength alongside a big amount of contractile impulse (IMP) in short periods of time of under 250 ms in specific upper arm motions has been found to have a strong relationship to SV (2) Because of this, regardless the methodology and the training mean that the coach selects, some specific indications may be essential towards improvement. That is, RFD and IMP may be effectively achieved either prescribing high-speed and low load or low-speed and high load resistance training as long they include explosive muscle contraction by achieving maximal intended velocity execution (2).

Following the idea of encouraging technical resemblance, some studies have focused on methods that mimic motion and technique in specific situations towards SV improvements. Ferrauti and Bastiaens (18) tested the effectiveness of a complex-throwing intervention of heavy or light ball-throws on SV, finding decrements in the high-loaded group and no changes in the light-throw participants. Genevois et al., (24) compared an overloaded racquet-based program and a MBT design, although this intervention tested results on forehand velocity. Despite the medicine ball group showed further improvements (11%) in SV than the overloaded group (5%), this last design did not have a detrimental effect on precision as happened when performing MBT. Following this idea, Colomar et al., (8) found the use of light weights around the wrist did not have a negative effect on accuracy or SV, suggesting it may be a valid option towards velocity improvement in the long term. Notwithstanding, it should be mentioned that overloading the racquet or limb may negatively affect joint angular velocity and upper body structures in consequence (53) as identified in previous overloaded throwing programs (34). Therefore, this type of training may be recommended and could be useful in preparation stages away from competition, however, further studies are needed to assess if the benefits are worth the risk and especially establish well defined prescriptions.

Specific tasks and approaches are presented to provide examples of exercises that intend to assess the previously mentioned key factors and respond to neuromuscular and technical needs (Figure 2). Load prescription will follow recommendations established by the position statement on resistance training for improving power levels in experienced youth populations (32). This states the importance of using light to moderate loads (30-60% 1RM) at an explosive lifting velocity for ≥ 3 sets of 1 to 6

repetitions. Recommended resting periods of 2-3 minutes towards offering the athlete sufficient recovery time to maintain technical integrity throughout these multijointed explosive motions. A weekly frequency of 2 to 3 sessions is suggested (12,32). Regarding MBT, prescriptions following loads similar to that offered by Fernández-Fernández et al., (14) seem a valid option towards improvements in young tennis players.

FLYWHEEL-BASED RESISTANCE TRAINING

As discussed previously, the tennis serve, due to its execution, demands a great deal of power output and players take advantage of the stretch-shortening cycle to enhance velocity (4). Towards this goal, the efficient use of pre-stretch and eccentric contraction to load energy to use in the following concentric phase, it would seem reasonable to include in SV enhancement programs exercises that involve these aspects. Eccentrically overloaded tasks have proven to induce certain neuromuscular adaptations, typically in the form of increases in overall strength, muscle power, and hypertrophy (33). Therefore, as devices such as flywheels or conical pulleys have been suggested to improve power-based actions, SV may also be increased following these training approaches (Table 1C). Canós et al., (6) found improvements in upper body power indicators tested via MBT after a flywheel-based program. Nevertheless, SV remained unaltered, most likely due to insufficient exercises simulating the serve physical needs included in the program. As the authors point out, exercises may have lacked to include rotations, various muscle groups, high velocities, and sufficient variability to induce significant changes. Therefore, although literature is scarce in testing these specific methodologies in junior tennis players, exercise and task suggestions are provided to deliver practitioners with interesting

options using inertial flywheel devices (Figure 3). Load prescription for youth populations using flywheel-based resistance training remains in constant revision. Little practical information is available regarding sets, repetitions, and intensities, especially for young athletes. Resistance training experience and overall strength levels seem to greatly affect the effectiveness of a flywheel-based program (46,47). Nevertheless, from a conservative position, most studies obtaining increases in hypertrophy, strength and power output used a design following 4 sets of 7 repetitions with 90 to 180 seconds of rest, no more than twice a week to ensure optimal recovery (49). Specific inertial loads towards detailed prescriptions are also scarce and literature seems to recommend that regardless the load, athletes resist the inertia during the first third of the eccentric action and then apply maximal force at the end of the range of motion (46,47). In any case, if training aims at an increase in power output, lower inertias should be used, while if the program targets force development, higher inertial loads should be chosen (49).

COMPLEX TRAINING

Following results seen in Canós et al., (6), researchers found the use of specific exercises in the form of MBT performed after general strength (i.e., machine or flywheel-based) exercises, achieved higher improvements in upper body power levels of young tennis players. It is suggested that the inclusion of transfer exercises following conventional resistance training tasks may have elicited the benefits of complex training layouts (10). This term is known as the completion of a high load resistance activity towards the enhancement of a posterior plyometric or ballistic action (20). Conventionally used in warm-up protocols to achieve an enhanced performance in the immediate posterior competition, it may also be an interesting

option to induce greater power levels in training and achieve SV improvements in the long term. The rationale behind this phenomenon suggests that increases in muscle temperature, intramuscular fluid accumulation and the beneficial changes in neural mechanisms elicited by heavy loaded exercises will evoke a post-activation performance enhancement (PAPE) that could be used towards more powerful exertions (20). A delayed window of action is associated to an effective PAPE, and this may depend on the initial exercise performed, the subsequent motion and the individual characteristics of the athlete. Literature has mainly focused on lower body activities, although some research has given some insight on predominantly upper body-based actions towards immediate performance enhancements. Non-specific exercises (i.e., bench press) seem to induce moderate PAPE responses in posterior similar actions (51). On the other hand, sport-specific conditioning activities found a greater induced PAPE when performing overweight implement throws (36) or cable-pulley specific movements (1). Specifically in tennis, (48) did not observe any improvements following a non-specific high loaded exercise (3 sets of 3 repetitions at 80% 1RM) in the form of a bench press, a half squat, or the combination of both in SV. These results are in line with moderate or low PAPE outcomes after general strength exercises observed previously (20). In a more serve-specific layout, including six upper body ballistic exercises (i.e., a combination of elastic tubing exercises and overweight implement throws), (23) found improvements in the subsequent SV of young tennis players (1 – 3 %), suggesting PAPE may be more effectively achieved when including resistance training in the form of plyometric or power-based exercises. Nevertheless, these results intended to obtain an immediate PAPE for the following SV enhancement. Contrary, literature is scarce regarding the effectiveness of complex training interventions, especially in predominantly upper

body or throwing and striking motions and youth populations. Which exercises induce effective PAPE, with which load prescription and after which specific window of action, remains to be further studied. In any case, the acute neural adaptations achieved by heavy-loaded resistance training exercises and the possibility of an increased strength and power production in subsequent tasks (45) seems of great interest to include in velocity production programs for the young tennis player. Therefore, around the previously discussed rationale, complex training blocks of exercises consisting of a heavy loaded conditioning activity followed by a plyometric task are provided to address the benefits of this training methodology (Figure 4). Generally, beneficial results have been observed in lower body actions after performing designs that implement heavy loaded exercises of around 65 to 85% of 1RM followed by a plyometric task (9). In this line, the traditional conditioning activity is suggested to be performed at the mentioned intensities while the subsequent plyometric or power-based exercise will follow maximal velocity intention with light loads of around 30 to 60% 1RM, as prescribed previously for power-based tasks (32).

CONCLUSIONS

In conclusion, conventional resistance training programs can result in increases in overall and relative strength levels, which moderately correlate to SV. Nevertheless, these methodologies may also have indirect benefits on important aspects that affect SV, such as favorable anthropometric traits (i.e., increased muscle mass ratios), asymmetry reductions, and neural adaptations for increased discharge rate and motor unit recruitment. Power-based training and SSC enhanced exercises such as plyometrics achieve large improvements in SV as they stimulate increases in relevant

strength and power characteristics for SV such as RFD and IMP. These positive adaptations may be attained using MBT or any other means of training (i.e., cable pulleys or elastic bands) if the selected exercises implicate the totality of the kinetic chain, include high velocity rotations, and especially if they resemble the technical execution of the serve. RFD and IMP can be successfully attained prescribing different loads and execution speeds of the force-velocity spectrum as long they include explosive muscle contraction by achieving maximal intended velocity execution (2). Methodologies that perform the specific serve action with slightly overweighted implements or limbs may be an option towards improving SV, although they should be assessed with caution as load prescription and risk of injury remain unclear. Flywheel-based training seems to respond to the contraction characteristics of the tennis serve, suggesting it may be a valid option towards SV increases. Nevertheless, literature is scarce in the effectiveness of these programs and further research would be of great interest. Last, complex training layouts may take advantage of the PAPE effect of executing a high load resistance exercise followed by a more specific plyometric task, making contrast designs interesting for the strength and conditioning coach to implement in young tennis players with a solid weightlifting background. Load prescriptions and specific rest time-windows remain to be further studied, but benefits achieved in other sporting actions may indicate this type of training a valid option for velocity production enhancement.

REFERENCES

1. Asencio P, Sabido R, García-Valverde A, and Hernández-Davó JL. Does handball throwing velocity increase after an eccentric overload-induced postactivation potentiation? *Eur J Hum Mov* 44, 2020. Available from:

<https://www.eurjhm.com/index.php/eurjhm/article/view/543>

2. Baiget E, Colomar J, and Corbi F. Upper-Limb Force–Time Characteristics Determine Serve Velocity in Competition Tennis Players. *Int J Sports Physiol Perform* Ahead of print: 1–9, 2021.
3. Baiget E, Corbi F, Fuentes JP, and Fernández-Fernández J. The Relationship Between Maximum Isometric Strength and Ball Velocity in the Tennis Serve. *J Hum Kinet* 53: 63–71, 2016.
4. Behringer M, Neuerburg S, Matthews M, and Mester J. Effects of Two Different Resistance-Training Programs on Mean Tennis-Serve Velocity in Adolescents. *Pediatr Exerc Sci* 25: 370–384, 2013.
5. Bishop C, Turner A, and Read P. Training Methods and Considerations for Practitioners to Reduce Interlimb Asymmetries. *Strength Cond J* 40: 40–46, 2018.
6. Canós J, Corbi F, Colomar J, Cirer-Sastre R, and Baiget E. Effects of isoinertial or machine-based strength training on performance in tennis players. *Biol Sport* 39: 505–513, 2022.
7. Colomar J, Baiget E, and Corbi F. Influence of Strength, Power, and Muscular Stiffness on Stroke Velocity in Junior Tennis Players. *Front Physiol* 11: 196, 2020.
8. Colomar J, Baiget E, Corbi F, and Muñoz J. Acute effects of in-step and wrist weights on change of direction speed, accuracy and stroke velocity in junior tennis players. *PLoS ONE* 15: e0230631, 2020.
9. Cormier P, Freitas TT, Rubio-Arias JÁ, and Alcaraz PE. Complex and Contrast Training: Does Strength and Power Training Sequence Affect Performance-Based Adaptations in Team Sports? A Systematic Review and Meta-analysis. *J Strength Cond Res* 34: 1461–1479, 2020.
10. Ebben WP. Complex training: A brief review. *J Sports Sci Med* 1: 42-46, 2002.

11. Elliott B. Biomechanics and tennis. *Br J Sports Med* 40: 392–396, 2006.
12. Faigenbaum AD, Kraemer WJ, Blimkie CJR, Jeffreys I, Micheli LJ, Nitka M, et al. Youth Resistance Training: Updated Position Statement Paper From the National Strength and Conditioning Association. *J Strength Cond Res* 23: S60–S79, 2009.
13. Fernandez-Fernandez J, De Villarreal ES, Sanz-Rivas D, and Moya M. The Effects of 8-Week Plyometric Training on Physical Performance in Young Tennis Players. *Pediatr Exerc Sci* 28: 77–86, 2016.
14. Fernandez-Fernandez J, Ellenbecker T, Sanz-Rivas D, Ulbricht A, and Ferrauti A. Effects of a 6-Week Junior Tennis Conditioning Program on Service Velocity. *J Sports Sci Med* 12: 232-239, 2013.
15. Fernandez-Fernandez J, Granacher U, Sanz-Rivas D, Sarabia Marín JM, Hernandez-Davo JL, and Moya M. Sequencing Effects of Neuromuscular Training on Physical Fitness in Youth Elite Tennis Players: *J Strength Cond Res* 32: 849–856, 2018.
16. Fernandez-Fernandez J, Nakamura FY, Moreno-Perez V, Lopez-Valenciano A, Del Coso J, Gallo-Salazar C, et al. Age and sex-related upper body performance differences in competitive young tennis players. *PLoS ONE* 14: e0221761, 2019.
17. Fernandez-Fernandez J, Ulbricht A, and Ferrauti A. Fitness testing of tennis players: How valuable is it? *Br J Sports Med* 48: i22–i31, 2014.
18. Ferrauti A and Bastiaens K. Short-term effects of light and heavy load interventions on service velocity and precision in elite young tennis players. *Br J Sports Med* 41: 750–753, 2007.
19. Fett J, Ulbricht A, and Ferrauti A. Impact of Physical Performance and Anthropometric Characteristics on Serve Velocity in Elite Junior Tennis Players: *J Strength Cond Res* 34: 192–202, 2020.

20. Finlay MJ, Bridge CA, Greig M, and Page RM. Upper-Body Post-activation Performance Enhancement for Athletic Performance: A Systematic Review with Meta-analysis and Recommendations for Future Research. *Sports Med*, 2021. Available from: <https://link.springer.com/10.1007/s40279-021-01598-4>
21. Fitzpatrick A, Stone JA, Choppin S, and Kelley J. Important performance characteristics in elite clay and grass court tennis match-play. *Int J Perform Anal Sport* 19: 942–952, 2019.
22. Fleisig G, Nicholls R, Elliott B, and Escamilla R. Tennis: Kinematics used by world class tennis players to produce high-velocity serves. *Sports Biomech* 2: 51–64, 2003.
23. Gelen E, Dede M, Bingul BM, Bulgan C, and Aydin M. Acute effects of static stretching, dynamic exercises, and high volume upper extremity plyometric activity on tennis serve performance. *J Sports Sci Med* 11: 600-605, 2012.
24. Genevois C, Frican B, Creveaux T, Hautier C, and Rogowski I. Effects of Two Training Protocols on the Forehand Drive Performance in Tennis: *J Strength Cond Res* 27: 677–682, 2013.
25. Girard O and Millet GP. Physical Determinants of Tennis Performance in Competitive Teenage Players: *J Strength Cond Res* 23: 1867–1872, 2009.
26. Hayes MJ, Spits DR, Watts DG, and Kelly VG. The Relationship Between Tennis Serve Velocity and Select Performance Measures: *J Strength Cond Res* 35: 190-197, 2021.
27. Kovacs MS and Ellenbecker TS. A Performance Evaluation of the Tennis Serve: Implications for Strength, Speed, Power, and Flexibility Training: *Strength Cond J* 33: 22–30, 2011.
28. Kraemer WJ, Hakkinen K, Travis Triplett-Mcbride N, Fry AC, Perry Koziris L,

Ratamess NA, et al. Physiological Changes with Periodized Resistance Training in Women Tennis Players: *Med Sci Sports Exerc* 35: 157–168, 2003.

29. Kraemer WJ, Ratamess N, Fry AC, Triplett-McBride T, Koziris LP, Bauer JA, et al. Influence of Resistance Training Volume and Periodization on Physiological and Performance Adaptations in Collegiate Women Tennis Players. *Am J Sports Med* 28: 626–633, 2000.

30. Kramer T, Huijgen BCH, Elferink-Gemser MT, and Visscher C. A Longitudinal Study of Physical Fitness in Elite Junior Tennis Players. *Pediatr Exerc Sci* 28: 553–564, 2016.

31. Lloyd RS, Cronin JB, Faigenbaum AD, Haff GG, Howard R, Kraemer WJ, et al. National Strength and Conditioning Association Position Statement on Long-Term Athletic Development. *J Strength Cond Res* 30: 1491–1509, 2016.

32. Lloyd RS, Faigenbaum AD, Stone MH, Oliver JL, Jeffreys I, Moody JA, et al. Position statement on youth resistance training: the 2014 International Consensus. *Br J Sports Med* 48: 498–505, 2014.

33. Maroto-Izquierdo S, García-López D, Fernandez-Gonzalo R, Moreira OC, González-Gallego J, and de Paz JA. Skeletal muscle functional and structural adaptations after eccentric overload flywheel resistance training: a systematic review and meta-analysis. *J Sci Med Sport* 20: 943–951, 2017.

34. Melugin HP, Smart A, Verhoeven M, Dines JS, and Camp CL. The Evidence Behind Weighted Ball Throwing Programs for the Baseball Player: Do They Work and Are They Safe? *Curr Rev Musculoskelet Med* 14: 88–94, 2021.

35. Mont MA, Cohen DB, Campbell KR, Gravare K, and Mathur SK. Isokinetic Concentric Versus Eccentric Training of Shoulder Rotators with Functional Evaluation of Performance Enhancement in Elite Tennis Players. *Am J Sports Med*

22: 513–517, 1994.

36. Montoya BS, Brown LE, Coburn JW, and Zinder SM. Effect of Warm-up With Different Weighted Bats on Normal Baseball Bat Velocity. *J Strength Cond Res* 23: 1566–1569, 2009.

37. Moreno-Pérez V, Lopez-Valenciano A, Barbado D, Moresid, J, Elvira JLL, and Vera-Garcia FJ. Comparisons of hip strength and countermovement jump height in elite tennis players with and without acute history of groin injuries. *Musculoskelet Sci Pract* 29: 144–149, 2017.

38. Palmer K, Jones D, Morgan C, and Zeppieri G. Relationship Between Range of Motion, Strength, Motor Control, Power, and the Tennis Serve in Competitive-Level Tennis Players: A Pilot Study. *Sports Health* 10: 462–467, 2018.

39. Pardos-Mainer E, Ustero-Pérez O, and Gonzalo-Skok O. Efectos de un entrenamiento pliométrico en extremidades superiores e inferiores en el rendimiento físico en jóvenes tenistas. [Effects of upper and lower body plyometric training on physical performance in young tennis players]. *Rev int cienc deporte* 13: 225–243, 2017.

40. Reid M, Elliott B, and Alderson J. Lower-Limb Coordination and Shoulder Joint Mechanics in the Tennis Serve. *Med Sci Sports Exer* 40: 308–315, 2008.

41. Reid M and Schneiker K. Strength and conditioning in tennis: Current research and practice. *J Sci Med Sport* 11: 248–256, 2008.

42. Sanchis-Moysi J, Idoate F, Álamo-Arce D, Calbet JAL, and Dorado C. The core musculature in male prepubescent tennis players and untrained counterparts: a volumetric MRI study. *J Sports Sci* 35: 791–797, 2017.

43. Sanchis-Moysi J, Idoate F, Izquierdo M, Calbet JAL, and Dorado C. Iliopsoas and Gluteal Muscles Are Asymmetric in Tennis Players but Not in Soccer Players.

PLoS ONE 6: e22858, 2011.

