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Musculoskeletal Asymmetry in Football Athletes: A Product of Limb Function over Time

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ABSTRACT

HART, N. H., S. NIMPHIUS, J. WEBER, T. SPITERI, T. RANTALAINEN, M. DOBBIN, and R. U. NEWTON. Musculoskeletal Asymmetry in Football Athletes: A Product of Limb Function over Time. *Med. Sci. Sports Exerc.*, Vol. 48, No. 7, pp. 1379–1387, 2016.

Purpose: Asymmetrical loading patterns are commonplace in football sports. Our aim was to examine the influence of training age and limb function on lower-body musculoskeletal morphology. **Methods:** Fifty-five elite football athletes were stratified into less experienced (≤ 3 yr; $n = 27$) and more experienced (> 3 yr; $n = 28$) groups by training age. All athletes underwent whole-body dual-energy x-ray absorptiometry scans and lower-body peripheral quantitative computed tomography tibial scans on the kicking and support limbs.

Results: Significant interactions between training age and limb function were evident across all skeletal parameters ($F_{16, 91} = 0.182$, $P = 0.031$, Wilks $\Lambda = 0.969$). Asymmetries between limbs were significantly larger in the more experienced players than the less experienced players for tibial mass ($P \leq 0.044$, $d \geq 0.50$), total cross-sectional area ($P \leq 0.039$, $d \geq 0.53$), and stress-strain indices ($P \leq 0.050$, $d \geq 0.42$). No significant asymmetry was evident for total volumetric density. More experienced players also exhibited greater lower-body tibial mass ($P \leq 0.001$, $d \geq 1.22$), volumetric density ($P \leq 0.009$, $d \geq 0.79$), cross-sectional area ($P \leq 0.387$, $d \geq 0.21$), stress-strain indices ($P \leq 0.012$, $d \geq 0.69$), fracture loads ($P \leq 0.018$, $d \geq 0.57$), and muscle mass and cross-sectional area ($P \leq 0.016$, $d \geq 0.68$) than less experienced players.

Conclusions: Asymmetries were evident in athletes as a product of limb function over time. Chronic exposure to routine high-impact gravitational loads afforded to the support limb preferentially improved bone mass and structure (cross-sectional area and cortex thickness) as potent contributors to bone strength relative to the high-magnitude muscular loads predominantly afforded to the kicking limb. **Key Words:** ADAPTATION, BONE, MUSCLE, IMBALANCE, LOADING, MORPHOLOGY

Professional athletes engage in full-time training and competitive workloads at the elite level, striving to maximize physical capacity, heighten performance and minimize injury in the pursuit of success (26). Practitioners subsequently prescribe training programs using various exercise modalities to explicitly increase musculoskeletal resilience; driven to optimize muscle size, strength, power and endurance concomitantly with bone size, strength and fatigue resistance. Accordingly, professional athletes engage in structured combinations of locomotive exercise (walking, running, and changing direction), resistance exercise (weight training), and impact exercise (jumping, kicking, and tackling) in controlled training environments to better withstand the volatile and unpredictable

competitive environments of their sport. These annual periodized training programs capitalize on the variety of myogenic and osteogenic benefits afforded to the musculoskeletal system through numerous, concurrently prescribed training modalities in addition to the plethora of benefits provided through sports participation, extrapolated over concurrent annual cycles throughout a footballer's career to develop a robust and resilient athlete over time.

