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Femur 3D-DXA Assessment in Female Football Players, Swimmers, and Sedentary Controls

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ABSTRACT

Cortical and trabecular volumetric bone mineral density (vBMD), cortical thickness and surface BMD (sBMD, density-to-thickness ratio) were analyzed in the proximal femur of elite female football players and artistic swimmers using three-dimensional dual-energy X-ray absorptiometry (3D-DXA) software and compared to sedentary controls. Football players had significantly higher ($p < 0.05$) vBMD (mg/cm^3) in the trabecular (263 ± 44) and cortical femur (886 ± 69) than artistic swimmers (224 ± 43 and 844 ± 89) and sedentary controls (215 ± 51 and 841 ± 85). Football players had also higher ($p < 0.05$) cortical thickness (2.12 ± 0.19 mm) and sBMD (188 ± 22 mg/cm^2) compared to artistic swimmers (1.85 ± 0.15 and 156 ± 21) and sedentary controls (1.87 ± 0.16 and 158 ± 23). Artistic swimmers did not show significant differences in any parameter analyzed for 3D-DXA when compared to sedentary controls. The 3D-DXA modeling revealed statistical differences in cortical thickness and vBMD between female athletes engaged in weight-bearing (football) and non-weight bearing (swimming) sports and did not show differences between the non-weight bearing sport and the sedentary controls. 3D-DXA modeling could provide insight into bone remodeling in the sports field, allowing evaluation of femoral trabecular and cortical strength from standard DXA scans.

Introduction

Osteoporosis affects millions of people around the world, mainly postmenopausal women [1]. The disease is characterized by a deterioration of bone microarchitecture, low bone mass, and increased risk of fractures [2]. The current standard clinical evaluation tool for fracture prediction is dual-energy X-ray absorptiometry (DXA) [3]. DXA measurements are limited to two-dimensional evaluation of integral bone mineral mainly at the lumbar spine and proximal femur and, unlike quantitative computed tomography (QCT), cannot differentiate between trabecular and cortical bone compartments. However, the high-dose radiation and cost as well as the limited access to QCT constitute some of the main limitations for its applicability in clinical practice [4]. Recently, a new software has been developed to evaluate the cortical and trabecular volumetric bone mineral density (vBMD) and cortical thickness of the proximal femur in 3D from standard DXA images [5, 6]. This 3D approach is relevant

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since the 3D distribution of the cortical and trabecular bone mass (in kg) and mineral density, i. e., how this bone mass is distributed ($g \cdot cm^{-2}$) in the proximal femur, are critical components in determining fracture resistance [7, 8].

Physical exercise is highly beneficial in terms of increasing BMD and bone mineral content, thereby reducing the risk of osteopenia, which leads to osteoporosis, and reducing the risk of frailty fractures [9]. Exercising during youth is a non-pharmacological preventive strategy, not only to increase muscle strength but also to stimulate bone formation [10]. Some prior studies have compared the effects of various types of exercise in different athletic populations, suggesting that high impact forces experienced by athletes involved in weight bearing sports are more osteogenic than those experienced in non-weight bearing activities [11–17]. The results emphasized that non-weight bearing activities, such as swimming, seems less effective than other exercise in providing a positive effect on bone strength. The potential effect this may have on the future development of osteoporosis is not well defined [16, 18]. Mechanical loads that arise from high impacts or impacts from atypical directions are strong external determinants of structure and strength of the femoral neck and the bone structure, and its specific characteristics have recently been suggested to be the most important factors underlying bone fragility and subsequent fractures, specifically in the femoral neck [19]. Prior studies have demonstrated that inactivity and disuse enhance or compromise the bone quantity and quality, mainly in the cortical compartment [20]. Thus, understanding and quantifying the bone response to loads derived from sports practice would make it possible to evaluate the fracture risks, especially in menopausal women.