44. Sanchis-Moysi J, Idoate F, Olmedillas H, Guadalupe-Grau A, Alayón, S, Carreras A, et al. The upper extremity of the professional tennis player: muscle volumes, fiber-type distribution and muscle strength: The tennis player upper extremity. *Scand J Med Sci Sports* 20: 524–534, 2009.

45. Seitz LB and Haff GG. Factors Modulating Post-Activation Potentiation of Jump, Sprint, Throw, and Upper-Body Ballistic Performances: A Systematic Review with Meta-Analysis. *Sports Med* 46: 231–240, 2016.

46. Suchomel TJ, Wagle JP, Douglas J, Taber CB, Harden M, Haff GG, et al. Implementing Eccentric Resistance Training—Part 1: A Brief Review of Existing Methods. *JFMK* 4: 38, 2019.

47. Suchomel TJ, Wagle JP, Douglas J, Taber CB, Harden M, Haff GG, et al. Implementing Eccentric Resistance Training—Part 2: Practical Recommendations. *JFMK* 4: 55, 2019.

48. Terraza-Rebollo M and Baiget E. Effects of Postactivation Potentiation on Tennis Serve Velocity and Accuracy. *Int J Sports Physiol Perform* 15: 340–345, 2020.

49. Tesch PA, Fernandez-Gonzalo R, and Lundberg TR. Clinical Applications of Iso-Inertial, Eccentric-Overload (YoYo™) Resistance Exercise. *Front Physiol* 8: 241, 2017.

50. Treiber FA, Lott J, Duncan J, Slavens G, and Davis H. Effects of Theraband and Lightweight Dumbbell Training on Shoulder Rotation Torque and Serve Performance in College Tennis Players. *Am J Sports Med* 26: 510–515, 1998.

51. Ulrich G and Parstorfer M. Effects of Plyometric Versus Concentric and Eccentric Conditioning Contractions on Upper-Body Postactivation Potentiation. *Int J*

Sports Physiol Perform 12: 736–741, 2017.

52. Vaverka F and Cernosek M. Association between body height and serve speed in elite tennis players. Sports Biomech 12: 30–37, 2013.

53. Whiteside D, Elliott B, Lay B, and Reid M. The effect of racquet swing weight on serve kinematics in elite adolescent female tennis players. J Sci Med Sport 17: 124–128, 2014.

54. Wooden MJ, Greenfield B, Johanson M, Litzelman L, Mundrane M, and Donatelli RA. Effects of Strength Training on Throwing Velocity and Shoulder Muscle Performance in Teenage Baseball Players. J Orthop Sports Phys Ther 15: 223–228, 1992.

STUDY 7 FIGURES AND TABLES

TABLES

Table 1. Training methods aiming to increase serve velocity (SV).

A. CONVENTIONAL RESISTANCE TRAINING							
Reference	n	Gender	Age	Level	Duration (weeks)	Training intervention	Changes (%; p)
Mont et al., (1994)	30	M	33	Pro	6	8 x 10 with 60 seconds' rest. Concentric internal and external shoulder rotation 8 x 10 with 60 seconds rest eccentric internal and external shoulder rotation	11.4%; 0.01 11.2%; 0.01
Treiber et al., (1998)	25	M = 12; F = 13	21.2	Elite	4	2 x 20 seconds with 30-40 seconds' rest. Internal and external shoulder rotation with Theraband	6%; 0.01 peak SV and 7.9%; 0.01 average SV
Kraemer et al. (2000)	24	F	19.8 ± 1.7	Collegiate	36	8 to 10 RM with 1-2 minutes rest. Non-periodized upper and lower body resistance training exercises 6, 8, 10, 12 and 15 RM with 2-3 minutes rest. Periodized upper and lower body resistance training exercises.	29%; 0.05 16%; 0.05
Kraemer et al., (2003)	30	F	19 ± 1	Elite	36	2-3 x 4-12 RM with 1.5 – 3 minutes rest. Upper and lower body resistance training exercises.	Increases in SV at 4, 6 and 9 months of training, 0.01
Smart et al., (2011)	35	M = 17; F = 18	25.2 ± 7	Intermediate	8	Core stability, strength, and power exercises	No changes in SV
Behringer et al., (2013)	36	M	15 ± 1.6	Junior	8	2 x 15 at 65 – 85% RM with 1 minute rest. Upper and lower body resistance training exercises.	1.18%; 0.05
Terraza-Rebollo et al., (2017)	20	M	15.5 ± 0.9	Junior	8	3 x 6-8 with 1 minute rest. Upper and lower body resistance training exercises.	4.09%; 0.01
Canós et al., (2021)	24	M	15.5 ± 1.2	Junior	8	3 x 6-8 at 50-70% RM with 1.5 – 3 minutes rest. Upper and lower body resistance training exercises.	No changes in SV
B. PLYOMETRIC, SSC ENHANCED AND SERVE SPECIFIC TRAINING							
Ferrauti & Bastiaens (2007)	13	M = 7; F = 6	12.3 ± 0.8	Junior	-	2, 4 or 6 throws with 600g or 200g MBT between serve sets	No changes in SV
Behringer et al., (2013)	36	M	15 ± 1.6	Junior	8	3 – 4 x 10 – 15 with 20 seconds' rest. Upper and lower body plyometric exercises	3.78%; 0.05

Fernandez-Fernandez et al., (2013)	30	M	14.2 ± 0.5	Junior	6	2 x 20 for core exercises; 2 x 20 with 45 s rest for elastic band exercises; 2 x 8 with 1 minute rest for MBT	4.9%; 0.01
Hernández-Dayo et al., (2014)	30	M = 20; F = 10	13 ± 1.52	Junior	4	2 x 10 with 30 s rest. Serves with position and base of support variations	7.68%; 0.05
Fernandez-Fernandez et al.,(2016)	60	M	12.5 ± 0.3	Junior	8	2 – 4 x 10 – 15 with 15 – 90 seconds' rest. Upper and lower body plyometric exercises	6.2%; 0.05
Pardos-Mainer et al., (2017)	21	M = 11; F = 10	14.3 ± 1.7	Junior	8	2 – 4 x 10 – 15 with 2 minutes rest. Upper and lower body plyometric exercises	3.5%; 0.05
Terraza-Rebollo et al., (2017)	20	M	15.5 ± 0.9	Junior	8	3 x 6 with 1 minute rest. Medicine ball and elastic band training	1.43%; 0.01
Fernández-Fernández et al., (2018)	16	M	12.9 ± 0.4	Junior	5	2 – 3 x 6 – 10 with 15 – 60 seconds' rest. Upper and lower body plyometric exercises before tennis training	2%; 0.05
Colomar et al., (2020)	17	M = 11; F = 6	16.5 ± 1.3	Junior	-	2 – 3 x 6 – 10 with 15 – 60 seconds' rest. Upper and lower body plyometric exercises after tennis training	No changes in SV
						4 x 8 serves with different light wrist weights	No changes in SV
C. FLYWHEEL-BASED RESISTANCE TRAINING							
Cañós et al., (2021)	24	M	15.5 ± 1.2	Junior	8	3 x 6-8 at 1-2 inertial overloads with 1.5 – 3 minutes rest. Upper and lower body conic flywheel exercises	No changes in SV

Values are mean ± SD; M = male; F = female; RM = repetition maximum; MBT = medicine ball throws

FIGURES

Figure 1. Conventional resistance training exercise examples.

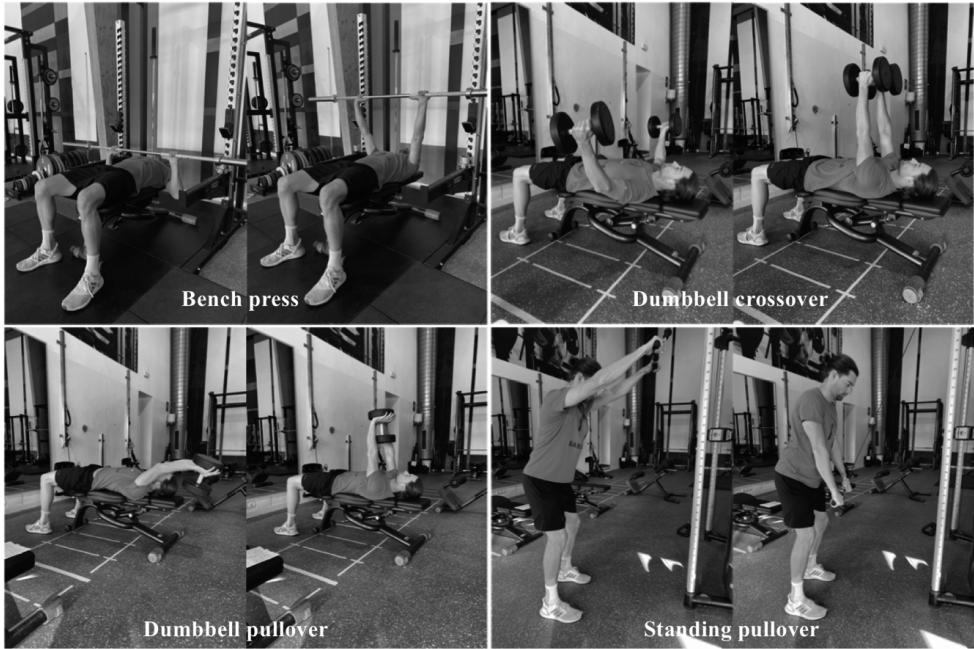


Figure 2. Plyometrics and stretch shortening cycle enhanced training exercise examples.

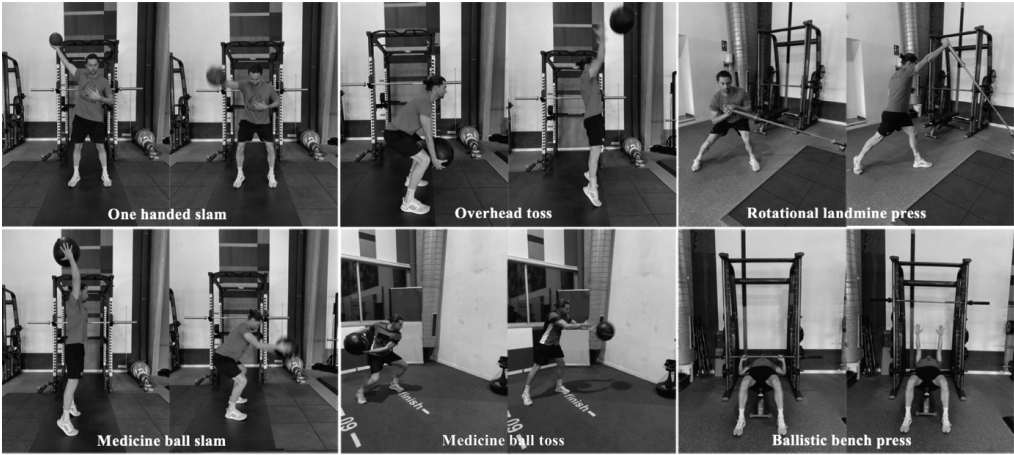


Figure 3. Flywheel-based resistance training exercise examples.

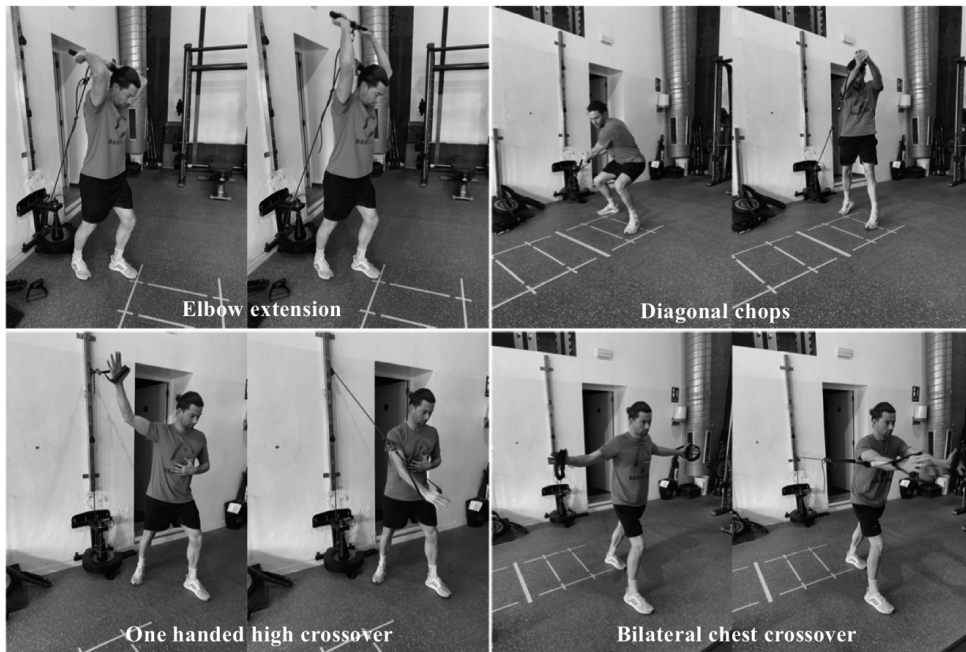
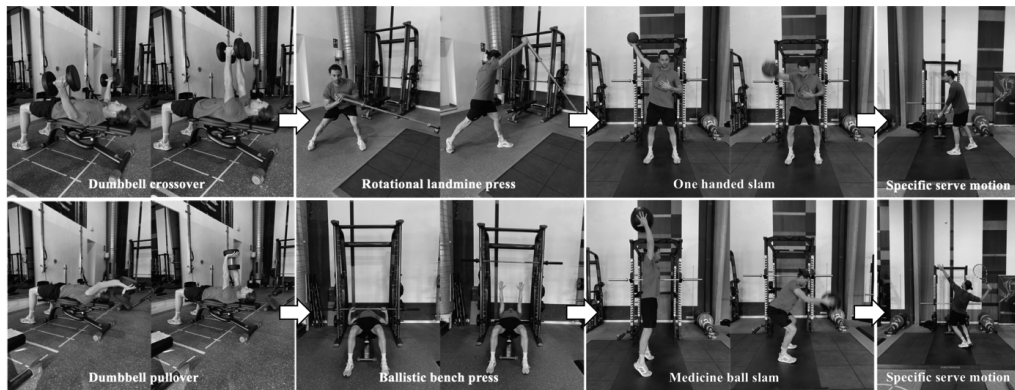


Figure 4. Complex training exercise examples.





STUDY 8

Determinant physical factors of tennis serve velocity. A brief review

Citation:

Colomar J, Baiget E, Corbi F. 2022. Determinant physical factors of tennis serve velocity. A brief review. Journal of Strength and Conditioning Research. [Under review].

doi: -

Journal information:

ISSN: -

Category: -

Impact Factor: -

Quartile: -

DETERMINANT PHYSICAL FACTORS OF TENNIS SERVE VELOCITY. A BRIEF REVIEW

ABSTRACT

The tennis serve is considered the most determinant stroke during competition. Serve velocity (SV), as one of the utmost influential factors affecting its effectiveness, has a multifactorial nature and is determined by technical, anthropometric, range of movement and strength parameters. Recent investigations have aimed at underpinning the rationale around velocity production to provide practitioners with science-based training options and recovery strategies. Nevertheless, to date, no study has aimed at bringing together the different parts of the puzzle that comprise SV. Accordingly, the present work intends to review the aspects that could positively and negatively influence SV. Serving appears to require a certain technical proficiency and previous literature has provided serving models towards generating faster serves. Nevertheless, depending on the model followed and the phase of the action, these necessities may vary. However, aspects such as lower leg drive, hip and trunk rotations and upper arm extension and internal rotations seem the major contributors to racquet and posteriorly ball speed. Anthropometric characteristics of tennis players have been shown to be important determinants of SV. A higher impact point achieved by body height or arm length, alongside a greater lean body mass, seem to positively influence SV. Strength and power indicators such as maximal isometric strength and rate of force development in specific joint positions involved in the kinetic chain, alongside performance while executing predominantly stretch-shortening actions have also been positively correlated to SV. On the other hand, the effects of prolonged match-play or high intensity training loads may impair the aforementioned factors and negatively influence SV.

Key words: performance; strength; fatigue; biomechanics; anthropometrics

INTRODUCTION

In modern tennis, the serve is considered the most determinant action (16,22,27). It directly influences the outcome of points and is the only stroke that entirely depends on the player's skill when performing it. The complexity of the action is given by the necessary coordination throughout the entire kinetic chain (26). The summation of forces in an optimal time and space during this movement sequence increases the velocity of the different body segments involved in the motion, and ultimately is transferred to the ball, resulting in the serve (22,27). If any of the links in the chain is not synchronized in an effective way, the result will not be optimal (24). This effectiveness is determined by several factors such as its speed, impact angle, spin, direction, and precision (4,27). In this sense, serve velocity (SV) has been identified as one of the most determinant factors in tennis performance (22,43). Consequently, SV has boosted in the professional tour and, in parallel, an increase in aces and a decrease in double faults can be observed when analyzing the data (39). Therefore, knowledge around mechanisms affecting the capacity of a player to apply speed to the stroke is of paramount importance for tennis players in terms of developing training programs that improve the action and develop strategies to avoid decrements in performance.

From a technical perspective, serving appears to require a certain execution to achieve desired results. Several studies have aimed at identifying the main biomechanical aspects an effective serve should include, although depending on the

serving model followed and the particular phase of the action (i.e., loading, cocking and impact), the necessities required towards generating faster serves may vary. Yet, it seems clear that lower leg drive, hip and trunk rotations and upper arm extension and internal rotations are the major contributors to racquet and posteriorly ball speed.

Besides technical indications, certain anthropometric characteristics have been found to have a positive relation to SV, making these factors important to be considered. The strength of correlations found varies across sexes and playing levels, although results seem to indicate the importance of obtaining higher peripheral racket velocity at ball impact, which could be increased due to greater body height (BH) or arm length (AL) (4,5,25,48). Similarly, body mass (BM) seems to influence SV as the principle of force (mass x acceleration) and torque production directly affect a player's velocity production capacity (15,49). This positive relation is more evident when analyzing the fastest serves registered in matches (4). Moreover, the influence that body composition or anthropometric traits seem to have on SV has led them to be considered valid talent identification variables.

Physical capacities and neuromuscular performance variables have also been studied in relation to their influence on SV. Maximal dynamic (MDS) (7,28,29) and isometric (MIS) strength (2,3,15,25), rate of force development (RFD), impulse (IMP) (2,25), range of motion (ROM) (14,36), muscle contractile properties (7), functional measurements of power such as medicine ball throws (MBT) or jumping capacity (10,15) have previously been in some way related to higher or lower SV. Nevertheless, although the influence of these traits seems clear, the importance and

impact of these variables on SV varies across sexes and playing levels due to interactions with other parameters present in the complex serve motion, such as biomechanics or technique. Thus, knowledge around specific physical indicators and how these may vary when assessing different participants seems important for tennis practitioners. In consequence, identifying those parameters that better predict a faster serve in different populations will be reviewed.