Football sports are characterized by their odd-impact loading profiles (28,30,32), involving rapid turns, stops, jumps, tackles, accelerations, decelerations, and lateral movements while sprinting, running, or kicking, simultaneously requiring footballers to constantly react to situational events within the field of play (2,15,26). Consequently, footballers develop and selectively use preferred limbs for most game-based activities, such as kicking, changing direction, and jumping (1,2,12,13,15). Most prevalent is the kicking skill, which requires players to routinely adopt unipedal postures to powerfully strike the ball with the kicking limb while forcefully planting the support limb to provide stability, balance, and support (1,13). Although it is advantageous to be equally proficient across both limbs, time, space, and accuracy constraints place pressure on players to use their most dominant movement patterns to produce desirable outcomes. Accordingly,

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asymmetrical loading patterns are commonplace in football sports, transmitting differential strain magnitudes, rates, and distributions of varying frequencies uniquely to each limb. In particular, the support limb experiences combinations of high-grade gravitational, impact, and muscular forces simultaneously (1,31), whereas the kicking limb experiences high-grade muscular forces when swinging the limb and low-grade impact forces when striking the ball (2,12,13).

Dynamic, fast-paced, and multidimensional environments predispose athletes to unpredictable, volatile, and asymmetrical lower-body loading patterns (13,16,26,39). As a result, compressive, torsional, transverse, and tensile loads are differentially applied in combination with and in isolation from hard tissue structures of each limb within football athletes, exposing the skeleton to stimuli that can lead to positive bone- and site-specific adaptations or subsequent stress reactions and fractures (7,27,28,30,32). In particular, muscle and bone strength adaptations are context specific to loading histories; thus, it is logical to expect athletes with higher training ages will illustrate higher musculoskeletal characteristics as a result of greater material and structural adaptations than athletes with lower training ages (18,23,33). Similarly, it is logical to expect a level of lateral dominance and asymmetrical adaptation in elite, high-performance football athletes on the basis of preferential function (12,13,15,16,39). Repetitious asymmetrical activities have been shown to generate asymmetrical hypertrophic responses in muscle (12,13,16,39) and in the hard tissue of athletes in sports such as tennis or jumpers (11,19,20,24). However, it is not yet known whether similar long-term adaptations are evident in lower-body hard tissue structures of Australian Football athletes and how these different long-term loading profiles influence lower-body skeletal morphology and bone strength over time.

Musculoskeletal adaptability to mechanical load provides strength and conditioning practitioners with important modifiable characteristics to screen, monitor, and target with exercise interventions. As muscle–bone strength is a measurable and trainable athletic feature, research is required to characterize lower-body musculoskeletal profiles of football athletes. There were three objectives of this research: 1) to provide a descriptive set of normative and comparative material, structural, and strength values of lower-body musculoskeletal properties in elite Australian footballers; 2) to identify the influence of training exposure (training age) on lower-limb muscle and bone morphology; and 3) to establish whether developmental laterality exists as a result of limb function during sport participation in Australian Football.

MATERIAL AND METHODS

Subjects

Sixty ($n = 60$) elite football athletes competing in the Australian Football League were recruited for participation in this study. Athletes with lower limb injuries or contraindications requiring immobilization within 3 months prior to data

collection or with metallic surgical implants located beneath the trunk were excluded from analysis. This rendered five elite players as unsuitable for inclusion, providing a total cohort of 55 athletes stratified by their training age at the elite level (yr), less experienced (≤ 3 yr) and more experienced (> 3 yr) groups (Table 1), owing to heightened injury susceptibility in younger football athletes (9). Players wore their club-issued football shorts during the data collection process, were notified of the potential risks involved, and provided written informed consent prior to participation. Data collection and management procedures conformed to the Code of Ethics (World Medical Association), Declaration of Helsinki, with ethics approval provided by the University Human Research Ethics Committee.

Experimental Design

This acute, cross-sectional study commenced with anthropometric measures including height (cm), weight (kg), and tibial length (mm), followed by a series of whole-body composition and lower-body bone densitometry scans performed at the commencement of preseason training. In particular, whole-body and segmental appendicular mass (lean, fat, bone, and total) were examined using dual-energy x-ray absorptiometry (DXA), whereas lower-body bone material, structure, and strength were assessed for both limbs using peripheral quantitative computed tomography (pQCT).