It has been shown that cortical thickness and vBMD are critical factors in determining the strength of bone structure and depend on the mechanical stressors along the structure [21]. The standard DXA technique allows quantifying aBMD but cannot assess vBMD, and hence does not provide information on bone geometrical parameters. Although assessing bone structural parameters using 3D-DXA technology is warranted to gather further insight into exercise-induced bone remodeling, no data are available detailing cortical thickness and trabecular and cortical bone mineral density in elite athletes. Therefore, the aim of the present study was to compare, using 3D analysis-DXA, cortical thickness and trabecular bone mineral density in elite female athletes involved in weight bearing and non-weight bearing sports.

Materials and Methods

Participants

A total of 85 elite athletes competing at a high level in their respective sport and 40 healthy controls with a sedentary lifestyle volunteered to participate in this study. Athletes consisted of a weight bearing group of football players (n = 60) and a non-weight bearing group of artistic swimmers (n = 25). According to the recent McKay et al. [22] training and performance Participant Classification Framework to characterize the caliber and training status of an individual or cohort, all participating athletes were in the tier 5 (World Class) group, i. e., “top players within top teams (teams with medal or in the most competitive leagues)”. Inclusion criteria for athletes to participate in the study were as follows: to be over 18 years old, with more than 8 years of sports practice and to have at least 3 years’ experience in high-level competition (World Championships and Olympic Games). Throughout the data collection period, all athletes trained for 12 to 15 hours per week and participated in 1 or 2 competitive events per week. All athletes underwent regular medical examinations and a questionnaire was used to collect data on their physical training, sports and clinical history, drug intake, stress fractures and gynecological history. Medical checkups were conducted at the High-Performance Centre (Sant Cugat del Vallés) medical department every season and conventional DXA bone densitometries at the FC Barcelona Medical Unit. The sedentary controls were selected from the CETIR (Centre for Technical Studies with Radioactive Isotopes, Barcelona, Spain) database, had no formal training, and did not reach the minimum physical activity recommended by the WHO. An epidemiological questionnaire was distributed for gathering information about their activity level as: sedentary lifestyle (occasional or 1 h/week), moderately active (< 5 h/week), and very active lifestyle (> 5 h/week). Only sedentary lifestyle subjects were selected, classified as tier 0 (Sedentary) in the McKay et al. [22] classification, i. e., participants who “do not meet minimum activity guidelines”. The exclusion criteria for all participants were as follows: 1) diagnosis of any medical condition, 2) use of medication known to affect bone metabolism, 3) contraindication for sports practice, 4) menstrual dysfunction, 5) use of oral contraceptives, 6) abnormal food intake.

This study was approved by the Institutional Review Board of Ethics and Clinical Research Committee of CETIR with all procedures conducted in accordance with the Helsinki Declaration. All participants provided informed consent prior to participation.

Nutrition

The diet of the athletes was controlled by nutritionist’s prescription and a follow-up questionnaire used to assess adherence to the prescription. All the athletes were controlled and evaluated monthly by the nutritionists, who determined a balanced diet and the intake of all basic nutrients during the training and competition seasons. The nutritionists evaluated the average energy output, calorie and calcium input, including a detailed 5-day nutritional intake record.

Measurement of BMD and body composition

Dual hip scans were performed using DXA absorptiometry (Lunar iDXA, v12.30; GE Healthcare, Chicago, IL, USA) measuring BMD at the proximal femur according to standard operating procedures [23] with a coefficient of variation of 1 %. Assessment by DXA is the reference method for measuring areal BMD and diagnosing osteopenia according to the WHO classification, specifically assessing the most susceptible sites of osteoporotic fractures, such as the lumbar spine and the neck of the femur [24]. Participants were evaluated in the supine position, with their feet in slight internal rotation for good visibility of the femoral neck. The evaluation was always made by the same technician and following the recommendations from the International Society of Clinical Densitometry [23].

3D-SHAPER software (v2.4; Galgo Medical, Barcelona, Spain) was used to assess the studied parameters from DXA scans of the participants. The method relies on a statistical shape and density model of the proximal femur built from a database of quantitative computed tomography (QCT) images [5]. To maximize the similarity between the volumetric 3D reconstruction and the 2D-DXA images, a reconstruction was performed in an intensity-based 3D-2D personalized registration process [5]. The 3D statistical model was registered onto the DXA scan to obtain a 3D patient-specific model of the proximal femur shape and BMD distribution. 3D-DXA measurements included the vBMD of the cortical and trabecular bone compartments and mean cortical thickness and cortical surface BMD (density-to-thickness ratio, sBMD). All 3D-DXA measurements were performed at the proximal femur. The cortical thickness and density were computed by fitting a mathematical function to the density profile computed along the normal vector at each node of the proximal femur surface mesh [25].