Moreover, impairments in these key factors seem to appear following match-play or certain training loads. Previous research has mainly focused on competition simulation or data analysis following official events, and although it seems clear that tennis play has the potential to affect key performance factors (18,20,23,34,35), how overall match-play loads, volume, intensity of play, calendar or travelling may influence these characteristics could be of further interest.

Thus, the goal of this investigation was to define the determinant physical factors affecting SV and approach differences regarding sex, level, and age. To gather relevant literature and research for this review search terms included "Tennis Serve", "Serve Speed", "Anthropometry", "Biomechanics" "Physical" and "Training". Criteria regarding participants included players considered as 'elite' (belonging to ATP or WTA rankings above 1000 at the time of the study), 'competition' (players over 18 years old participating in competitive events without a ranking above 1000 and collegiate players), 'junior' (players under 18 years old participating in relevant competitive events of their age group). Studies performed with players considered as 'amateur' or 'recreational' were not considered.

BIOMECHANICS AND MOVEMENT COMPETENCY

From a technical standpoint, the tennis serve seems to demand a certain technical execution to achieve the most efficient and effective results. Numerous studies have aimed at identifying the main biomechanical aspects an effective serve should include. As a key starting point, the speed of the head of the racquet and posterior transfer to the ball is the main aspect to achieve towards this goal (11). The height of impact and the amount of momentum and forward rotation applied to the ball seems the principal contributors towards increasing the head of the racquet's speed. Thus, the influence of angular velocity vectors of the upper arm, forearm, and hand in generating this speed seems essential. Specifically, hand and upper arm flexion, trunk rotation, and abduction alongside the internal rotation of the shoulder are of paramount importance to produce fast speeds (12). This internal rotation gesture has been recognized as the major contributor to speed as it is mainly in charge of accelerating the upper arm and building up angular velocity in the swing to impact. Yet, this explains the moment of impact in the upper arm, while the serve is a multifaceted motor skill involving several body structures and stages. In this line, arm pronation is responsible for racquet orientation while elbow extension has a high influence on impact height, which is an added contributor to head racquet speed (11,12). Additionally, authors have recognized rotation and side positioning of the trunk as an enabler of generating extra rotation in the horizontal plane to produce a shoulder-over-shoulder orientation, increasing available space and energy storage to transfer to the consequent phase (11,12). Also, the authors indicate the significance of lower limb and pelvic drive as the starting point of the kinetic chain. Extension moments in the legs and internal rotation motion in the back hip seem essential towards increasing velocity (11,38,44). Because of the fact of being a skill with

several phases, the ideal biomechanical layout for faster serves depends on which specific stage of the stroke is being examined. Kovacs and Ellenbecker (2011), suggested the use of a multi-stage analysis of the serve involving eight stages. Depending on the phase, biomechanical demands vary. Those phases responsible for velocity build-up seem to be the loading, cocking, acceleration, and impact phases. During the loading phase, kinematics mainly refers to lower body positions in which the authors identify two main techniques (i.e., the foot-back and the foot-up). Although the foot-up seems to generate greater vertical forces which would be interesting to transfer throughout the kinetic chain, no ball velocity differences are observed between these two techniques. The foot-back style provides greater upward and forward push-up while the foot-up provides a stable axis of rotation on which players rely to generate momentum. Also, during the loading phase, the importance of shoulder and pelvis lateral tilt has been identified, as this specific alignment facilitates the development of angular momentum through lateral trunk flexion during forward swing (27). The cocking phase is known for the importance of driving the racquet down and behind the torso allowing greater storage of elastic energy and an increased path before impact. Maximal shoulder external rotation is reached and a close parallel position between racquet and trunk seems important. Accelerating the racquet from this position until impact is known as the acceleration phase. A rapid rotation force occurs from the lumbar spine and forceful concentric internal rotation movements oversee generating velocity. Trunk rotation, elbow extension, shoulder internal rotation, and hand flexion are the main contributors to momentum in this phase (11,12,17,33,40). During contact, the best kinematic models indicate that the shoulder should be slightly abducted and the elbow, wrist, and lead knee somewhat flexed. It is suggested that optimal impact point should happen at

110° angle of elevation between the upper arm and trunk (27). Last, all these structures bear a great level of eccentric forces towards decelerating the movement, although no velocity is being generated from this phase onwards. In short, depending on the serving model followed and the specific phase of the motion, certain biomechanical and technical needs are present towards generating faster serves, however, it seems clear that literature establishes knee extension and lower leg drive, hip and trunk rotation and elbow extension, shoulder internal rotation, and hand/wrist flexion as the major contributors to angular momentum towards transferring speed to the head of the racquet and posteriorly to the ball. These motions and body positions seem to be the most correlated to successful fast serves and performed by those players capable to apply speed to the ball effectively (17). In this line, main aspects mainly differentiating younger and lower ranked players with their more experienced peers appears to be the spatial position of the hand with respect to the hip before impact.

ANTHROPOMETRIC CHARACTERISTICS

The height of the impact location of the ball during the serve and the BH of the player seem to be the most important factors affecting the capacity to produce high velocity serves (48) (Table 1). Biomechanically, hitting the ball in a higher spot increases the available space towards the opponents serve box. Because of this, hitting the ball in higher locations allows the player to offer a more optimal trajectory and achieve a higher SV (48). Literature has identified BH, AL and jumping height as the main conditioning factors affecting the height of ball impact (10,15,48) and therefore are highly related to the capacity of a player to serve faster. BH, besides being a key factor allowing to achieve higher ball impact points (15,41) has previously been

identified as the anthropometric characteristic that mostly affects SV in male participants (4,15,35). These studies identify this characteristic being of greater importance than in female players. Although being these differences present, many investigations have mentioned the positive relationship between SV and first (4,5,15,25,36,48) and second (5,48) serves in both, male and female competitors. These studies show that the sub-maximal nature of the second serve and prioritizing control over attaining a greater SV makes this stroke have a lower relation with BH than the first serve (48). In fact, Baiget et al., (2022) found that BH did not correlate significantly with SV in the second serve in male elite players (4). Besides this, the length of the racquet-arm complex has proven to have an influence on impact point height and therefore SV (15,25). Fett et al., (2018) and Bonato et al., (2014) found considerable positive correlations between AL and SV in all groups of ages included in their study ($r = 0.24^* - 0.56^{**}$). In this case, longer limbs would not only increase the point of impact but would give the opportunity to the player to transfer a greater tangential and achieve greater SV (5,15,25). Further anthropometric characteristics such as BM and body mass index (BMI) have also been studied in relation to SV and have found certain correlation between these parameters. Fett et al., (2018), Hayes et al., (2018) and Baiget et al., (2022) found important relationships between BM and SV ($\text{♂ } r = 0.44^{**} - 0.57^{**}$ and $\text{♀ } r = 0.35^{**} - 0.39^{**}$; $r = 0.68$); $r = 0.593^{**}$, respectively). Also, Fett et al., (2018) and Wong et al., (2014) found positive correlations between BMI and SV ($r = 0.12 - 0.40^{**}$; $r = 0.577^{**}$), while no significant relations between this variable and SV were found in elite players in either the first or second serve in Baiget et al., (2022). In terms of an athlete's capacity of being able to produce strength levels, and following allometric theory (49), an increment in BM in accordance with BH is traduced into an increment in torque production.

Consequently, greater BM or BMI may assist in the capacity of producing faster strokes and increasing SV, always considering that an increment in these variables without a close control on lean mass and fat ratios could negatively affect agility and change of direction (4). Contrary to BH, BM has showed strong relations to SV in female participants (14,15). In this line, considering the advantages of producing greater strength levels, it seems tennis demands of female competition (i.e., lower stroke frequency) would demand profiles to shift towards players with a tendency to endomorph body types (15) unlike male competitors, which may rely more thoroughly on BH and other physical factors influencing SV. A factor to consider is that BM and BMI are modifiable parameters from training (28,29)(28,29) and it is suggested that the optimization of programs could have positive effects on performance, always considering the detrimental effect on speed and agility a non-optimal program of these characteristics could have.

****Insert Table 1 about here****

STRENGTH, POWER AND ROM

Beyond the importance of anthropometric parameters in achieving greater SV, knowledge around physical factors affecting this stroke has also received thorough attention in literature. Studies have established different strength aspects as determinants of SV (Table 2). Initially, MDS needs during strokes seem to be low (28), as the weight of the implement (i.e., racquet) ranges from 200 to 400 g and in this line, studies assessing this variable via bench press have not found strong associations between this variable and SV (7,28). Because of this, investigations have typically aimed at analyzing MIS values at specific joint angles observed

throughout the kinetic chain, involving upper and lower body structures. Most of these studies concluded that the main contributor to a greater SV is shoulder internal rotation (6,12). More recently, literature has focused on different positions around the upper limbs and has included lower body in testing. These investigations found positive relations between MIS and SV in most arm positions tested involved in the serve kinetic chain (2,3,25), being the wrist flexion, extension, shoulder flexion and internal rotation the movements with stronger associations ($r = 0.54-0.67^*$). Notwithstanding, Baiget et al., (2016) considered these positive correlations present in specific positions and involving MIS of few muscle groups would not be a strong predictor of SV by themselves but only accounted for one piece of the puzzle. In this line, authors perform a multiple regression analysis indicating a 55% of SV variability could be explained by the combination of shoulder internal rotation and shoulder flexion MIS. Added to this, besides the combination of different joint positions and movements involved in the serve, certain strength levels regarding RFD and IMP may also positively influence SV. Baiget et al., (2021) investigated the influence of RFD at different time intervals (i.e., 0-250 ms) alongside IMP on SV. Authors conclude that the ability to produce force rapidly (RFD) and the accumulation of force over a given period (IMP), especially in rotational movements, seem to be more determinant than MIS to generate high velocity serves. As the authors point, although the early phases of RFD in the shoulder internal rotation account for roughly 50% of SV variability, the multiple regression analysis showed other shoulder positions and force-time characteristics as important contributors to faster serves. Therefore, while all mentioned aspects seem important contributors to velocity production, the combination and interaction of these variables, alongside those of a different nature (i.e., anthropometry, technique, ROM, etc) seem to determine the capacity of a

player to produce fast serves.

As greater upper body strength and power levels seem to positively influence SV, the role of lower body values is not as clear. The elevation the body experiences with respect to the floor when extending ankles, knees and hips affects the height of the ball impact spot (10,27). Following this idea, it could be considered beneficial to have greater strength and power levels in the lower body, that could derive into higher impact points and therefore increasing SV. In any case, the low relationship between SV and CMJ assessments or leg extension maximal isometric contractions (3,7,10) indicates that the influence of this variable may be relatively low. The authors emphasize the differences between both motions and suggest the introduction and use of more specific jumping tests that include both upper and lower body (i.e., sergeant jump). Literature seems to agree to grant the lower body a coordinate role in the serve motion, most likely linked to coordination and technique rather than affecting SV by themselves. However, some studies have found a positive effect of lower body strength and power parameters and SV, showing knee extension velocity ($r = 0.751^{**}$) (49), knee extension strength ($r = 0.36$) (37), isometric mid-thigh pull test (IMTP) ($r = 0.87^{**}$) (Hayes et al., 2018), jumping height in a CMJ ($r = 0.715^{**}$; 0.77^{**}) (13,25), hop tests ($r = 0.31^* - 0.36^*$) (36) or even the level of stiffness of the gastrocnemius muscle ($r = 0.45^*$) (7) as predictors of velocity in this stroke. These studies give importance to the role of ground reaction forces (GRF) and the ability to transfer to the upper segments of the body. As higher power levels in the lower limbs seem to relate to generating greater GRF (26,36), these parameters would also be beneficial for SV. Because of these reasons, although the lower body seems to have a more coordinative role than a velocity generator, greater strength and power levels

could favor an appearance of GRF of greater magnitude and, if the transfer throughout the kinetic chain is effective, SV would be enhanced. Regarding the stabilization functions and transfer of the generated GRF, the trunk is considered essential towards effective serving. Some studies (1,31) agree in granting this region not only a coordinative role but as a force transfer link in the kinetic chain. Although literature has generally not investigated relations between trunk power and strength levels and SV, Wong et al., (2014) found that peak velocity of hip extension positively influenced SV ($r = 0.657^*$).

Although as mentioned, certain isometric force-time curve values seem to be indicators of SV, literature considers power and the effective use of the SSC as more specific indicators. The technical execution of a serve implies a pre-stretching of most of the muscle groups involved in the motion, being the elastic energy storage and rebound capacity of the muscle of great importance for the action. Medicine ball throws (MBT) have proven to be a useful tool to assess upper power (14,15). This type of assessment allows the summation and transfer of forces throughout the entire kinetic chain and is considered an interesting method to obtain values of power in tennis specific motions. A great number of studies have found positive correlations between MBT distance or speed and SV or even other tennis strokes (9,14,15,46). Fernández-Fernández et al., (2019) point out that MBT distance is an important predictor of SV in male tennis players ($r = 0.418 - 0.638^*$). Fett et al., (2018) show that power values established from MBT is one of the best predictors for SV ($r = 0.2 - 0.63^{**}$), in both male and female competitors and especially as age advances. In younger players, although distance in MBT could be useful to predict SV, this would present a stronger interaction with SV in male competitors (14,15). Added, it has

previously been hypothesized that the influence of these abilities seems to rise in importance as the players level and age increase (7,15)(7,15). These investigations theorized that technical and coordinative aspects seem more relevant in young inexperienced players, as physical factors might become more important as technical capacity is solid in all performers.

Besides strength and power values and measurements, ROM of joints involved in the serve motion have shown important relationships with SV (6,36,49). Cohen et al., (1994) found positive relations between SV, wrist flexion ROM ($r = 0.338^*$) and shoulder internal rotation ($r = 0.324^*$). Wong et al., (2014) point out an important relation between SV and shoulder ROM during the deceleration phase of the serve ($r = 0.616^*$) and with the knee in the sagittal plane. Last, Palmer et al., (2018) found relations between SV and hip ROM ($r = 0.39$), establishing the capacity of a player to achieve certain movement degrees, especially in the shoulder complex can aid SV and therefore increase performance.

****Insert Table 2 about here****

FACTORS NEGATIVELY AFFECTING SV

The previously discussed physical parameters positively related to greater SV may be altered by tennis match-play. As these variables are directly linked to the multifactorial nature of the tennis serve, fatigue is considered as a triggering aspect negatively influencing SV. Metabolic exhaustion, muscle impairment, soreness and functionality are directly related to a descent in muscular strength (34) and have the potential to negatively affect SV. More specifically, literature indicates that the main

performance aspect negatively affected by fatigue is precision (8,21,42). Davey et al., (2002) and Rota et al., (2014) found reductions in serve accuracy after performing a maximal intermittent activity (-30% and -11.7% respectively), attributed to lactate accumulation. Added to effects on precision, fatigue in certain regions and on determinant strength and power variables seem to be main contributors to decreases in SV (8). Notwithstanding, this fatigue does not seem to affect all players in the same way and is most likely determined by match load, experience and playing level. Terraza and Baiget (2021) (45) found no reductions in accuracy or SV following a resistance training or MBT protocol, suggesting although impairments could have appeared in strength and power levels, players may rely on different neuromuscular parameters to maintain performance during the serve. Maquirrain et al., (2016) (30) and Moreno-Pérez et al., (2019) did not observe reductions in precision or speed of elite tennis players after 5-set matches. On the contrary, studies have found reductions in SV (3.9 – 4% and 2 km·h⁻¹) in competition players of lower level (32,42,47) or age (19), suggesting experienced athletes could be able to find strategies to avoid the reduction of SV in fatiguing situations. Nevertheless, investigations are limited when examining the influence of fatigue on SV in young competitors, making of great interest further studies on the topic. Research has not uniquely focused on fatigue caused by the direct outcome of tennis practice or competition but has investigated the effect of prolonged play or repetitive bouts of play on SV (Table 3). In this line, the organization model tennis follows has proven to negatively affect SV (18,21). Gallo-Salazar et al., (2017) found reductions in SV attributed to playing two tennis matches in one same day. One of the main reasons these decreases happen is the loss of functionality around the shoulder region caused by activities maintained and repeated in short periods of time (32,35). These

studies show shoulder strength deficits and ROM impairments in internal and external rotation values after performing a certain volume of tennis-play. Authors agree and recommend the application of intervention programs including strategies to reestablish values before competition or practice, especially in players without a sufficient experience and level to take advantage of technical proficiency or tactical decisions to replace reductions in SV.

Insert Table 3 about here

PRACTICAL APPLICATIONS

- Depending on the serving model followed and the specific phase of the motion, certain needs are present towards generating faster serves, however, it seems clear that knee extension and lower leg drive, hip and trunk rotation and elbow extension, shoulder internal rotation, and hand/wrist flexion are the major contributors to angular momentum towards transferring speed to the head of the racquet and posteriorly to the ball. These indications should be encouraged by coaches towards technical proficiency.
- Talent identification programs should consider that BH and AL, as the capacity of reaching higher ball impact locations seems to correlate strongly with SV. Also, it has been found that BM has a positive influence on SV, although the importance of muscle mass and lean increases should be considered.
- Force-time parameters (MIS, RFD, and IMP) around the shoulder joint are good predictors of SV across sexes and especially as age and level increase. Nevertheless, lower body values do not seem to correlate as strongly, and literature seems to agree that they should be considered as an important link in transferring

velocity production throughout the kinetic chain. Added, MBT seem a valid option to assess upper body power values as they mimic the serve motion and require rotating actions executed at high velocities.

- Intense match-play or training sessions performed regularly have the capacity to reduce SV and accuracy. Elite and experienced players seem to be able to maintain SV relying on other aspects involved in the execution of an optimal serve (i.e., ROM, technique, or tactical decisions), but repetition of competitive bouts or intense match-play will most-likely end up negatively influencing SV. Thus, effective recovery strategies to reestablish initial strength and power values as soon as possible should be implemented, especially in younger and inexperienced populations in which the negative outcome could be more evident.

REFERENCES

1. Bahamonde, RE. Changes in angular momentum during the tennis serve. *Journal of Sports Sciences* 18: 579–592, 2000.
2. Baiget, E, Colomar, J, and Corbi, F. Upper-Limb Force–Time Characteristics Determine Serve Velocity in Competition Tennis Players. *International Journal of Sports Physiology and Performance* Ahead of print: 1–9, 2021.
3. Baiget, E, Corbi, F, Fuentes, JP, and Fernández-Fernández, J. The Relationship Between Maximum Isometric Strength and Ball Velocity in the Tennis Serve. *Journal of Human Kinetics* 53: 63–71, 2016.
4. Baiget, E, Corbi Soler, F, and López, JL. Influence of anthropometric, ball impact and landing location parameters on serve velocity in elite tennis competition. *Biology of Sport* Accepted, December 2021.
5. Bonato, M, Maggioni, M, Rossi, C, Rampinchi, S, Latorre, A, and Merati, G.

Relationship between anthropometric or functional characteristics and maximal serve velocity in professional tennis players. *The Journal of Sports Medicine and Physical Fitness* Epub ahead of print, 2014.

6. Cohen, DB, Mont, MA, Campbell, KR, Vogelstein, BN, and Loewy, JW. Upper Extremity Physical Factors Affecting Tennis Serve Velocity. *Am J Sports Med* 22: 746–750, 1994.