Anthropometry

Stature was recorded to the nearest 0.1 cm using a wall-mounted stadiometer (Model 222, Seca, Hamburg, DE), with body mass recorded to the nearest 0.1 kg using an electronic weighing scale (AE Adams CPW Plus-200; Adam Equipment Inc., CT, USA). Tibial length of the kicking leg was assessed using a retractable measuring tape (Model 4414; Tech-Med Services, NY, USA), from the tibial plateau at the knee joint (proximal end) to the medial malleolus of the Tibia (distal end), and was recorded to the nearest 0.1 cm. Stature and tibial length measures were performed three times for each participant, with the average of each variable retained for analysis.

TABLE 1. Descriptive characteristics of less experienced ($n = 27$) and more experienced ($n = 28$) elite football athletes.

	Less Experienced (≤ 3 yr), $n = 27$	More Experienced (> 3 yr), $n = 28$	Effect (d)	Significance (P)
Age (yr)	19.1 \pm 1.5	25.0 \pm 3.0	2.49 ^a	0.001**
Height (cm)	188.7 \pm 6.5	189.2 \pm 7.8	0.07	0.797
Weight (kg)	82.6 \pm 7.4	88.2 \pm 8.3	0.71 ^b	0.012*
BMI (kg·m ⁻²)	23.2 \pm 1.5	24.6 \pm 1.2	1.03 ^b	0.001**
Bone mass (%)	4.0 \pm 0.3	4.2 \pm 0.3	0.67 ^b	0.013*
Lean mass (%)	85.4 \pm 1.4	85.9 \pm 1.8	0.31 ^c	0.316
Fat mass (%)	10.6 \pm 1.5	9.9 \pm 1.8	0.42 ^c	0.166
Tibial length (mm)	435.6 \pm 24.8	435.0 \pm 31.7	0.02	0.947

Values are presented as mean \pm SD. BMI, body mass index; Bone mass, whole-body bone mineral content; Effect, effect size.

^aLarge effect ($d \geq 1.2$).

^bModerate effect ($d \geq 0.6$).

^cSmall effect ($d \geq 0.2$).

*Statistical significance ($P \leq 0.05$).

**Statistical significance ($P \leq 0.01$).

All measures were reliably performed by the same accredited exercise scientist (CV ≤ 0.23%; ICC ≥ 0.996).

Scan Procedures

DXA. Whole-body scans were performed using DXA (QDR-1500; Hologic Discovery A, Waltham, MA). Subjects assumed a stationary, supine position on the scanning bed with both arms pronated by their side. To ensure consistent and reproducible subject positioning, the same DXA operator manually assisted all subjects to straighten their head, torso, and pelvis; internally rotate and fixate their legs and feet at 45°; and position their arms next to the body within the DXA scanning zone. This has produced a scan/rescan coefficient of variation less than 1% in our laboratory (12–14).

Using the in-built scan analysis software (Version 12.4; QDR for Windows, Hologic, Waltham, MA), full-body images were defined in accordance with Hologic's whole body model (13). Two subregions were also created using the subregion analysis tool to quantify the shank segments for each limb (13,14), from the tibiofemoral joint (knee axis) through to the talocrural joint (ankle axis). All hard tissue and soft tissue variables for the whole-body segment and shank segments were retained for analysis; including bone area, areal bone mineral content (aBMC), areal bone mineral density (aBMD), fat mass, lean mass, and total mass.

pQCT. Tibial scans were performed on each limb using pQCT (XCT-3000; Stratec Medizintechnik, Pforzheim, Germany). Subjects were required to sit on a height-adjustable chair with their lower limb fully extended through the acrylic cylinder and central gantry of the pQCT machine and secured to the foothold attachment (Fig. 1). Four pQCT scan slices were then measured at 4%, 14%, 38% and 66% of tibial length (distal to proximal). Before scan commencement, the central gantry

was positioned at the base of the medial malleolus to acquire a 30-mm image identifying the talocrural joint, used as the internal reference point from which the scan commenced (Fig. 1).