Models and measurements provided by the 3D-DXA software were evaluated by comparing 3D-DXA analysis with measurements performed by QCT. Correlation coefficients (R) between the 3D-DXA and QCT measurements were 0.86, 0.93, and 0.95 for the vBMD at the trabecular, cortical, and integral compartments respectively, and 0.91 for the mean cortical thickness [5].

Statistical analysis

All quantitative variables are presented with means and standard deviations (SD). The Kolmogorov–Smirnov test showed that the sample was normally distributed ($p > 0.05$) for all the variables. For determining differences in 3D-DXA and DXA between groups, one-way ANOVA tests were run using Scheffe's test as a post hoc procedure for multiple comparisons. To compare the volumetric densities between the different groups, the mean 3D-DXA density instance was computed and projected onto the mean femoral shape for the group. A frontal slice was computed for each group for comparison purposes. R 3.3.2 software (www.r-project.org) was used to perform the statistical analysis [26]. Effect size (ES) of the differences between groups (Cohen's d) were also calculated. The magnitude of the differences was considered to be trivial ($ES < 0.20$), small ($0.21 \le ES < 0.60$), moderate ($0.61 \le ES < 1.20$), large ($1.21 \le ES < 2.00$), very large ($2.01 \le ES < 4.00$), and extremely large (≥ 4.00) [27]. All hypothesis tests with p-values lower than 0.05 were considered statistically significant.

Results

The group's means for anthropometric and training data are summarized in ▶ **Table 1**. Football players and artistic swimmers were significantly ($p < 0.05$) taller, lighter, and had a lower fat mass percentage and higher fat-free mass than sedentary controls. Football players were also significantly ($p < 0.05$) heavier than artistic swimmers. The average detailed 5-day caloric and calcium intake record in the football players was 3,600 kcal/day and 1,400 mg/day of calcium while in the artistic swimmers it was 2,034 kcal/day and 943 mg/day, respectively. This intake was homogeneous throughout the season.

▶ **Table 2** shows aBMD measurements. Football players displayed significantly higher aBMD ($p < 0.001$) than artistic swimmers and sedentary controls in all femoral zones with moderate ($ES = 0.99$) to large ($ES = 1.78$) magnitude of the differences. Significantly higher aBMD were also found in artistic swimmers when compared to sedentary controls in the neck ($p = 0.002$, $ES = 0.75$) and trochanter ($p = 0.015$, $ES = 0.57$). Neck Z-score and total femur Z-score were significantly higher ($p < 0.001$) in football players when compared to artistic swimmers and sedentary controls with an ES between 0.94 and 1.60. Finally, artistic swimmers showed a significantly higher neck Z-score when compared to sedentary controls ($p < 0.001$, $ES = 0.67$).

The 3D-DXA proximal femoral measurements are shown in ▶ **Table 3**. Football players had significantly higher vBMD values in the integral, trabecular, and cortical femur when compared to sedentary controls ($p < 0.001$; ES range 0.59 to1.02) and to artistic swimmers ($p < 0.05$; ES range 0.55 to 0.92). Football players also had a higher cortical thickness and sBMD compared to artistic swimmers and sedentary controls ($p < 0.001$, ES range 1.40 to 1.51).

▶ **Fig. 1** shows the color maps depicting the percentages of differences in cortical sBMD of the proximal femur for all pairwise comparisons. The color maps show that the most significant differences were found between football players and sedentary controls (▶ **Fig. 1c**) and football players and artistic swimmers (▶ **Fig. 1a**) in the neck and trochanter zones. Significant differences in the neck are also evident between football players, artistic swimmers, and sedentary controls (▶ **Fig. 1b–c**).

▶ **Table 1** Demographic and training characteristics in female football players, artistic swimmers, and sedentary controls [mean (SD)].