7. Colomar, J, Baiget, E, and Corbi, F. Influence of Strength, Power, and Muscular Stiffness on Stroke Velocity in Junior Tennis Players. *Front Physiol* 11: 196, 2020.

8. Davey, PR, Thorpe, RD, and Williams, C. Fatigue decreases skilled tennis performance. *Journal of Sports Sciences* 20: 311–318, 2002.

9. Delgado-García, G, Vanrenterghem, J, Muñoz-García, A, Molina-Molina, A, and Soto-Hermoso, VM. Does stroke performance in amateur tennis players depend on functional power generating capacity? *J Sports Med Phys Fitness* 59, 2019. Available from: <https://www.minervamedica.it/index2.php?show=R40Y2019N05A0760>

10. Dossena, F, Rossi, C, Torre, AL, and Bonato, M. The role of lower limbs during tennis serve. *The Journal of Sports Medicine and Physical Fitness*, 2018. Available from: <https://www.minervamedica.it/index2.php?show=R40Y2018N03A0210>

11. Elliott, B. Biomechanics and tennis. *British Journal of Sports Medicine* 40: 392–396, 2006.

12. Elliott, BC, Marshall, RN, and Noffal, GJ. Contributions of Upper Limb Segment Rotations during the Power Serve in Tennis. *Journal of Applied Biomechanics* 11: 433–442, 1995.

13. Eriksrud, O, Ghelem, A, Henrikson, F, Englund, J, and Brodin, N. Upper and lower body power tests predict serve performance in national and international level male tennis players. *SPSR* 42(1): 1-5, 2018.
14. Fernandez-Fernandez, J, Nakamura, FY, Moreno-Perez, V, Lopez-Valenciano, A, Del Coso, J, Gallo-Salazar, C, et al. Age and sex-related upper body performance differences in competitive young tennis players. *PLoS ONE* 14: e0221761, 2019.
15. Fett, J, Ulbricht, A, and Ferrauti, A. Impact of Physical Performance and Anthropometric Characteristics on Serve Velocity in Elite Junior Tennis Players: *Journal of Strength and Conditioning Research* 34: 192–202, 2020.
16. Fitzpatrick, A, Stone, JA, Choppin, S, and Kelley, J. Important performance characteristics in elite clay and grass court tennis match-play. *International Journal of Performance Analysis in Sport* 19: 942–952, 2019.
17. Fleisig, G, Nicholls, R, Elliott, B, and Escamilla, R. Tennis: Kinematics used by world class tennis players to produce high-velocity serves. *Sports Biomechanics* 2: 51–64, 2003.
18. Gallo-Salazar, C, Del Coso, J, Barbado, D, Lopez-Valenciano, A, Santos-Rosa, FJ, Sanz-Rivas, D, et al. Impact of a competition with two consecutive matches in a day on physical performance in young tennis players. *Appl Physiol Nutr Metab* 42: 750–756, 2017.
19. Gallo-Salazar, C, Del Coso, J, Sanz-Rivas, D, and Fernandez-Fernandez, J. Game Activity and Physiological Responses of Young Tennis Players in a Competition With 2 Consecutive Matches in a Day. *International Journal of Sports Physiology and Performance* 14: 887–893, 2019.
20. Gescheit, DT, Cormack, SJ, Duffield, R, Kovalchik, S, Wood, TO, Omizzolo,

M, et al. A multi-year injury epidemiology analysis of an elite national junior tennis program. *Journal of Science and Medicine in Sport* 22: 11–15, 2019.

21. Gescheit, DT, Cormack, SJ, Reid, M, and Duffield, R. Consecutive Days of Prolonged Tennis Match Play: Performance, Physical, and Perceptual Responses in Trained Players. *International Journal of Sports Physiology and Performance* 10: 913–920, 2015.

22. Gillet, E, Leroy, D, Thouvarecq, R, and Stein, J-F. A Notational Analysis of Elite Tennis Serve and Serve-Return Strategies on Slow Surface: *Journal of Strength and Conditioning Research* 23: 532–539, 2009.

23. Girard, O. Changes in exercise characteristics, maximal voluntary contraction, and explosive strength during prolonged tennis playing. *British Journal of Sports Medicine* 40: 521–526, 2006.

24. Girard, O and Millet, GP. Physical Determinants of Tennis Performance in Competitive Teenage Players: *Journal of Strength and Conditioning Research* 23: 1867–1872, 2009.

25. Hayes, MJ, Spits, DR, Watts, DG, and Kelly, VG. Relationship Between Tennis Serve Velocity and Select Performance Measures. *Journal of Strength and Conditioning Research* 35: 190–197, 2021.

26. Kibler, WB, Chandler, TJ, Shapiro, R, and Conuel, M. Muscle activation in coupled scapulohumeral motions in the high performance tennis serve. *British Journal of Sports Medicine* 41: 745–749, 2007.

27. Kovacs, MS and Ellenbecker, TS. A Performance Evaluation of the Tennis Serve: Implications for Strength, Speed, Power, and Flexibility Training: *Strength and Conditioning Journal* 33: 22–30, 2011.

28. Kraemer, WJ, Kkinen, K, Travis Triplett-Mcbride, N, Fry, AC, Perry Koziris,

- L, Ratamess, NA, et al. Physiological Changes with Periodized Resistance Training in Women Tennis Players: *Medicine & Science in Sports & Exercise* 35: 157–168, 2003.
29. Kraemer, WJ, Ratamess, N, Fry, AC, Triplett-McBride, T, Koziris, LP, Bauer, JA, et al. Influence of Resistance Training Volume and Periodization on Physiological and Performance Adaptations in Collegiate Women Tennis Players. *Am J Sports Med* 28: 626–633, 2000.
30. Maquirriain, J, Baglione, R, and Cardey, M. Male professional tennis players maintain constant serve speed and accuracy over long matches on grass courts. *European Journal of Sport Science* 16: 845–849, 2016.
31. Marshall, RN and Elliott, B. Long-axis rotation: The missing link in proximal-to-distal segmental sequencing. *Journal of Sports Sciences* 18: 247–254, 2000.
32. Martin, C, Bideau, B, Delamarche, P, and Kulpa, R. Influence of a Prolonged Tennis Match Play on Serve Biomechanics. *PLoS ONE* 11: e0159979, 2016.
33. Martin, C, Kulpa, R, Delamarche, P, and Bideau, B. Professional tennis players' serve: correlation between segmental angular momentums and ball velocity. *Sports Biomechanics* 12: 2–14, 2013.
34. Mendez-Villanueva, A, Fernandez-Fernandez, J, and Bishop, D. Exercise-induced homeostatic perturbations provoked by singles tennis match play with reference to development of fatigue. *British Journal of Sports Medicine* 41: 717–722, 2007.
35. Moreno-Pérez, V, López-Samanes, Á, Domínguez, R, Fernández-Elías, VE, González-Frutos, P, Fernández-Ruiz, V, et al. Acute effects of a single tennis match on passive shoulder rotation range of motion, isometric strength and serve speed in professional tennis players. *PLoS ONE* 14: e0215015, 2019.

36. Palmer, K, Jones, D, Morgan, C, and Zeppieri, G. Relationship Between Range of Motion, Strength, Motor Control, Power, and the Tennis Serve in Competitive-Level Tennis Players: A Pilot Study. *Sports Health* 10: 462–467, 2018.
37. Pugh, S, Kovaleski, J, Heitman, R, and Gilley, W. Upper and lower body strength in relation to ball speed during a serve by male collegiate tennis players. *Perceptual and Motor Skills* 97: 867–872, 2003.
38. Reid, M, Elliott, B, and Alderson, J. Lower-Limb Coordination and Shoulder Joint Mechanics in the Tennis Serve. *Medicine & Science in Sports & Exercise* 40: 308–315, 2008.
39. Reid, M, Morgan, S, and Whiteside, D. Matchplay characteristics of Grand Slam tennis: implications for training and conditioning. *Journal of Sports Sciences* 34: 1791–1798, 2016.
40. Reid, M, Whiteside, D, and Elliott, B. Serving to different locations: set-up, toss, and racket kinematics of the professional tennis serve. *Sports Biomechanics* 10: 407–414, 2011.
41. Roetert, EP, Ellenbecker, TS, and Reid, M. Biomechanics of the Tennis Serve: Implications for Strength Training: *Strength and Conditioning Journal* 31: 35–40, 2009.
42. Rota, S, Morel, B, Saboul, D, Rogowski, I, and Hautier, C. Influence of fatigue on upper limb muscle activity and performance in tennis. *Journal of Electromyography and Kinesiology* 24: 90–97, 2014.
43. Signorile, JF, Sandler, DJ, Smith, WN, Stoutenberg, M, and Perry, AC. Correlation Analyses and Regression Modeling Between Isokinetic Testing and On-Court Performance in Competitive Adolescent Tennis Players. *J Strength Cond Res* 19: 519, 2005.

44. Sweeney, M, Reid, M, and Elliott, B. Lower Limb and Trunk Function in the High Performance Tennis Serve. 9: 9, 2012.
45. Terraza-Rebollo, M and Baiget, E. Acute and delayed effects of strength training in ball velocity and accuracy in young competition tennis players. PLoS ONE 16: e0260825, 2021.
46. Terraza-Rebollo, M, Baiget, E, Corbi, F, and Planas Anzano, A. Efectos del entrenamiento de fuerza en la velocidad de golpeo en tenistas jóvenes / Effects of Strength Training on Hitting Speed in Young Tennis Players. *rimcafd* 66, 2017. Available from: <https://revistas.uam.es/rimcafd/article/view/7999>
47. Tooth, C, Schwartz, C, Fransolet, C, Tubez, F, Colman, D, Croisier, J-L, et al. Influence of scapular dyskinesis, kinesiotaping and fatigue on tennis serve performance. *International Journal of Performance Analysis in Sport* 20: 456–469, 2020.
48. Vaverka, F and Cernosek, M. Association between body height and serve speed in elite tennis players. *Sports Biomechanics* 12: 30–37, 2013.
49. Wong, FK, Keung, JH, Lau, NM, Ng, DK, Chung, JW, and Chow, DH. Effects of Body Mass Index and Full Body Kinematics on Tennis Serve Speed. *Journal of Human Kinetics* 40: 21–28, 2014.

STUDY 8 TABLES

TABLES

Table 1. Anthropometric characteristics related to Serve Velocity (SV).

Reference	Description and goals	Gender	n	Age	Level	Variables tested	Correlation
Vaverka & Cernosek (2013)	Determine the association between BH and SV in elite players during Grand Slams.	M	78 - 84	-		BH (cm): 185.0 ± 7.0	SF: $r = 0.52 \pm 0.06$ S1: $r = 0.55 \pm 0.07$ S2: $r = 0.37 \pm 0.11$
		F	70 - 78	-	Elite	BH (cm): 173.0 ± 7.0	SF: $r = 0.52 \pm 0.06$ S1: $r = 0.52 \pm 0.03$ S2: $r = 0.35 \pm 0.08$
Bonato et al., (2014)	Investigate the relationship between anthropometric and functional parameters and SV in professional players	M	8	23.1 ± 3.9	Elite	BH (cm): 181.8 ± 4.1	1st Serve: $r = 0.78^*$ 2nd Serve: $r = 0.80^*$
						BM (kg): 79.7 ± 4.3	r 1st Serve = -0.22 r 2nd Serve = -0.15
Sigut (2016)	Determine possible relations between SV and body height	M	16	13.81 ± 1.11	Junior	BH (cm): 163.3 ± 11.42	$r = 0.678$
		F	17	13.35 ± 1.37		BH (cm): 159.5 ± 0.08	$r = 0.49$
Palmer et al., (2018)	To explore the relation between BH, ROM, strength, motor control and power and SV.	M	42	23.9 ± 5.82	Competition	BH (cm): 180.2 ± 7.23	$r = 0.46^{**}$
Hayes et al., (2018)	Determine if a relationship exists between anthropometric measures and SV in elite junior tennis players	M	12	16.5 ± 2.0	Elite	BM (kg): 66.5 ± 10.6	$r = 0.68^*$
						BMI (kg/m ²): 21.22 ± 1.5	$r = 0.31$
		F	9	16.0 ± 2.2		BH (cm): 178.2 ± 9.9	$r = 0.80^{**}$
						BM (kg): 63.9 ± 6.5	$r = 0.68^*$
						BMI (kg/m ²): 22 ± 1.3	$r = 0.31$
						BH (cm): 170.3 ± 4.6	$r = 0.80^{**}$
M	124	11.3 ± 0.4	Junior	BM (kg): 38.8 ± 5.8	$r = 0.47^{**}$		
				BH (cm): 149.9 ± 7.7	$r = 0.40^{**}$		
	(n = 625)					BMI (kg/m ²): 17.2 ± 1.4	$r = 0.36^{**}$

		12.6 ± 0.3	BM (kg): 49.1 ± 7.3	r = 0.489*
28	Junior	U15:	BH (cm): 166.3 ± 5.7	r = 0.319
		14.6 ± 0.3	BM (kg): 56.8 ± 5.4	r = 0.066
<p>To analyze the associations between SV and anthropometric, ball impact and landing location parameters in WSV and FSV in professional tennis players during</p>				
M	Elite	26.4 ± 5.4	BH (cm): 186.9 ± 7.4	r 1st Serve = 0.503*
			BM (kg): 81.6 ± 7.1	r 2nd Serve = 0.486*
			BMI (kg/m ²): 23.4 ± 1.1	r 1st Serve = 0.593** r 2nd Serve = 0.466*

Bajic et al., (2022)

Values are Mean ± SD; M = male; F = female; BMI = body mass index; BH = body height; BM = body mass; SF = fastest serve in a match; S1 = average first serve velocity; S2 = average second serve velocity; U12 = under twelve; U14 = under fourteen; U16 = under sixteen; U18 = under eighteen. ** = p < 0.01; * = p < 0.05.

Table 2. Strength, power, and ROM variables related to Serve Velocity (SV)

Reference	Description and Goals	Gender	n	Age	Level	Variables tested	Correlation
ohen et al., 994)	Determine the relation between strength variables, ROM and SV in competition players	M	40	33.7 ± 7.1	Competition	Elbow extension torque	r = 0.474**
						Dominant wrist flexion ROM	r = 0.338*
						Shoulder internal rotation ROM	r = 0.324*
						60° shoulder internal rotation eccentric contraction	r = 0.361*
						60° shoulder internal rotation concentric contraction	r = 0.372*
180° shoulder internal rotation eccentric contraction	r = 0.310*						
180° shoulder internal rotation concentric contraction	r = 0.335*						
ugh et al., 003)	Study the relation between lower body, shoulder and grip strength and SV in college players	M	15	20.8 ± 2.0	Competition	Knee extension strength	r = 0.36
						Shoulder internal rotation strength	r = 0.29
gnorile et al., 005)	Examine the correlations between isokinetic peak torque and SV	M (n = 23) and F (n = 10)	33	14.97 ± 1.36	Junior	Diagonal Throwing Peak Torque	r = 0.69**
						Knee ROM during phases I and II of the serve	r = 0.705*
'ong et al., 014)	Investigate the effects of kinematics on serve velocity in elite players	M	12	20.5 ± 3.8	Elite	Knee extension velocity during phase II of the serve	r = 0.751**
						Peak hip extension speed during phase II of the serve	r = 0.657*
						Shoulder ROM during phase III of the serve	r = 0.616*
						Peak elbow extension velocity during phase II of the serve	r = 0.708**
aliget et al., 016)	Investigate the relation between maximal isometric strength and SV in competition players	M	12	17.2 ± 1.0	Junior	Shoulder internal rotation maximum isometric strength	r = 0.67*
						Shoulder internal rotation + shoulder flexion maximum isometric strength	r = 0.76*

ayes et al., (018)	Determine if there is a relation between IMTP, CMJ, BH, shoulder internal and external rotation strength and SV in elite adolescent players	M	21	M:	Junior	IMTP peak strength	r = 0.87**	
		(n=12) and F		16.5 ± 2			CMJ height	r = 0.77**
		(n=9)		16.0 ± 2.2			IMP at 300ms	r = 0.71**
							IMP at 200ms	r = 0.58**
							IMP at 100ms	r = 0.64**
ossena et al., (018)	Investigate the relationship between jumping capacity and SV in professional tennis players.	M	8	20 ± 3	Competition	90° shoulder internal rotation	r = 0.63**	
						<90° shoulder external rotation	r = 0.63**	
						Maximal jumping height during 1 st serve	r = 0.71*	
						Maximal jumping height during 2 nd serve	r = 0.71*	
almer et al., (018)	Determine if upper and lower body power variables are predictive of SV in elite players	M	42	23.9 ± 5.82	Elite	Hip external rotation ROM	r = 0.39**	
						Single leg hop (ipsilateral)	r = 0.36*	
						Single leg hop (contralateral)	r = 0.31*	
						Dominant arm seated shot-put throw	r = 0.30*	
riksrud et al., (018)	Determine the relationship between power, strength and dynamic balance and SV in competition players	M	12	28.3 ± 10.3	Competition	CMJ	r = 0.715**	
						Dominant arm vertical press	r = 0.650*	
						Bilateral arm overhead anterior push	r = 0.643*	
						Grip Strength	r = 0.43**	
			124	UI12: 11.3 ± 0.4		Junior	MBO	r = 0.55**
							MBF	r = 0.49**
							MBB	r = 0.55*
			248	UI14: 12.9 ± 0.5		Junior	Grip Strength	r = 0.59**
							MBO	r = 0.52**
							MBF	r = 0.63**
	156	UI16: 14.9 ± 0.5	Junior	MBB	r = 0.58**			
				Grip Strength	r = 0.59**			
				MBO	r = 0.60**			

Fett et al., (2018)	Determine the relationship between strength and power variables and SV in elite junior players	97	U18: 16.8 ± 0.5	Junior	MBB	r = 0.60***					
					Grip Strength	r = 0.57**					
					MBO	r = 0.52**					
					MBF	r = 0.55**					
					MBB	r = 0.51**					
					Grip Strength	r = 0.37**					
					MBO	r = 0.20*					
					MBF	r = 0.29*					
					MBB	r = 0.21					
					Grip Strength	r = 0.36**					
					MBO	r = 0.39**					
					MBF	r = 0.56**					
					MBB	r = 0.50**					
					Grip Strength	r = 0.34**					
					MBO	r = 0.54**					
MBF	r = 0.59**										
MBB	r = 0.60**										
Grip Strength	r = 0.27*										
MBO	r = 0.48**										
MBF	r = 0.51**										
MBB	r = 0.38*										
Fernandez-Fernandez et al., (2019)	Analyze the functional profile of the shoulder and establish relations between the tested variables and SV	32	U13: 12.6 ± 0.2	Junior	MBO	r = 0.557					
					MBF	r = 0.638*					
					MBB	r = 0.442*					
					MBO	r = 0.418*					
					MBF	r = 0.582*					
					MBB	r = 0.532*					
					MBO	r = 0.433*					
					MBF	r = 0.295					
					MBB	r = 0.307					
					MBO	r = 0.202					
					MBF	r = 0.413*					
					MBB	r = 0.098					
					Fernandez-Fernandez et al., (2019)	Analyze the functional profile of the shoulder and establish relations between the tested variables and SV	36	U15: 14.6 ± 0.3	Junior	MBO	r = 0.557
										MBF	r = 0.638*
										MBB	r = 0.442*
MBO	r = 0.418*										
MBF	r = 0.582*										
MBB	r = 0.532*										
MBO	r = 0.433*										
MBF	r = 0.295										
MBB	r = 0.307										
MBO	r = 0.202										
MBF	r = 0.413*										
MBB	r = 0.098										
Fernandez-Fernandez et al., (2019)	Analyze the functional profile of the shoulder and establish relations between the tested variables and SV	32	U13: 12.6 ± 0.3	Junior						MBO	r = 0.557
										MBF	r = 0.638*
										MBB	r = 0.442*
					MBO	r = 0.418*					
					MBF	r = 0.582*					
					MBB	r = 0.532*					
					MBO	r = 0.433*					
					MBF	r = 0.295					
					MBB	r = 0.307					
					MBO	r = 0.202					
					MBF	r = 0.413*					
					MBB	r = 0.098					
					Fernandez-Fernandez et al., (2019)	Analyze the functional profile of the shoulder and establish relations between the tested variables and SV	28	U15: 14.6 ± 0.3	Junior	MBO	r = 0.557
										MBF	r = 0.638*
										MBB	r = 0.442*
MBO	r = 0.418*										
MBF	r = 0.582*										
MBB	r = 0.532*										
MBO	r = 0.433*										
MBF	r = 0.295										
MBB	r = 0.307										
MBO	r = 0.202										
MBF	r = 0.413*										
MBB	r = 0.098										

Author (Year)	Study Title	M	F	Age	Measure	Correlation (r)			
Golomar et al., 2020)	Study the influence of strength, power, and muscle stiffness on SV in junior tennis players	M	21	17.0 ± 0.8	Junior	Gastrocnemius stiffness	r = 0.45*		
						Infraspinatus stiffness	r = 0.42*		
								IF 30 ms	r = 0.01 – 0.49
								WF IF 50 ms	r = 0.54*
								WE, WF, SHF IF 90 ms	r = 0.49 – 0.56*
								WE, WF, SHF, SHIR IF 100 ms	r = 0.52 – 0.58*
								WE, WF, SHF, SHIR IF 150 ms	r = 0.5 – 0.67**
								WE, EE, SHE, WF, SHF, SHIR IF 200 ms	r = 0.51 – 0.7**
								WE, EE, SHE, WF, SHF, SHIR IF 250 ms	r = 0.54 – 0.72**
								Peak IF	r = 0.54 – 0.7**
								WE, RFD 0-30 ms	r = 0.66**
								WE, SHE, SHIR RFD 0-50 ms	r = 0.52 – 0.69**
								WE, SHE, SHF, SHIR RFD 0-90 ms	r = 0.5 – 0.69**
WE, EE, SHE, SHF, SHIR RFD 0-100 ms	r = 0.49 – 0.69**								
Lajegat et al., 2021)	To analyze the associations between SV and various single-joint upper limb isometric force time parameters (IF, RFD and IMP)	M (n = 12) and F (n = 5)	17	16.8 ± 1.1	Junior	WE, EE, SHE, WF, SHF, SHIR RFD 0-150 ms	r = 0.5 – 0.7**		
						WE, EE, SHE, WF, SHF, SHIR RFD 0-200 ms	r = 0.58 – 0.69**		
								WE, EE, SHE, WF, SHF, SHER, SHIR RFD 0-250 ms	r = 0.5 – 0.71**
								IMP 30 ms	r = 0.04 – 0.48
								WF IMP 50 ms	r = 0.5*
								WF IMP 90 ms	r = 0.58*
								WF IMP 100 ms	r = 0.59*
								WE, SHE, WF, SHF, SHIR IMP 150 ms	r = 0.52 – 0.64**
								WE, EE, SHE, WF, SHF, SHIR IMP 200 ms	r = 0.5 – 0.66**
								WE, EE, SHE, WF, SHF, SHIR IMP 250 ms	r = 0.52 – 0.66**

Values are Mean ± SD; M = male; F = female; ROM = range of motion; IMTP = isometric mid-thigh pull; CMJ = countermovement jump; MBT = medicine ball throw; RFD = rate of force development; IMP = impulse; WE = wrist extension; WF = wrist flexion; EE = elbow extension; SHF = shoulder flexion; SHE = shoulder extension; SHIR = shoulder internal rotation; SHER = shoulder external rotation; MBO = medicine ball throw overhead; MBF = medicine ball throw forehead; MBB = medicine ball throw backhand. ** = p < 0.01; * = p < 0.05

Table 3. Factors negatively affecting Serve Velocity (SV).

Reference	Description and Goals	Gender	n	Age	Level	Fatiguing condition	Findings
Javey et al., (2002)	Examine the effect of fatigue on specific sporting abilities	M (n = 9) and F (n = 9)	18	20.7 ± 0.9 and 21.7 ± 0.6	Competition	High intensity intermittent activity	SV was not reduced but precision declined 30%*
Jajala and Hakkinen, (2013)	To examine changes in selected physiological and performance variables during a 3-day tennis tournament.	M	8	23 ± 3.8	Elite	3-day tennis tournament	Serve velocity was significantly lower before the third match compared to the first match (-2.72%*)
Kota et al., (2014)	Examine the effect of fatigue on upper body muscular activity and tennis performance	M	10	23.8 ± 4.0	Competition	High intensity intermittent specific activity	SV is reduced 4.5%* and precision 11.7%*
Rescheit et al., (2015)	Determine how playing matches in consecutive days affects performance, physiological and perceptual responses	M	7	21.4 ± 2.2	Competition	Matches on consecutive days	SV is moderately increased day-by-day. Precision decreases during consecutive days
Asquith et al., (2016)	Analyze SV and accuracy in prolonged male professional matches played on grass courts	M	30	-	Elite	Wimbledon five set matches	No significant changes were registered
Martin et al., (2016)	Examine changes in shoulder ROM and SV during a 3-hour tennis match	M	8	20.4 ± 2.8	Competition	3-hour match	1.8m/s (-3.9%*) reductions after 3 hours of play. No reductions at 90 minutes
Sallo-Salazar et al., (2019)	Analyze how playing two consecutive matches on the same day affects performance in young tennis players	M	12	14.4 ± 0.9	Junior	Playing two matches in the same day	Trivial reductions in SV from 151.7 ± 13.94 to 149 ± 15.09 km/h

oreno-Pérez et al., (2019)	Determine the acute effects of a tennis match on SV and shoulder ROM	M	26	20.4 ± 4.4	Elite	One tennis match	No significant decreases in SV
oth et al., (2020)	Assess the influence of scapular muscle fatigue on tennis performance	M	15	22.8 ± 3.45	Competition	Elastic band exercise until exhaustion on racquet velocity	Significantly decreased racquet velocity (4%*) and accuracy (55%**)
Traza-Rebollo & Jeger (2021)	Acute and delayed effect of strength training on SV and accuracy	M (n = 4) and F (n = 6)	10	15.3 ± 3.45	Competition	MBT or resistance training exercises	No significant reductions in SV or accuracy

Values are Mean ± SD; M = male; F = female; ROM = range of motion; MBT = medicine ball throws. ** = p < 0.01; * = p < 0.05.





DISCUSSION



As the main body of this thesis comprises a number of studies of various topics responding to different goals, the discussion will be organized in different sections. Determinant physical factors related to age and level will be discussed first, while competition-induced fatigue results from studies 3, 4 and 5 will be reviewed posteriorly. Finally, some insights on the analysis of training methodologies towards stroke velocity improvement will be discussed.

DETERMINANT PHYSICAL FACTORS AFFECTING STROKE VELOCITY

Studies 1 and 2 focused on trying to establish those main physical factors affecting velocity production in young players. In the upcoming section and following the obtained results, how different strength variables affect speed in a specific sample of tennis players will be reviewed. Comparisons with previous investigations testing similar variables in other population samples will be discussed. Also, novel strength indicators such as mechanical muscle properties and force-time curve variables will be argued as their influence on stroke velocity remains a limited field of study. Study 8 will not be discussed as it constitutes a brief review of all those previously studied physical variables that affect SV mentioned in the framework of this work.

Upper body strength and power variables

Stroke velocity, especially studied in the serve, seems to be a clear capacity of multifactorial nature. Previous literature established four main pillars when speaking of those factors affecting velocity production. Biomechanics or technique (B. Elliott, 2006), range of motion (Palmer et al., 2018; Wong et al., 2014), anthropometrics (Bonato et al., 2014; Vaverka & Cernosek, 2013) Baiget et al., 2022), and

neuromuscular levels (Baiget et al., 2016, 2021; Fett et al., 2020; Hayes et al., 2021) shape the final speed of a players' stroke. Nevertheless, preceding investigations had mainly focused on male competitive players and maximal measures of MIS and upper body explosiveness via MBT in relation to SV without including groundstroke speed analysis. Study 1 added to the rationale a group of relatively unstudied neuromuscular variables in junior players with an international tennis number (ITN) of around 3-4, alongside forehand and backhand velocity measurements. Results showed no significant positive correlations between stroke velocity and most of the tested variables. In line with previous investigations that found low to moderate relations between MDS and velocity production (Kraemer et al., 1995), no positive associations were found here in this sense. Maximal power output in a relatively unspecific exercise layout such as the bench press showed no correlations to any of the tested strokes, restating MDS may not be the best predictor for velocity production in young competitors. Tennis strokes are performed with relatively low loads at high speed of execution while performing a global movement with several body segments involved. Thus, it may not be properly assessed with such a decontextualized measurement (Fernandez-Fernandez et al., 2014) regarding mobilized loads and movement specificity. On the other hand, regarding MIS measurements in different joint positions and upper body power tests using MBT, results were rather surprising, as previous investigations have established these variables as highly related to stroke velocity (Baiget et al., 2016; Fernandez-Fernandez et al., 2019; Fett et al., 2020). Outcomes concluded from study 1 may indicate certain differences in the strength of associations of the multiple variables that form a stroke's speed depending on the subjects analyzed. In a similar way as seen previously in young participants (Fett et al., 2020), strength and power variables

may not be as relevant as anthropometric traits and technical proficiency in lower ranked competitors as those included in study 1 (majority of ITN 3-4). It may be that the variables that discriminate the most in groups of players of these characteristics continue to be of a more coordinative and technical nature than those that stand out as age and level increase and anthropometric and kinematic traits stabilize (Girard & Millet, 2009). Heights of determination of fitness characteristics explaining SV variance have previously seen to increase with age (Figure 18) (Fett et al., 2020). It is assumed that SV is a less predominant factor at younger ages and lower levels, and that the velocity production of a stroke may be more strongly dependent on technical factors, suggesting training interventions should focus on technical development in these cases. From a long-term perspective, physical performance will be greatly important in later stages of the player's development (Fett et al., 2020).

TABLE 3. Statistics of multiple regression analysis.*

Male					Female				
U12	R	R ²	F	Sig F.	U12	R	R ²	F	Sig F.
	0.64	0.41	37.8	0.000		0.43	0.19	16.0	0.000
		Beta	T	Sig T.			Beta	T	Sig T.
MBT backhand		0.359	3.91	0.00	Grip strength		0.431	4.00	0.00
MBT overhead		0.351	3.82	0.00					
U14	R	R ²	F	Sig F.	U14	R	R ²	F	Sig F.
	0.82	0.66	108.9	0.000		0.65	0.43	59.2	0.000
		Beta	T	Sig T.			Beta	T	Sig T.
MBT forehand		0.386	5.18	0.00	MBT forehand		0.514	7.08	0.00
Arm span		0.199	3.20	0.00	Body mass		0.209	2.89	0.01
MBT overhead		0.163	2.70	0.01					
Grip strength		0.152	2.28	0.02					
U16	R	R ²	F	Sig F.	U16	R	R ²	F	Sig F.
	0.79	0.62	77.6	0.000		0.67	0.45	32.4	0.000
		Beta	T	Sig T.			Beta	T	Sig T.
Grip strength		0.330	4.72	0.00	MBT backhand		0.416	3.63	0.00
MBT overhead		0.284	3.65	0.00	MBT overhead		0.313	2.73	0.01
MBT backhand		0.281	3.52	0.00					
U18	R	R ²	F	Sig F.	U18	R	R ²	F	Sig F.
	0.68	0.46	37.7	0.000		0.66	0.43	16.5	0.000
		Beta	T	Sig T.			Beta	T	Sig T.
Grip strength		0.436	4.63	0.00	MBT overhead		0.529	4.51	0.00
MBT forehand		0.329	3.50	0.00	Body mass		0.244	2.08	0.04

*BMI = body mass index; MBT = medicine ball throw.

Figure 18. Multiple regression analysis including fitness characteristics variables and relation to SV. Adapted from Fett et al., 2020.

Added to MDS, MIS and power measurements via MBT, study 2 tested the influence of force-time curve variables and SV in young players. Previous studies established strong associations between the capacity of producing high levels of force in short time intervals in several joint positions of the upper arm and SV in older competitive players (Baiget et al., 2021). Study 2 aimed at investigating this issue in younger competitors, including female participants and lower body measurements. Results indicate that PRFD, RFD and IMP in short time intervals of under 200 ms significantly influence the capacity of serving faster, also in young adolescent participants. Moreover, the combination of multiple body positions present in the serve kinetic chain explains a great deal of the variation in SV. Results of study 2, in combination with non-significant relations between MDS and SV found in study 1, restate the influence of rapid force production influencing a stroke's speed, over maximal values of strength or power output in unspecific positions and movements not present in the kinetic chain.

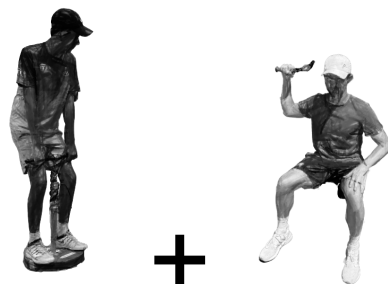


Figure 19. Importance of the inclusion of upper and lower body joint positions in force-time curve testing for stroke velocity assessment

This is important towards velocity production assessment and program prescription, as exercises aiming at improving stroke speed should intend great force production in short time intervals. Added to this, results in study 2 showed that 79% of the

variance in SV was determined by the combination of upper and lower body joint positions involved in the serve motion (Figure 19 and Table 2). This seems to indicate that not only the capacity of producing force in short periods of time is important to apply speed to the ball, but to be able to produce these levels of RFD and IMP in several joint positions in a coordinated manner is greatly determinant.

Table 2. Isometric force-time curve variables included in the stepwise multiple regression analysis to explain the variance on mean SV.

Step	Independent variables entered	Correlations			SEE	p	Regression equation
		r	r ²	Adj. r ²			
1	PRFD_IMTP	0.80	0.64	0.61	7.7	<0.001	$y = 116.18 + (0.004 \times \text{PRFD_IMTP})$
2	SHF_IMP ₀₋₂₀₀	0.91	0.82	0.79	5.6	<0.001	$y = 102.59 + (0.003 \times \text{PRFD_IMTP}) + (1.433 \times \text{SHF_IMP}_{0-200})$

PRFD_IMTP = isometric mid-thigh pull; SHF_IMP₀₋₂₀₀ = impulse from 0 to 200 ms; Adj. r² = adjusted coefficient of determination; SEE = standard error of estimate.

Lower body influence on stroke velocity

Regarding lower body, studies 1 and 2 tested the influence of these body segments in stroke velocity. Previously, some investigations found positive correlations between isokinetic testing and SV (Girard & Millet, 2009; Kraemer et al., 1995; Palmer et al., 2018; Pugh et al., 2003; Wong et al., 2014). These studies restate the importance of GRF and the capacity to transfer energy from lower to upper body segments. As greater strength and power levels could favor an appearance of GRF of superior magnitude (Palmer et al., 2018), these parameters would also be beneficial for enhanced stroke velocity. Nevertheless, studies included in this work did not test the influence of isokinetic testing of lower limb motions but approached

this issue with explosiveness and power measurements, as they seem more specific to strength needs of the tennis actions. Previous works tested the relationship between jumping capacity and SV. Dossena et al., (2018) found moderate positive associations between this variable and first and second serves, while other approaches found no significant associations (Bonato et al., 2014). In this line, results from the studies included here found no significant positive results between the squat jump (SJ) and CMJ and any of the tested strokes (serve, forehand or backhand). Although the legs are considered a key link in the kinetic chain, explosiveness and power values registered with jumping tests seem unclear to be representative of a player's capacity to hit the ball faster. This may not necessarily indicate that this body segment is not important or has low contribution to velocity production. On the contrary, it is suggested that this contribution is of a more coordinative nature rather than a velocity generator. Jumping capacity alone may not be representative of faster strokes, on the other hand, it might be indicative of the capacity of transferring energy from lower to upper body segments in which the final velocity of the stroke is shaped (Bonato et al., 2014; Fett et al., 2020). Nevertheless, if this coordinative link and energy transfer fails, speed will most likely be negatively affected. Moreover, this idea is supported by results found in study 2. The IMTP testing was included in the mentioned investigation to provide insights on the influence of lower body motion force-time curve variables on SV. Results showed strong associations between maximal voluntary contraction (MVC), PRFD, RFD and IMP in short time intervals in young competitors. As suggested in previous investigations, obtaining higher values of force in short periods of time in the lower body will traduce in velocity gradually increasing from the legs towards the long-axis rotational elements such as the upper arm (Girard et al., 2005; Hayes et al., 2021).

Added to this, time availability during the concentric phase of the stroke is extremely short, restating the importance, as happens when analyzing upper body, of generating force rapidly in short time windows (<250 ms). Furthermore, in a similar way to the concept mentioned regarding the summation of force-time values in several upper body joint positions, the multiple regression analysis performed in study 2 showed a great deal of SV variance when combining a lower body motion such as the IMTP and SHF. This indicates the importance of assessing MVC, RFD and IMP values in a global manner to properly approach whole body motions such as tennis strokes (Figure 20). Moreover, the coordinative influence of the legs in combination with the importance of including multiple body segments and coordinative elements for young and lower ranked players restates the importance of training this key capacity in a global manner with full body fast executed tasks.