Outcome measures	Sedentary controls (n = 40)	Artistic swimmers (n = 25)	Football players (n = 60)
Age (years)	22.0 (3.1)	20.4 (5.3)	21.9 (4.2)
Height (m)	1.62 (7.4)	1.71 (6.4)[a]	1.69 (7.2)[a]
Body mass (kg)	60.1 (16.7)	56.4 (6.2)	62.6 (9.4)[b]
BMI (kg/m²)	22.8 (5.6)	19.4 (1.5)[a]	21.8 (2.2)[b]
FM (%)	19.5 (8.7)	13.8 (2.6)[a]	14.6 (3.9)[a]
FFM (kg)	37.4 (4.2)	41.1 (4.3)[a]	42.5 (4.5)[a]
FFM arms (kg)	–	4.5 (0.5)	4.2 (0.6)
FFM legs (kg)	–	13.5 (1.7)	15.5 (1.6)[b]
Water training (h/week)	–	36	0
Non-water training(h/week)	–	3	12–15

BMI, body mass index; FM, fat mass; FFM, fat-free mass. *a*: statistically significant differences ($p < 0.05$) versus sedentary controls; *b*: statistically significant differences ($p < 0.05$) versus artistic swimmers.

▶ **Table 2** Areal bone mineral density (aBMD) in neck, trochanter, shaft, and total femur for the three groups studied [mean (SD)].

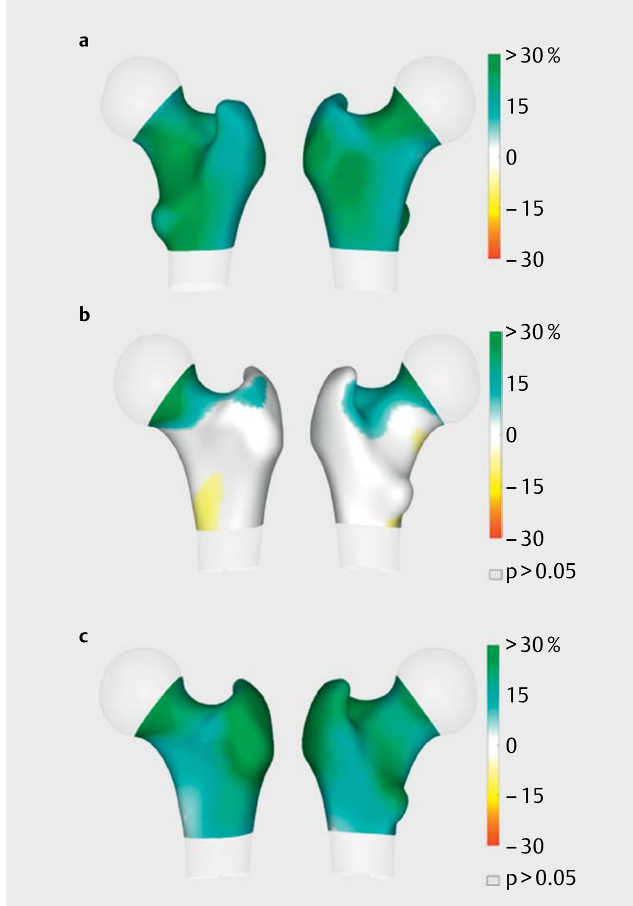
Outcome measures	Sedentary controls (n = 40)	Artistic swimmers (n = 25)	Football players (n = 60)
Femoral neck (g/cm²)	1.010 (0.121)	1.103 (0.131)[a]	1.234 (0.133)[ab]
Femoral trochanter (g/cm²)	0.781 (0.120)	0.856 (0.147)[a]	1.015 (0.140)[ab]
Femoral shaft (g/cm²)	1.221 (0.159)	1.176 (0.158)	1.416 (0.176)[ab]
Femoral total (g/cm²)	1.032 (0.130)	1.034 (0.134)	1.223 (0.146)[ab]
Z-score femoral neck	0.3 (1.0)	1.0 (1.1)[a]	2.1 (1.2)[ab]
Z-score femoral total	0.2 (1.1)	0.3 (1.1)	1.8 (1.2)[ab]

a: statistically significant differences ($p < 0.05$) versus sedentary controls; *b*: statistically significant differences ($p < 0.05$) versus artistic swimmers.