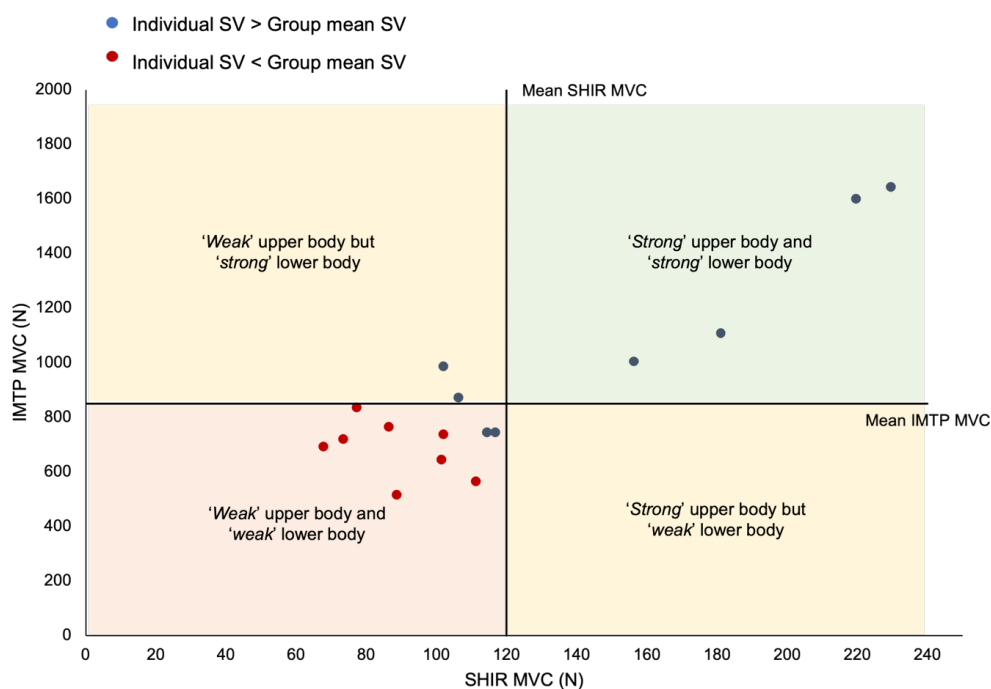


Figure 20. Quadrant chart showing relationship between SHIR and IMTP values of players that serve above and below group average SV.

Muscle contractile properties

Study 1 included an interesting unstudied concept regarding physical aspects that may influence stroke velocity. Predominantly lower body actions such as sprinting, jumping, and changing direction have previously been linked to greater stiffness of the muscle-tendon unit (Brughelli & Cronin, 2008; Kalkhoven & Watsford, 2018; Pruyn et al., 2014). It is suggested that this enhanced stiffness allows the athlete to store more elastic energy during ground contact and generate greater force output at push-off, increasing running speed or jumping capacity (Brazier et al., 2019). Being the tennis strokes actions with several SSC phases throughout the entire kinetic chain, it seemed interesting to analyze the influence of complex neuromuscular aspects such as contractile properties. Results showed an increased stiffness of the gastrocnemius ($r = 0.45$) and infraspinatus ($r = 0.42$) alongside a decreased level in the pectoralis major ($r = 0.45$) positively correlated to faster serves and forehands. This indicates a certain influence of the level of stiffness on stroke velocity, nevertheless, if a greater or lower level of this capacity is beneficial or detrimental remains unclear. The capacity of a stiff structure to absorb and re-use rapidly greater amounts of elastic energy for a given force (Kalkhoven & Watsford, 2018) would certainly seem beneficial for highly dynamic actions such as strokes. On the other hand, results in study 1 showed positive associations between lower levels of stiffness in the pectoralis major and forehand velocity. This suggests that an enhanced level of stiffness in certain muscle groups could be counterproductive for velocity production. Complex motor skills such as strokes may rely highly on technical aspects and effective coordination that could be high jacked by high levels of stiffness. Tightness and increased peak forces may affect ROM and consequently velocity would be negatively affected. As suggested in study 1, a stiff structure could

be beneficial for reducing electromechanical delay and enhance RFD, but at the same time, a greater level of this variable may influence technical parameters and ROM, resulting in negatively affected strokes. A 'sweet spot' regarding contractile property values remains to be established, but there seems to be a certain influence of these levels on velocity production in young tennis players, making interesting further studies on this matter. Moreover, the inclusion of active measurements of stiffness would be of extreme interest as investigations included in this thesis measured these variables in a passive, relaxed state (Figure 21).



Figure 21. Mechanical muscle property measurement in relaxed state.

COMPETITION-INDUCED FATIGUE AND ITS INFLUENCE ON DETERMINANT PHYSICAL FACTORS OF STROKE VELOCITY

The following section will review the findings resulting of studies 3, 4 and 5. Changes on the relevant physical factors mentioned in the previous section induced by competition-induced fatigue will be discussed and differentiated by either short-term acute effects or long-term adaptations to prolonged tennis exposure.

Acute effects on mechanical muscle properties

Study 3 tested the effects of an 80-minute simulated tennis match on relevant muscle mechanical properties involved in tennis actions. These factors, although relatively unstudied, seem important towards effective velocity production in tennis strokes. Therefore, how these variables are affected by typical match loads present in youth competitive events could be of interest. A series of conclusions can be drawn out from the results obtained. First, mechanical property measures seemed unaffected by the particular load layout proposed in the investigation. This may be due to a series of factors that would explain generally unaltered values. Previous works found MVC and ROM around the shoulder and hip to be negatively affected by match-play (Gallo-Salazar et al., 2017; Gescheit et al., 2015). Nevertheless, these alterations appeared in response to generally greater volumes of play or even consecutive matches. Tennis competition certainly seems to have the potential to induce muscle damage and coupling impairment (Mendez-Villanueva et al., 2007), which generally lead to redistribution of sarcomere length and increased stiffness and tone. Notwithstanding, following repetitive predominantly SSC actions, inflammatory responses and edema can appear, and these are associated with reduced muscle

and joint stiffness. In any case, generally unaltered results were found, thus indicating that these fatiguing mechanisms did not affect the measured variables either way (Figure 22).

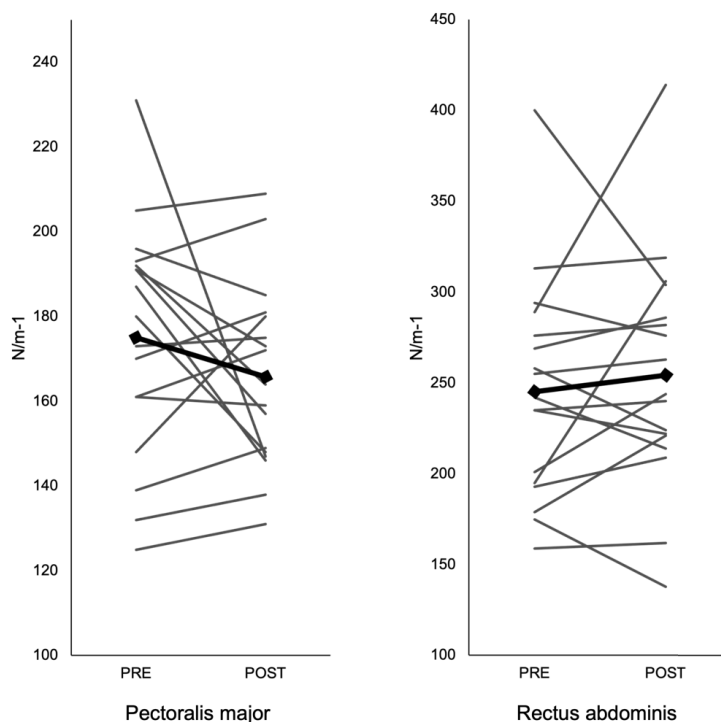


Figure 22. Generally unaltered measures of stiffness from pre to post 80-minute simulated match play. Bold line is group mean value.

This may be indicative of insufficient match load or the ability of players to overcome fatigue by different pathways, as it is affected by multiple mechanisms. Assumptions drawn out from the results indicate that overall match-load may have been of an insufficient magnitude to evoke changes in mechanical muscle properties. Mean values of heart rate indicated a predominantly submaximal effort for the participants, indicating internal load was relatively load. Regarding external load, number of strokes and changes of direction were not registered, although registered data was in accordance with previous studies involving similar populations and competition

duration. Youth competitors and lower ranked players seem to perform less actions at high intensity, a smaller number of strokes and accelerations and decelerations due to lower fitness levels (Hoppe et al., 2014; Kovalchik & Reid, 2017; Perri et al., 2018). This may indicate that the proposed match load and intensity of play was not of a sufficient magnitude to induce changes in the tested variables. In accordance, central fatigue measures in the form of balance testing were also unaltered. This variable was included to establish how players may have used different mechanisms towards minimizing the effects of match fatigue and use various compensatory pathways to avoid this issue. Notwithstanding, although results showed a certain trend towards decreases and this may be indicative of finding negative changes if greater load exposures are present, results were generally unaltered. In short, although match-load responded to typical efforts seen in single non-consecutive events performed by young tennis players, this was of an insufficient magnitude to induce changes in mechanical muscle characteristics or central system fatigue indicators. Relatively low loads could be explained by the age or competitive level of the assessed players, and consecutive bouts of play or a greater competitive intensity may be necessary to affect the tested variables.

Chronic effects on mechanical muscle properties

Muscle contractile characteristics may be affected by repetitive bouts of competition or tennis practice. As 80-minutes of match play seemed insufficient to affect the tested variables, study 4 intended to examine the prolonged effects of tennis exposure on mechanical properties established as important for velocity production. Thirty-four players were analyzed and results comparing dominant and non-dominant limbs showed small-to-moderate differences in some of the muscle groups tested. In

general, greater stiffness, tone, and contractile derivatives of these variables (i.e., elasticity and time to relaxation) were found for those muscle groups highly present in some relevant tennis action. For instance, in comparison to the non-dominant side of the body, the dominant rectus abdominis showed a greater level of elasticity, meaning a higher capacity of the muscle to return to its initial shape. In response to repetitive contractions induced by the serve action, the rectus abdominis presents structural differences with enhanced hypertrophy in the non-dominant side of the body (Sanchis-Moysi et al., 2010). In a similar way, elasticity or stiffness derivative measurements could be affected by repetitive bouts of match-play or tennis training. This was also observable in other muscle groups such as the pectoralis major and infraspinatus, indicating that prolonged tennis exposure affects to some extent muscle contractile properties and mechanical characteristics (Figure 23).

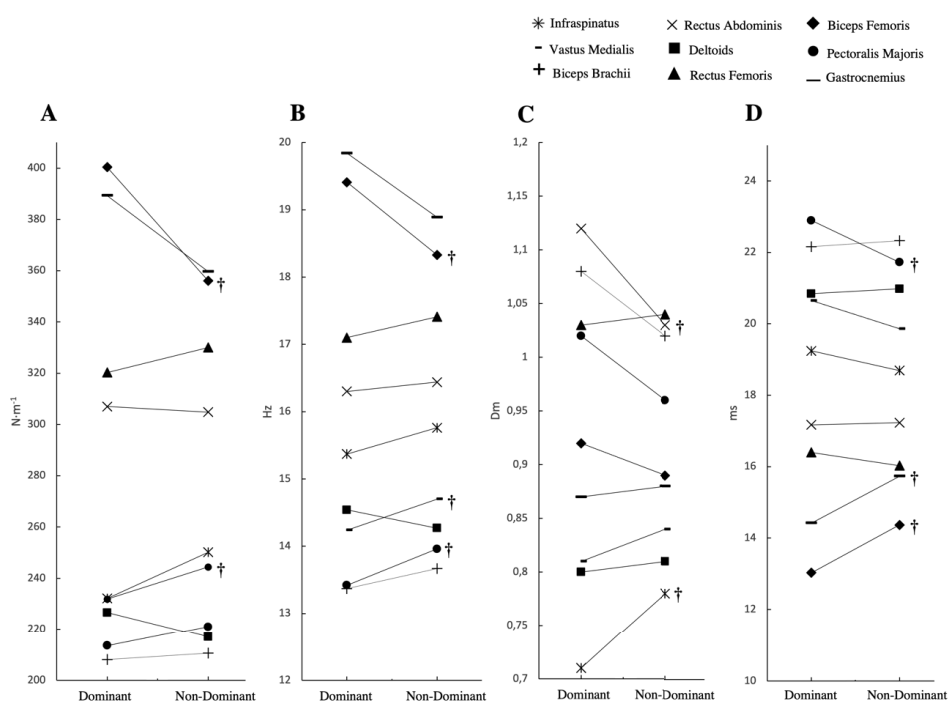


Figure 23. Mechanical muscle property differences between dominant and non-dominant limbs (n = 34). A = stiffness; B = tone; C = elasticity; D = time to relaxation.

Nevertheless, measurements showed rather low effect sizes when comparing a relatively unaffected limb as the non-dominant and the leading side of the body, restating the idea that passive measurements of contractile properties may not be the best form of assessment. Tennis strokes are performed with a fast execution and explosive predominance which would make interesting adding active assessments to future research. Moreover, the positive influence of stiffness to enhanced velocity production and the possible counterproductive effect it may also have on technical integrity and ROM remains unclear. As a future perspective it would also be interesting to examine the relationship between mechanical muscle property measurements and their association to injury risk.

Acute effects on strength and power parameters

Study 5 examined the acute effects of competition on strength and power variables that were concluded essential towards effective velocity production in the young tennis player. Following this idea, PRFD, RFD and IMP at different time intervals were tested before and after an 80-minute simulated tennis match. Interestingly, upper, and lower body measurements were included, alongside joint positions that seem to respond to the motion of the forehand and backhand. This intended to provide information on how repetitive groundstrokes and not only serves could also affect force production in short time windows. In addition to these assessments, pre- and post-match SV was registered to analyze if a functional measurement followed strength and power outcomes. As observed in study 3, force-time curve variables were generally unaltered following the simulated tennis match (Figure 24).

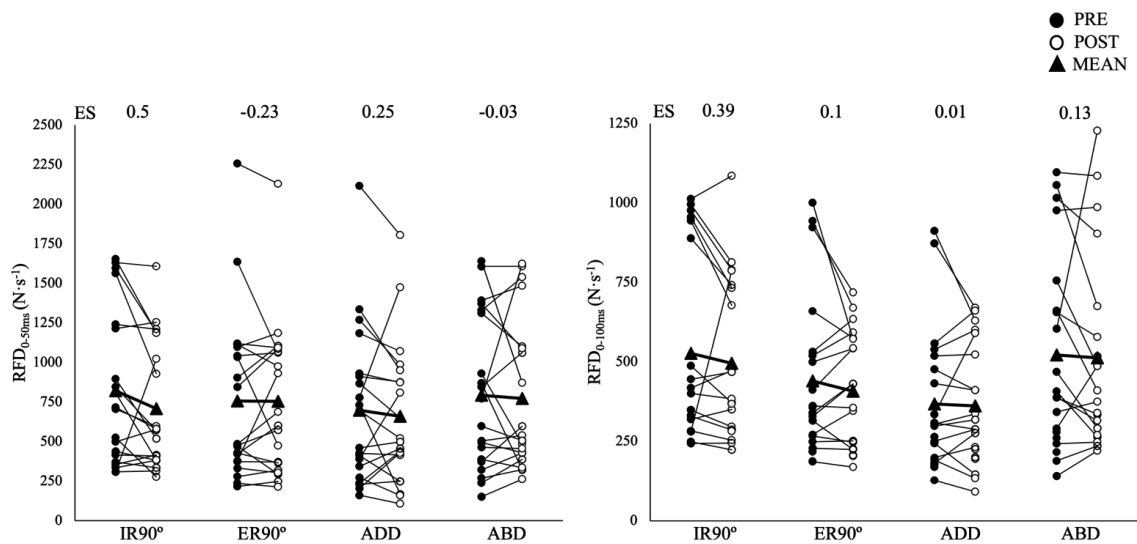


Figure 24. Pre- and post-match measurements of RFD at different time intervals at different joint positions. IR90° = shoulder internal rotation; ER90° = shoulder external rotation; ADD = shoulder horizontal adduction; ABD = shoulder horizontal abduction; ES = effect size.

Previous investigations found reductions in MVC and PRFD following bouts of competitive match-play (Gescheit et al., 2015; Girard, 2006; Girard et al., 2008, 2011; Ojala & Häkkinen, 2013). Results here may seem surprising, although when analyzing match load characteristics and comparing to those interventions that observed reductions, several reasons appear. First, most studies that found significant decreases in strength and power measurements were performed for longer durations than 80 minutes of play (Gescheit et al., 2015; Girard, 2006; Girard et al., 2008, 2011; Ojala & Häkkinen, 2013) proposed here. The match duration suggested in study 5 responded to typical young adolescent match-play length (Galé-Ansodi et al., 2017; Hoppe et al., 2014). Nevertheless, competitions of greater duration or in consecutive days may be necessary to affect the force-time curve variables tested, especially in players with a high load training background. Second, the level of players certainly seems to be relevant to the resulting match-load, despite

equal match durations. As observed in comparative match durations across levels and ages, professional older competitors present a higher number of strokes and high intensity bouts of play compared to younger participants with a lower ranking (Kovalchik & Reid, 2017; Perri et al., 2018) as those included in study 5. This fact could be the main reason no significant changes appeared and would restate that as age and playing level increase, match loads follow this increment and build the potential to affect key strength and power variables that affect velocity production. Following this idea, including programs that incorporate exercises focused on speed, power and velocity production following competition, far from being counterproductive, could be a valid option towards effective use of training time. On the other hand, performing these interventions after matches of longer duration or in consecutive days that result in greater match-loads, may not be recommended and coaches should address training in consequence. Also, with the idea of minimizing the effect of competition-induced fatigue on stroke velocity, giving players the tools to overcome this issue remains important. Analyzing investigations observing elite players in highly competitive events, results indicate SV can be unaltered following long match durations of great load. This may happen because older more experienced players may be able to maintain velocity production by relying more thoroughly on some of the mechanisms that affect stroke velocity. Percentual contribution to final speed remains unclear and it seems that it is the result of the summation of technical proficiency, anthropometrical aspects, ROM, and strength levels. Under fatiguing conditions, high level players may rely on one of these aspects over another to compensate the reduction of an affected aspect. If this is so, it would explain the capacity of elite players to maintain SV even in matches of a very high level and long duration (Maquirriain et al., 2016), hence suggesting training

interventions should aim at providing the tennis player with enhanced relevant strength levels, anthropometric traits, ROM, and movement competency.

TRAINING METHODS AIMING AT ENHANCED STROKE VELOCITY

Study 7 reviewed those training methods that better addressed the specific needs of the tennis serve alongside program designs that enhance those physical factors established as determinant for velocity production. These methods were mentioned and examined in the framework section of this work, together with specific exercise prescription suggestions presented in study 7. Briefly summarizing the concepts already mentioned, programs intending to increase velocity production in the serve, or any other tennis stroke are recommended to follow a series of premises to obtain positive adaptations. First, designs and protocols aiming at optimizing this key factor should include exercises performed with maximal intended velocity regardless the load. This seems to stimulate the improvement in strength and power values that are essential towards increasing velocity (i.e., RFD and IMP). Added to this, the importance of movement resemblance and exercise specificity seems relevant to obtain greater results, especially in young participants that would thoroughly benefit from coordinated motions that implicate the totality of the kinetic chain while mobilizing loads. Designs including plyometric tasks and specific gestures seem to obtain greater results in young populations than those programs that offer decontextualized heavy loads in unspecific body motions (Behringer et al., 2013; Fernandez-Fernandez et al., 2016). Following this idea, some investigations have offered results on stroke velocity improvements after following layouts using weighted rackets (Genevois et al., 2013). This seems to be logical as these motions are highly specific to the tennis motion and are performed at maximal velocity with light loads. For this reason, study 6 aimed at observing the acute effects of using light wrist weights (50 – 200 g) on stroke velocity in young participants (Figure 26).



Figure 25. Light wrist weights ranging 50 to 200 g used in study 6.

Results showed no significant changes in forehand, backhand or serve velocity with any of the different wrist-weights. Nevertheless, trends towards slower speeds could be observed when using 200 g alongside improvements in accuracy with 100 g. The main conclusion of this study was that wrist weights unalter stroke velocity, nonetheless, only acute effects were tested, and it would be interesting to perform an intervention protocol to observe possible changes in the long term. In a similar way to results observed when using weighted rackets (Genevois et al., 2013) or balls in other overhead sports such as baseball (Reinold et al., 2018), these training methods seem to respond to explosive force production in short periods of time to overcome an external load, thus if velocity is unaffected or increased as an acute effect, these could be valid options towards stroke velocity enhancement if applied longitudinally. Notwithstanding, the use of weighted rackets may interfere in technical parameters (Whiteside 2014), thus making interesting to perform a kinematic analysis of the main tennis strokes whilst using the mentioned wrist weights. Added to this, exercise prescription is unclear, and this mean of exercise accounts for a relatively novel approach to training. Melugin et al., (2021) performed a review concluding weighted throwing programs could be of interest for improving velocity, although injury risk and effect on harmful mechanisms are still not well understood. In this line, further studies

are needed to establish wrist weights as a valid training approach towards increasing stroke velocity in young tennis players. Nevertheless, results found in study 6 seem an interesting starting point towards this idea, as no negative effects on speed were found for any of the tested conditions.

CONCLUSIONS

In the following section, conclusions based on the 8 publications will be discussed. Each of the objectives and goals set for this thesis will be answered in order to determine the outcome of the project.

Objective 1: To define the main physical factors determining stroke velocity in young tennis players.

- MDS measurements do not seem to positively correlate to stroke velocity in young tennis players. This may possibly be due to the lack of similarity with the demands of specific tennis actions, which involve fast executions in small time windows and relatively low loads.

- PRFD, RFD and IMP at different time intervals in multiple joint positions present in the kinetic chain positively correlate to those young players that serve faster. This indicates the importance of a player's capacity to generate force in short periods of time not only in the upper arm complex but in a global manner involving multiple body segments.

- Contractile muscle properties such as stiffness and its related variables (i.e., tone, elasticity, and time to relaxation) seem to influence stroke velocity to some extent. Nevertheless, results indicate an increased value in some muscle groups may be an important aspect towards enhanced velocity production, while it may also interpose ROM and movement competency and be detrimental for this aspect.

Objective 2: To investigate the acute and chronic effects of prolonged tennis training and competition-induced fatigue on main physical factors affecting stroke velocity.

- Force-time curve variables (i.e., PRFD, RFD and IMP) are generally unaltered following an 80-minute simulated match in young players. This specific competitive layout failed to elicit a sufficient stress to affect the tested variables, possibly due to lower match loads present in competitive events of younger less experienced players.

- Contractile properties seem unaffected by 80 minutes of simulated competition in young players, indicating a stimulus of this magnitude seems insufficient to elicit changes in these variables.

- Prolonged exposure to tennis training and competition seems to induce low to moderate side-to-side asymmetries in muscle contractile properties in young competitors. Nevertheless, passive measures of mechanical muscle characteristics do not seem to reflect a great deal of adaptations to tennis match-play and training.

Objective 3. To establish how physical factors affecting stroke velocity are influenced by age and playing level.

- Upper body MIS and MBT measurements did not seem to correlate strongly to stroke velocity in players with an ITN of 3-4. This may indicate that strength and power measurements are not as determinant in players of a younger age and level.

Therefore, this suggests these traits may rise in importance as they increase, while anthropometrics and technical proficiency would be of greater importance at these stages.

Objective 4. *To examine new programs and training methods towards enhancing velocity production in main tennis strokes.*

- The use of light weights does not seem to acutely affect stroke velocity of young competitors. Nevertheless, a tendency to increased speed and accuracy with 100 g wristbands suggests this may be a valid training option towards velocity production enhancement. In any case, these approaches should be performed with caution as specific load prescriptions and injury risk remain unstudied.

- Several methodologies seem valid to enhance velocity production. Benefits have been observed regardless the load used if the intended velocity of execution is maximal. However, methodologies with a strong tendency to enhanced SSC and specific motion resemblance seem to obtain further benefits, especially in young competitors that would benefit from the coordinative demand of the exercise.



LIMITATIONS AND FUTURE PERSPECTIVES

Various limitations from this work can be pointed out. The different publications and studies included in the thesis discuss most of them and must be considered when interpreting the outcomes. Notwithstanding, they will be reminded in the following section as they also stand as future research suggestions and options.

- Studies 2, 5 and 6 included players of different sex in the measurements. Although playing level and training background were similar and no significant differences between groups were observed, results could be affected to some extent. Biological growth and maturation can highly differ at adolescent ages between male and female participants making interesting similar studies that separate by group. In the same way as this work intended to establish determinant stroke velocity variables in young competitors, to determine sex and age group differences would be of great interest.

- Passive values of the muscle state seem to influence to some extent stroke velocity. Nevertheless, active measurements of these variables seem more appropriate to assess highly dynamic actions such as tennis strokes. Because of this, the inclusion of dynamic testing of contractile properties seems of great interest. Also, studies aiming at establishing specific stiffness values to enhanced performance or injury risk may be an interesting starting point towards determining if higher or lower levels are predictors of these two factors.

- Studies 3 and 5 registered changes in relevant physical factors affecting stroke velocity following simulated matches. Although durations responded to those

typical involved in youth tennis competition, the fact that these were performed in a simulated condition could decrease the participants effort and affect results. As a future perspective, including pre- and post-measurements in competitive events alongside separating by sex, age and playing levels would be of great interest.

· Last, evaluating the effects of light weight interventions on stroke velocity in the long term would be interesting towards new training methodologies. Added, evaluation of the risk-to-benefit outcome of this type of tasks would give insights on the usefulness of this method of training.

REFERENCES

- Asencio, P., Sabido, R., García-Valverde, A., & Hernández-Davó, J. L. (2020). Does handball throwing velocity increase after an eccentric overload-induced postactivation potentiation? *European Journal of Human Movement*, 44(1). <https://doi.org/10.21134/eurjhm.44.543>
- Bahamonde, R. E., & Knudson, D. (2003). Kinetics of the upper extremity in the open and square stance tennis forehand. *Journal of Science and Medicine in Sport*, 6(1), 88–101. [https://doi.org/10.1016/S1440-2440\(03\)80012-9](https://doi.org/10.1016/S1440-2440(03)80012-9)
- Baiget, E., Colomar, J., & Corbi, F. (2021). Upper-Limb Force–Time Characteristics Determine Serve Velocity in Competition Tennis Players. *International Journal of Sports Physiology and Performance*, Ahead of print, 1–9. <https://doi.org/10.1123/ijsp.2021-0254>
- Baiget, E., Corbi, F., Fuentes, J. P., & Fernández-Fernández, J. (2016). The Relationship Between Maximum Isometric Strength and Ball Velocity in the Tennis Serve. *Journal of Human Kinetics*, 53(1), 63–71. <https://doi.org/10.1515/hukin-2016-0028>
- Barber-Westin, S. D., Hermeto, A. A., & Noyes, F. R. (2010). A Six-Week Neuromuscular Training Program for Competitive Junior Tennis Players: *Journal of Strength and Conditioning Research*, 24(9), 2372–2382. <https://doi.org/10.1519/JSC.0b013e3181e8a47f>
- Bazyler, C. D., Beckham, G. K., & Sato, K. (2015). The Use of the Isometric Squat as a Measure of Strength and Explosiveness: *Journal of Strength and Conditioning Research*, 29(5), 1386–1392. <https://doi.org/10.1519/JSC.0000000000000751>
- Behringer, M., Neuerburg, S., Matthews, M., & Mester, J. (2013). Effects of Two

- Different Resistance-Training Programs on Mean Tennis-Serve Velocity in Adolescents. *Pediatric Exercise Science*, 25(3), 370–384. <https://doi.org/10.1123/pes.25.3.370>
- Bishop, C., Turner, A., & Read, P. (2018). Training Methods and Considerations for Practitioners to Reduce Interlimb Asymmetries. *Strength & Conditioning Journal*, 40(2), 40–46. <https://doi.org/10.1519/SSC.0000000000000354>
- Bonato, M., Maggioni, M., Rossi, C., Rampinchi, S., Latorre, A., & Merati, G. (2014). Relationship between anthropometric or functional characteristics and maximal serve velocity in professional tennis players. *The Journal of Sports Medicine and Physical Fitness*, Epub ahead of print.
- Brazier, J., Maloney, S., Bishop, C., Read, P. J., & Turner, A. N. (2019). Lower Extremity Stiffness: Considerations for Testing, Performance Enhancement, and Injury Risk. *Journal of Strength and Conditioning Research*, 33(4), 1156–1166. <https://doi.org/10.1519/JSC.0000000000002283>
- Brughelli, M., & Cronin, J. (2008). A review of research on the mechanical stiffness in running and jumping: Methodology and implications: Mechanical stiffness. *Scandinavian Journal of Medicine & Science in Sports*, 18(4), 417–426. <https://doi.org/10.1111/j.1600-0838.2008.00769.x>
- Canós, J., Corbi, F., Colomar, J., Cirer-Sastre, R., & Baiget, E. (2022). Effects of isoinertial or machine-based strength training on performance in tennis players. *Biology of Sport*, 39(3), 505–513.
- Cohen, D. B., Mont, M. A., Campbell, K. R., Vogelstein, B. N., & Loewy, J. W. (1994). Upper Extremity Physical Factors Affecting Tennis Serve Velocity. *The American Journal of Sports Medicine*, 22(6), 746–750. <https://doi.org/10.1177/036354659402200604>

- Cools, A. M., Palmans, T., & Johansson, F. R. (2014). Age-Related, Sport-Specific Adaptions of the Shoulder Girdle in Elite Adolescent Tennis Players. *Journal of Athletic Training*, 49(5), 647–653. <https://doi.org/10.4085/1062-6050-49.3.02>
- Davey, P. R., Thorpe, R. D., & Williams, C. (2002). Fatigue decreases skilled tennis performance. *Journal of Sports Sciences*, 20(4), 311–318. <https://doi.org/10.1080/026404102753576080>
- Delgado-García, G., Vanrenterghem, J., Muñoz-García, A., Molina-Molina, A., & Soto-Hermoso, V. M. (2019). Does stroke performance in amateur tennis players depend on functional power generating capacity? *The Journal of Sports Medicine and Physical Fitness*, 59(5). <https://doi.org/10.23736/S0022-4707.18.08518-3>
- Dossena, F., Rossi, C., Torre, A. L., & Bonato, M. (2018). The role of lower limbs during tennis serve. *The Journal of Sports Medicine and Physical Fitness*, 3. <https://doi.org/10.23736/S0022-4707.16.06685-8>
- Ebben, W. P. (2002). Complex training: A brief review. *Journal of Sports Science and Medicine*, 1, 42–46.
- Elliott, B. (2006). Biomechanics and tennis. *British Journal of Sports Medicine*, 40(5), 392–396. <https://doi.org/10.1136/bjism.2005.023150>
- Elliott, B., Marshall, R., & Noffal, G. (1995). Contributions of Upper Limb Segment Rotations during the Power Serve in Tennis. *Journal of Applied Biomechanics*, 11(4), 433–442. <https://doi.org/10.1123/jab.11.4.433>
- Fernandez-Fernandez, J., De Villarreal, E. S., Sanz-Rivas, D., & Moya, M. (2016). The Effects of 8-Week Plyometric Training on Physical Performance in Young Tennis Players. *Pediatric Exercise Science*, 28(1), 77–86.

<https://doi.org/10.1123/pes.2015-0019>

Fernandez-Fernandez, J., Ellenbecker, T., Sanz-Rivas, D., Ulbricht, A., & Ferrauti, A. (2013). Effects of a 6-Week Junior Tennis Conditioning Program on Service Velocity. *Journal of Sports Science and Medicine*, *12*, 232–239.

Fernandez-Fernandez, J., Granacher, U., Sanz-Rivas, D., Sarabia Marín, J. M., Hernandez-Davo, J. L., & Moya, M. (2018). Sequencing Effects of Neuromuscular Training on Physical Fitness in Youth Elite Tennis Players: *Journal of Strength and Conditioning Research*, *32*(3), 849–856.
<https://doi.org/10.1519/JSC.0000000000002319>

Fernandez-Fernandez, J., Nakamura, F. Y., Moreno-Perez, V., Lopez-Valenciano, A., Del Coso, J., Gallo-Salazar, C., Barbado, D., Ruiz-Perez, I., & Sanz-Rivas, D. (2019). Age and sex-related upper body performance differences in competitive young tennis players. *PLOS ONE*, *14*(9), e0221761.
<https://doi.org/10.1371/journal.pone.0221761>

Fernandez-Fernandez, J., Sanz-Rivas, D., & Mendez-Villanueva, A. (2009). A Review of the Activity Profile and Physiological Demands of Tennis Match Play: *Strength and Conditioning Journal*, *31*(4), 15–26.
<https://doi.org/10.1519/SSC.0b013e3181ada1cb>

Fernandez-Fernandez, J., Ulbricht, A., & Ferrauti, A. (2014). Fitness testing of tennis players: How valuable is it? *British Journal of Sports Medicine*, *48*(Suppl 1), i22–i31. <https://doi.org/10.1136/bjsports-2013-093152>

Ferrauti, A., & Bastiaens, K. (2007). Short-term effects of light and heavy load interventions on service velocity and precision in elite young tennis players. *British Journal of Sports Medicine*, *41*(11), 750–753.
<https://doi.org/10.1136/bjism.2007.036855>

- Fett, J., Ulbricht, A., & Ferrauti, A. (2020). Impact of Physical Performance and Anthropometric Characteristics on Serve Velocity in Elite Junior Tennis Players: *Journal of Strength and Conditioning Research*, 34(1), 192–202. <https://doi.org/10.1519/JSC.0000000000002641>
- Finlay, M. J., Bridge, C. A., Greig, M., & Page, R. M. (2021). Upper-Body Post-activation Performance Enhancement for Athletic Performance: A Systematic Review with Meta-analysis and Recommendations for Future Research. *Sports Medicine*. <https://doi.org/10.1007/s40279-021-01598-4>
- Fitzpatrick, A., Stone, J. A., Choppin, S., & Kelley, J. (2019). Important performance characteristics in elite clay and grass court tennis match-play. *International Journal of Performance Analysis in Sport*, 19(6), 942–952. <https://doi.org/10.1080/24748668.2019.1685804>
- Fleisig, G., Nicholls, R., Elliott, B., & Escamilla, R. (2003). Tennis: Kinematics used by world class tennis players to produce high-velocity serves. *Sports Biomechanics*, 2(1), 51–64. <https://doi.org/10.1080/14763140308522807>
- Galé-Ansodi, C., Castellano, J., & Usabiaga, O. (2017). Physical profile of young tennis players in the tennis match-play using global positioning systems. *Journal of Physical Education and Sport*, 17(2), 826–832.
- Gale-Watts, A. S., & Nevill, A. M. (2016). From endurance to power athletes: The changing shape of successful male professional tennis players. *European Journal of Sport Science*, 16(8), 948–954. <https://doi.org/10.1080/17461391.2016.1192690>
- Gallo-Salazar, C., Del Coso, J., Barbado, D., Lopez-Valenciano, A., Santos-Rosa, F. J., Sanz-Rivas, D., Moya, M., & Fernandez-Fernandez, J. (2017). Impact of a competition with two consecutive matches in a day on physical

- performance in young tennis players. *Applied Physiology, Nutrition, and Metabolism*, 42(7), 750–756. <https://doi.org/10.1139/apnm-2016-0540>
- Gallo-Salazar, C., Del Coso, J., Sanz-Rivas, D., & Fernandez-Fernandez, J. (2019). Game Activity and Physiological Responses of Young Tennis Players in a Competition With 2 Consecutive Matches in a Day. *International Journal of Sports Physiology and Performance*, 14(7), 887–893. <https://doi.org/10.1123/ijsp.2018-0234>
- Gelen, E., Dede, M., Bingul, B. M., Bulgan, C., & Aydin, M. (2012). Acute effects of static stretching, dynamic exercises, and high volume upper extremity plyometric activity on tennis serve performance. *Journal of Sports Science and Medicine*, 11, 600–605.
- Genevois, C., Fracan, B., Creveaux, T., Hautier, C., & Rogowski, I. (2013). Effects of Two Training Protocols on the Forehand Drive Performance in Tennis: *Journal of Strength and Conditioning Research*, 27(3), 677–682. <https://doi.org/10.1519/JSC.0b013e31825c3290>
- Genevois, C., Reid, M., Rogowski, I., & Crespo, M. (2015). Performance Factors Related to the Different Tennis Backhand Groundstrokes: A Review. *Journal of Sports Science and Medicine*, 14(1), 194–202.
- Gescheit, D. T., Cormack, S. J., Reid, M., & Duffield, R. (2015). Consecutive Days of Prolonged Tennis Match Play: Performance, Physical, and Perceptual Responses in Trained Players. *International Journal of Sports Physiology and Performance*, 10(7), 913–920. <https://doi.org/10.1123/ijsp.2014-0329>
- Gillet, E., Leroy, D., Thouvarecq, R., & Stein, J.-F. (2009). A Notational Analysis of Elite Tennis Serve and Serve-Return Strategies on Slow Surface: *Journal of Strength and Conditioning Research*, 23(2), 532–539.

<https://doi.org/10.1519/JSC.0b013e31818efe29>

Girard, O. (2006). Changes in exercise characteristics, maximal voluntary contraction, and explosive strength during prolonged tennis playing. *British Journal of Sports Medicine*, 40(6), 521–526.
<https://doi.org/10.1136/bjism.2005.023754>

Girard, O., Lattier, G., Maffiuletti, N. A., Micallef, J.-P., & Millet, G. P. (2008). Neuromuscular fatigue during a prolonged intermittent exercise: Application to tennis. *Journal of Electromyography and Kinesiology*, 18(6), 1038–1046.
<https://doi.org/10.1016/j.jelekin.2007.05.005>

Girard, O., Micallef, J.-P., & Millet, G. P. (2005). Lower-Limb Activity during the Power Serve in Tennis: Effects of Performance Level. *Medicine & Science in Sports & Exercise*, 37(6), 1021–1029.