▶ **Table 3** Proximal femoral 3D-DXA measurements for each studied group [mean (SD).

Outcome measures	Sedentary controls (n = 40)	Artistic swimmers (n = 25)	Football players (n = 60)
vBMD Integral (mg/cm³)	369 (65)	373 (56)	422 (52)[ab]
vBMD Trabecular (mg/cm³)	215 (51)	224 (43)	263 (44)[ab]
vBMD Cortical (mg/cm³)	841 (85)	844 (89)	886 (69)[ab]
Cortical thickness (mm)	1.87 (0.16)	1.85 (0.15)	2.12 (0.19)[ab]
sBMD (mg/cm²)	158 (23)	156 (21)	188 (22)[ab]

vBMD, volumetric bone mineral density; sBMD, surface bone mineral density (ratio between density and thickness). *a*: statistically significant differences ($p < 0.05$) versus sedentary controls; *b*: statistically significant differences ($p < 0.05$) versus artistic swimmers.



▶ **Fig. 1** Color scale showing the distribution of cortical surface bone mineral density (sBMD) average differences between the different groups studied in the proximal femur. Panel **a**, football players versus artistic swimmers; **b**, artistic swimmers versus sedentary controls; **c**, football players versus sedentary controls. The intense green and blue color expresses significant differences in cortical bone sBMD between groups. Right panel: anterior view (Panel **a**) and posterior view (Panel **b** and **c**). Left panel: anterior view (Panel **b** and **c**) and posterior view.

Discussion

Main findings

The present study used standard DXA to compare aBMD in the femoral neck, trochanter, and shaft between elite female football players and artistic swimmers as well as a sedentary control group. Moreover, new 3D-DXA software calculated sBMD, cortical thickness, and proximal femoral vBMD at the trabecular and cortical levels. We obtained significantly higher mean aBMD, sBMD, vBMD, and cortical thickness values in the athletes involved in the weight bearing sport (football players) compared to non-weight bearing sport practitioners (artistic swimmers) and to sedentary controls at all measured sites. Overall, the magnitude of the differences, as deduced from Cohen's d ES, ranged from moderate to large when comparing football players to swimmers or sedentary controls, whereas the comparisons between swimmers and sedentary controls displayed small to moderate ES magnitude.

Artistic swimmers

Several authors [16, 18, 28] reported a neutral or even negative effect of swimming in neck femoral aBMD (analyzed with DXA) and vBMD (analyzed with QCT), similar to sedentary controls and lower than in impact or anti-gravitational sports. Our results provide additional evidence to these previous findings by using 3D-DXA, showing that artistic swimmers had femoral neck, trochanter, and shaft aBMD and trabecular and cortical vBMD values significantly lower than those of football players and similar to sedentary controls. These results are indicative of the positive bone adaptations generated from impact forces in football. Moreover, the lack of impact activities in swimming and the hypogravitational medium where this sport is performed from an early age [15, 29] could also contribute to explain these findings. Regarding this subject, a recent study performed in our laboratory in artistic swimmers has shown the importance of considering a complementary workout out of the water to improve femoral neck aBMD [30]. Moreover, research performed on professional ballet dancers using 3D-DXA modeling revealed a significantly higher aBMD, trabecular and cortical vBMD, and cortical thickness compared to sedentary controls [31]. Artistic swimmers perform similar movements and have analogous aesthetic characteristics as ballet dancers except for the weight-bearing forces generated by the impacts with the floor, which could explain the higher bone density values found in ballet dancers. However, from our results we can deduce some positive bone adaptations in artistic swimmers, since a higher aBMD in neck ($p = 0.002$, ES = 0.75) and trochanter ($p = 0.015$, ES = 0.57) and significantly higher neck Z-score ($p < 0.001$, ES = 0.67) compared to sedentary controls were found.

Football players

Football is a sport with special biomechanical characteristics: changes of direction, speed, jumps, and kicks that offers additional mechanical stress in lower extremities due to the force of reaction against the ground during these actions. The repetitive high impact exercises generated by this sport increase cortical bone density making the bones more resistant to fractures [32]. It is well documented that football practice in girls during childhood and adolescence provides positive effects on aBMD compared to sedentary behaviors and other sports such swimming, especially at the femoral neck and trochanter, which are the most sensitive areas to the mechanical stress of the football actions [33]. Our results are in line with these previous findings showing that football players had the highest femoral neck, trochanter, and shaft aBMD. Moreover, the 3D-DXA modeling adds further data on the effect of this sport on trabecular and cortical vBMD, sBMD, and cortical thickness in the proximal femur. The differences in bone mass between femoral sub regions depend on the magnitude and the directions of the forces contacting the hip. Thus, vertical impacts of high magnitude favor aBMD gain at the superior femoral neck while high and moderate impacts from odd directions induced larger bone mass gain rates at the anterior and posterior sub-regions [34], and exercise involving hip flexion targets mechanical loading in the femoral neck [8]. The presence of these different types of mechanical loading in football players may provide femoral neck strength at the vulnerable regions during aging resulting in vBMD, sBMD, and cortical thickness gains in adulthood.

3D-DXA modeling in elite sport

Comparisons with previous studies are difficult to conduct considering the lack of studies reporting descriptions of trabecular and cortical femur characteristics using 3D-DXA modeling in elite athletes. The vast majority of descriptive and exercise intervention studies have relied upon aBMD measures derived from DXA or QCT for estimating vBMD [15]. A study that evaluated models and measurements provided by the 3D-DXA and QCT showed that the correlation coefficients (R) for the vBMD between both methodologies were 0.86, 0.93, and 0.95 at the trabecular, cortical, and integral femur respectively, and 0.91 for the mean cortical thickness [5]. 3D-DXA provides a detailed analysis of the proximal femur, including a separate assessment of the cortical layer and trabecular macrostructure. Besides that, the contribution of altered bone geometry to fracture risk is unappreciated by clinical assessment using DXA, because this technique cannot distinguish between cortical and trabecular bone. Conversely, 3D imaging methods can measure the femoral shape, the trabecular macrostructure, and the cortex separately, allowing independent evaluation of the fragility fracture of each zone [5]. There is data in populations other than elite athletes, such as post-menopausal women, in which 3D-DXA-derived measurements could provide additional indicators to improve patient monitoring in clinical practice [35]. The modeling technique has also been used to improve the prediction of hip fracture risk in osteoporosis patients [36], to study the evolution of bone parameters in patients with recent spinal cord injury [4], and to assess trabecular and cortical characteristics of the hip in women with high bone mass [26]. In all these cases, 3D-DXA has been postulated as a good tool for following up bone strength and the effects of different therapies. Considering these previous data on this topic, we believe that 3D-DXA modeling might be a promising approach to quantify cortical thickness and vBMD using clinical routine imaging techniques to be applied in the sports field [37].

Limitations and strengths

The present study has two main limitations. First, the inaccuracy of the 3D-DXA software algorithms to estimate a 3D shape from a 2D image could presumably be affected by the variations in hip rotation. Second, since 3D-DXA has not been specifically evaluated for athletes, its validity in individual cases should be interpreted with caution. The present study has also two strengths. First, the participants were classified as elite World Class [22] female athletes since football players were from a team (FC Barcelona) participating in the most competitive leagues and the artistic swimmers were part of the national Spanish artistic swimming team (medalist in world championships and the Olympic Games), thus representing a population where few studies have been published. Second, the 3D-DXA technology is based on standard hip DXA scans, allowing the use of retrospective data for obtaining measurements of vBMD of the proximal femur.

Conclusion

3D-DXA modeling of the proximal femur in elite female athletes participating in weight bearing (football) and non-weight bearing (artistic swimming) sports, and compared to sedentary controls, showed that football players had the highest trabecular and cortical vBMD, sBMD, and cortical thickness. Artistic swimmers showed no significant differences compared to sedentary controls in any bone mineral density-related parameter as a result of the absence of impact forces during swimming. 3D-DXA modeling could provide insight into bone remodeling in the sports field, allowing evaluation of femoral trabecular and cortical strength from standard DXA scans.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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