Girard, O., & Millet, G. P. (2009). Physical Determinants of Tennis Performance in Competitive Teenage Players: *Journal of Strength and Conditioning Research*, 23(6), 1867–1872.
<https://doi.org/10.1519/JSC.0b013e3181b3df89>

Girard, O., Racinais, S., Micallef, J.-P., & Millet, G. P. (2011). Spinal modulations accompany peripheral fatigue during prolonged tennis playing: Spinal reflexes in tennis. *Scandinavian Journal of Medicine & Science in Sports*, 21(3), 455–464. <https://doi.org/10.1111/j.1600-0838.2009.01032.x>

Hayes, M. J., Spits, D. R., Watts, D. G., & Kelly, V. G. (2021). Relationship Between Tennis Serve Velocity and Select Performance Measures. *Journal of Strength and Conditioning Research*, 35(1), 190–197.
<https://doi.org/10.1519/JSC.0000000000002440>

Hernández-Davó, J. L., Moreno, F. J., Sanz-Rivas, D., Hernández-Davó, H., Coves,

- Á., & Caballero, C. (2019). Variations in kinematic variables and performance in the tennis serve according to age and skill level. *International Journal of Performance Analysis in Sport*, 19(5), 749–762. <https://doi.org/10.1080/24748668.2019.1653036>
- Hoppe, M. W., Baumgart, C., Bornefeld, J., Sperlich, B., Freiwald, J., & Holmberg, H.-C. (2014). Running Activity Profile of Adolescent Tennis Players During Match Play. *Pediatric Exercise Science*, 26(3), 281–290. <https://doi.org/10.1123/pes.2013-0195>
- Johnson, C., & McHugh, M. (2006). Performance demands of professional male tennis players. *British Journal of Sports Medicine*, 40(8), 696–699. <https://doi.org/10.1136/bjism.2005.021253>
- Kalkhoven, J. T., & Watsford, M. L. (2018). The relationship between mechanical stiffness and athletic performance markers in sub-elite footballers. *Journal of Sports Sciences*, 36(9), 1022–1029. <https://doi.org/10.1080/02640414.2017.1349921>
- Kibler, W. B., Chandler, T. J., Shapiro, R., & Conuel, M. (2007). Muscle activation in coupled scapulohumeral motions in the high performance tennis serve. *British Journal of Sports Medicine*, 41(11), 745–749. <https://doi.org/10.1136/bjism.2007.037333>
- Ko, C.-Y., Choi, H.-J., Ryu, J., & Kim, G. (2018). Between-day reliability of MyotonPRO for the non-invasive measurement of muscle material properties in the lower extremities of patients with a chronic spinal cord injury. *Journal of Biomechanics*, 73, 60–65. <https://doi.org/10.1016/j.jbiomech.2018.03.026>
- Kovacs, M. S. (2006). Applied physiology of tennis performance. *British Journal of Sports Medicine*, 40(5), 381–386. <https://doi.org/10.1136/bjism.2005.023309>

- Kovacs, M. S., & Ellenbecker, T. S. (2011). A Performance Evaluation of the Tennis Serve: Implications for Strength, Speed, Power, and Flexibility Training: *Strength and Conditioning Journal*, 33(4), 22–30. <https://doi.org/10.1519/SSC.0b013e318225d59a>
- Kovalchik, S. A., & Reid, M. (2017). Comparing Matchplay Characteristics and Physical Demands of Junior and Professional Tennis Athletes in the Era of Big Data. *Journal Sports Science and Medicine*, 16(4), 489–497.
- Kraemer, W. J., H??Kkinen, K., Travis Triplett-Mcbride, N., Fry, A. C., Perry Koziris, L., Ratamess, N. A., Bauer, J. E., Volek, J. S., Mcconnell, T., Newton, R. U., Gordon, S. E., Cummings, D., Hauth, J., Pullo, F., Michael Lynch, J., Mazzetti, S. A., & Knuttgen, H. G. (2003). Physiological Changes with Periodized Resistance Training in Women Tennis Players: *Medicine & Science in Sports & Exercise*, 35(1), 157–168. <https://doi.org/10.1097/00005768-200301000-00024>
- Kraemer, W. J., Ratamess, N., Fry, A. C., Triplett-McBride, T., Koziris, L. P., Bauer, J. A., Lynch, J. M., & Fleck, S. J. (2000). Influence of Resistance Training Volume and Periodization on Physiological and Performance Adaptations in Collegiate Women Tennis Players. *The American Journal of Sports Medicine*, 28(5), 626–633. <https://doi.org/10.1177/03635465000280050201>
- Kraemer, W. J., Triplett, N. T., Fry, A. C., koziris, L. P., Bauer, J. E., Lynch, J. M., McConnell, T., Newton, R. U., Gordon, S. E., Nelson, R. C., & Knuttgen, H. G. (1995). An In-Depth Sports Medicine Profile of Women College Tennis Players. *Journal of Sport Rehabilitation*, 4(2), 79–98. <https://doi.org/10.1123/jsr.4.2.79>
- Landlinger, J., Lindinger, S. J., Stöggl, T., Wagner, H., & Müller, E. (2010).

- Kinematic differences of elite and high-performance tennis players in the cross court and down the line forehand. *Sports Biomechanics*, 9(4), 280–295. <https://doi.org/10.1080/14763141.2010.535841>
- Landlinger, J., Stöggel, T., Lindinger, S., Wagner, H., & Müller, E. (2012). Differences in ball speed and accuracy of tennis groundstrokes between elite and high-performance players. *European Journal of Sport Science*, 12(4), 301–308. <https://doi.org/10.1080/17461391.2011.566363>
- Lloyd, R. S., Cronin, J. B., Faigenbaum, A. D., Haff, G. G., Howard, R., Kraemer, W. J., Micheli, L. J., Myer, G. D., & Oliver, J. L. (2016). National Strength and Conditioning Association Position Statement on Long-Term Athletic Development. *Journal of Strength and Conditioning Research*, 30(6), 1491–1509. <https://doi.org/10.1519/JSC.0000000000001387>
- Maquirriain, J., Baglione, R., & Cardey, M. (2016). Male professional tennis players maintain constant serve speed and accuracy over long matches on grass courts. *European Journal of Sport Science*, 16(7), 845–849. <https://doi.org/10.1080/17461391.2016.1156163>
- Maroto-Izquierdo, S., García-López, D., Fernandez-Gonzalo, R., Moreira, O. C., González-Gallego, J., & de Paz, J. A. (2017). Skeletal muscle functional and structural adaptations after eccentric overload flywheel resistance training: A systematic review and meta-analysis. *Journal of Science and Medicine in Sport*, 20(10), 943–951. <https://doi.org/10.1016/j.jsams.2017.03.004>
- Martin, C., Bideau, B., Delamarche, P., & Kulpa, R. (2016). Influence of a Prolonged Tennis Match Play on Serve Biomechanics. *PLOS ONE*, 11(8), e0159979. <https://doi.org/10.1371/journal.pone.0159979>
- Martin, C., Kulpa, R., Delamarche, P., & Bideau, B. (2013). Professional tennis

players' serve: Correlation between segmental angular momentums and ball velocity. *Sports Biomechanics*, 12(1), 2–14.
<https://doi.org/10.1080/14763141.2012.734321>

Melugin, H. P., Smart, A., Verhoeven, M., Dines, J. S., & Camp, C. L. (2021). The Evidence Behind Weighted Ball Throwing Programs for the Baseball Player: Do They Work and Are They Safe? *Current Reviews in Musculoskeletal Medicine*, 14(1), 88–94. <https://doi.org/10.1007/s12178-020-09686-0>

Mendez-Villanueva, A., Fernandez-Fernandez, J., & Bishop, D. (2007). Exercise-induced homeostatic perturbations provoked by singles tennis match play with reference to development of fatigue. *British Journal of Sports Medicine*, 41(11), 717–722. <https://doi.org/10.1136/bjism.2007.037259>

Mont, M. A., Cohen, D. B., Campbell, K. R., Gravare, K., & Mathur, S. K. (1994). Isokinetic Concentric Versus Eccentric Training of Shoulder Rotators with Functional Evaluation of Performance Enhancement in Elite Tennis Players. *The American Journal of Sports Medicine*, 22(4), 513–517. <https://doi.org/10.1177/036354659402200413>

Montoya, B. S., Brown, L. E., Coburn, J. W., & Zinder, S. M. (2009). Effect of Warm-up With Different Weighted Bats on Normal Baseball Bat Velocity. *Journal of Strength and Conditioning Research*, 23(5), 1566–1569. <https://doi.org/10.1519/JSC.0b013e3181a3929e>

Moreno-Pérez, V., López-Samanes, Á., Domínguez, R., Fernández-Elías, V. E., González-Frutos, P., Fernández-Ruiz, V., Pérez-López, A., & Fernández-Fernández, J. (2019). Acute effects of a single tennis match on passive shoulder rotation range of motion, isometric strength and serve speed in professional tennis players. *PLOS ONE*, 14(4), e0215015.

<https://doi.org/10.1371/journal.pone.0215015>

- Moreno-Pérez, V., Moreside, J., Barbado, D., & Vera-Garcia, F. J. (2015). Comparison of shoulder rotation range of motion in professional tennis players with and without history of shoulder pain. *Manual Therapy, 20*(2), 313–318. <https://doi.org/10.1016/j.math.2014.10.008>
- Nesbit, S. M., Serrano, M., & Elzinga, M. (2008). The role of knee positioning and range-of-motion on the closed-stance forehand tennis swing. *Journal of Sports Science and Medicine, 7*, 117–124.
- O'Donoghue, P., & Ingram, B. (2001). A notational analysis of elite tennis strategy. *Journal of Sports Sciences, 19*(2), 107–115. <https://doi.org/10.1080/026404101300036299>
- Ojala, T., & Häkkinen, K. (2013). Effects of the Tennis Tournament on Players' Physical Performance, Hormonal Responses, Muscle Damage and Recovery. *Journal of Sports Science and Medicine, 12*(2), 240–248.
- Palmer, K., Jones, D., Morgan, C., & Zeppieri, G. (2018). Relationship Between Range of Motion, Strength, Motor Control, Power, and the Tennis Serve in Competitive-Level Tennis Players: A Pilot Study. *Sports Health: A Multidisciplinary Approach, 10*(5), 462–467. <https://doi.org/10.1177/1941738118785348>
- Pardos-Mainer, E., Ustero-Pérez, O., & Gonzalo-Skok, O. (2017). Efectos de un entrenamiento pliométrico en extremidades superiores e inferiores en el rendimiento físico en jóvenes tenistas. [Effects of upper and lower body plyometric training on physical performance in young tennis players]. *RICYDE. Revista internacional de ciencias del deporte, 13*(49), 225–243. <https://doi.org/10.5232/ricyde2017.04903>

- Perri, T., Norton, K. I., Bellenger, C. R., & Murphy, A. P. (2018). Training loads in typical junior-elite tennis training and competition: Implications for transition periods in a high-performance pathway. *International Journal of Performance Analysis in Sport*, 18(2), 327–338. <https://doi.org/10.1080/24748668.2018.1475198>
- Pluim, B. M. (2006). Tennis injuries: Occurrence, aetiology, and prevention. *British Journal of Sports Medicine*, 40(5), 415–423. <https://doi.org/10.1136/bjism.2005.023184>
- Pruyn, E. C., Watsford, M., & Murphy, A. (2014). The relationship between lower-body stiffness and dynamic performance. *Applied Physiology, Nutrition, and Metabolism*, 39(10), 1144–1150. <https://doi.org/10.1139/apnm-2014-0063>
- Pugh, S., Kovaleski, J., Heitman, R., & Gilley, W. (2003). Upper and lower body strength in relation to ball speed during a serve by male collegiate tennis players. *Perceptual and Motor Skills*, 97, 867–872.
- Reid, M., Elliott, B., & Alderson, J. (2008). Lower-Limb Coordination and Shoulder Joint Mechanics in the Tennis Serve. *Medicine & Science in Sports & Exercise*, 40(2), 308–315. <https://doi.org/10.1249/mss.0b013e31815c6d61>
- Reid, M., Giblin, G., & Whiteside, D. (2015). A kinematic comparison of the overhand throw and tennis serve in tennis players: How similar are they really? *Journal of Sports Sciences*, 33(7), 713–723. <https://doi.org/10.1080/02640414.2014.962572>
- Reid, M., & Schneiker, K. (2008). Strength and conditioning in tennis: Current research and practice. *Journal of Science and Medicine in Sport*, 11(3), 248–256. <https://doi.org/10.1016/j.jsams.2007.05.002>
- Reinold, M. M., Macrina, L. C., Fleisig, G. S., Aune, K., & Andrews, J. R. (2018).

- Effect of a 6-Week Weighted Baseball Throwing Program on Pitch Velocity, Pitching Arm Biomechanics, Passive Range of Motion, and Injury Rates. *Sports Health: A Multidisciplinary Approach*, 10(4), 327–333. <https://doi.org/10.1177/1941738118779909>
- Roetert, E. P., Ellenbecker, T. S., & Reid, M. (2009). Biomechanics of the Tennis Serve: Implications for Strength Training: *Strength and Conditioning Journal*, 31(4), 35–40. <https://doi.org/10.1519/SSC.0b013e3181af65e1>
- Roetert, E. P., Kovacs, M., Knudson, D., & Groppe, J. L. (2009). Biomechanics of the Tennis Groundstrokes: Implications for Strength Training: *Strength and Conditioning Journal*, 31(4), 41–49. <https://doi.org/10.1519/SSC.0b013e3181aff0c3>
- Rota, S., Morel, B., Saboul, D., Rogowski, I., & Hautier, C. (2014). Influence of fatigue on upper limb muscle activity and performance in tennis. *Journal of Electromyography and Kinesiology*, 24(1), 90–97. <https://doi.org/10.1016/j.jelekin.2013.10.007>
- Sanchis-Moysi, J., Idoate, F., Álamo-Arce, D., Calbet, J. A. L., & Dorado, C. (2017). The core musculature in male prepubescent tennis players and untrained counterparts: A volumetric MRI study. *Journal of Sports Sciences*, 35(8), 791–797. <https://doi.org/10.1080/02640414.2016.1189589>
- Sanchis-Moysi, J., Idoate, F., Dorado, C., Alayón, S., & Calbet, J. A. L. (2010). Large Asymmetric Hypertrophy of Rectus Abdominis Muscle in Professional Tennis Players. *PLoS ONE*, 5(12), e15858. <https://doi.org/10.1371/journal.pone.0015858>
- Seitz, L. B., & Haff, G. G. (2016). Factors Modulating Post-Activation Potentiation of Jump, Sprint, Throw, and Upper-Body Ballistic Performances: A Systematic

- Review with Meta-Analysis. *Sports Medicine*, 46(2), 231–240.
<https://doi.org/10.1007/s40279-015-0415-7>
- Sheehan, W. B., Watsford, M. L., & Pickering Rodriguez, E. C. (2019). Examination of the neuromechanical factors contributing to golf swing performance. *Journal of Sports Sciences*, 37(4), 458–466.
<https://doi.org/10.1080/02640414.2018.1505185>
- Sweeney, M., Reid, M., & Elliott, B. (2012). *Lower Limb and Trunk Function in the High Performance Tennis Serve*. 9(1), 9.
- Terraza-Rebollo, M., & Baiget, E. (2021). Acute and delayed effects of strength training in ball velocity and accuracy in young competition tennis players. *PLOS ONE*, 16(12), e0260825. <https://doi.org/10.1371/journal.pone.0260825>
- Terraza-Rebollo, M., Baiget, E., Corbi, F., & Planas Anzano, A. (2017a). Efectos del entrenamiento de fuerza en la velocidad de golpeo en tenistas jóvenes / Effects of Strength Training on Hitting Speed in Young Tennis Players. *Revista Internacional de Medicina y Ciencias de la Actividad Física y del Deporte*, 66(2017). <https://doi.org/10.15366/rimcafd2017.66.009>
- Terraza-Rebollo, M., Baiget, E., Corbi, F., & Planas Anzano, A. (2017b). Efectos del entrenamiento de fuerza en la velocidad de golpeo en tenistas jóvenes / Effects of Strength Training on Hitting Speed in Young Tennis Players. *Revista Internacional de Medicina y Ciencias de la Actividad Física y del Deporte*, 66(2017). <https://doi.org/10.15366/rimcafd2017.66.009>
- Tooth, C., Schwartz, C., Fransolet, C., Tubez, F., Colman, D., Croisier, J.-L., & Forthomme, B. (2020). Influence of scapular dyskinesis, kinesiotaping and fatigue on tennis serve performance. *International Journal of Performance Analysis in Sport*, 20(3), 456–469.

<https://doi.org/10.1080/24748668.2020.1761672>

- Tous-Fajardo, J., Moras, G., Rodríguez-Jiménez, S., Gonzalo-Skok, O., Busquets, A., & Mujika, I. (2016). W5" Test: A simple method for measuring mean power output in the bench press exercise. *European Journal of Sport Science*, *16*(8), 940–947. <https://doi.org/10.1080/17461391.2016.1184318>
- Treiber, F. A., Lott, J., Duncan, J., Slavens, G., & Davis, H. (1998). Effects of Theraband and Lightweight Dumbbell Training on Shoulder Rotation Torque and Serve Performance in College Tennis Players. *The American Journal of Sports Medicine*, *26*(4), 510–515. <https://doi.org/10.1177/03635465980260040601>
- Ulbricht, A., Fernandez-Fernandez, J., Mendez-Villanueva, A., & Ferrauti, A. (2016). Impact of Fitness Characteristics on Tennis Performance in Elite Junior Tennis Players: *Journal of Strength and Conditioning Research*, *30*(4), 989–998. <https://doi.org/10.1519/JSC.0000000000001267>
- Ulrich, G., & Parstorfer, M. (2017). Effects of Plyometric Versus Concentric and Eccentric Conditioning Contractions on Upper-Body Postactivation Potentiation. *International Journal of Sports Physiology and Performance*, *12*(6), 736–741. <https://doi.org/10.1123/ijsp.2016-0278>
- Vaverka, F., & Cernosek, M. (2013). Association between body height and serve speed in elite tennis players. *Sports Biomechanics*, *12*(1), 30–37. <https://doi.org/10.1080/14763141.2012.670664>
- Whiteside, D., Elliott, B., Lay, B., & Reid, M. (2014). The effect of racquet swing weight on serve kinematics in elite adolescent female tennis players. *Journal of Science and Medicine in Sport*, *17*(1), 124–128. <https://doi.org/10.1016/j.jsams.2013.03.001>

Wong, F. K., Keung, J. H., Lau, N. M., Ng, D. K., Chung, J. W., & Chow, D. H. (2014). Effects of Body Mass Index and Full Body Kinematics on Tennis Serve Speed. *Journal of Human Kinetics*, 40(1), 21–28. <https://doi.org/10.2478/hukin-2014-0003>

Wooden, M. J., Greenfield, B., Johanson, M., Litzelman, L., Mundrane, M., & Donatelli, R. A. (1992). Effects of Strength Training on Throwing Velocity and Shoulder Muscle Performance in Teenage Baseball Players. *Journal of Orthopaedic & Sports Physical Therapy*, 15(5), 223–228. <https://doi.org/10.2519/jospt.1992.15.5.223>