Variables across all tibial slices were retained for analysis. Trabecular density (Tb.vBMD) and trabecular area (Tb.Ar) were obtained from the 4% slice; cortical density (Ct.vBMD), cortical area (Ct.Ar), cortical thickness (Ct.Th), periosteal area (Ps.Ar), and endocortical area (Ec.Ar) were averaged across the 14% and 38% tibial slices; marrow density (Ma.vBMD), marrow area (Ma.Ar), muscle density (Mu.Den), and muscle area (Mu.Ar) were obtained from the 66% slice; and total density (Tt.vBMD), total area (Tt.Ar), and tibial mass were averaged across the 4%, 14%, and 38% tibial slices. Stress–strain index (SSIPOL) and fracture loads (FL.Ab) in the sagittal and frontal planes were averaged to represent whole bone strength for each limb. Relative fracture load (FL.Rel) was subsequently determined by dividing the absolute fracture load (N) by the body mass of the athlete (N). The resultant fracture load (FL.Ratio) was established by dividing the sagittal plane fracture load by frontal plane fracture load, thus a value higher than 1 (>1.0) reflects greater strength in the sagittal plane, and a value less than 1 (<1.0) reflects greater strength in the frontal plane.

Symmetry Index

The symmetry index (SI) was determined for tibial mass, total density (Tt.vBMD), total area (Tt.Ar), and stress–strain index (SSIPOL) using a previously established calculation (13):

$$SI = \frac{\text{Support leg} - \text{Kicking leg}}{0.5 \times (\text{Support leg} + \text{Kicking leg})} \times 100.$$

These skeletal variables were chosen to represent key material, structural, and strength measures. A negative score represents

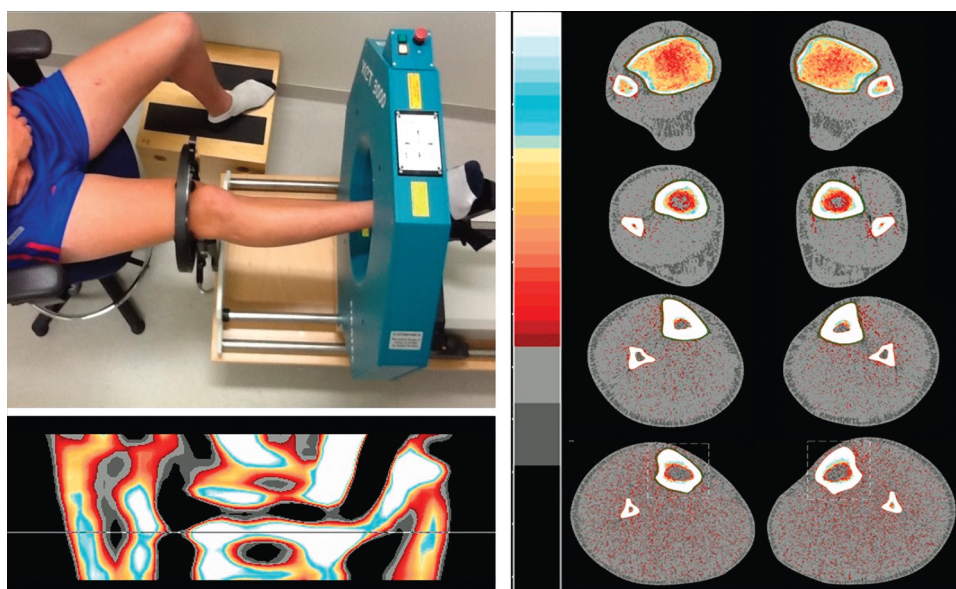


FIGURE 1—A tibial scan of the right lower limb using pQCT (top), with the talocrural joint identified (bottom), producing cross-sectional tibial slices at 4%, 14%, 38%, and 66% of tibial length (right).

lateral dominance toward the kicking leg, whereas a positive score represents lateral dominance toward the support leg.

Statistical Analysis

Independent *t*-tests were conducted to determine whether significant differences were evident between groups (less experienced, more experienced) for 1) subject characteristics 2) muscle–bone characteristics of the kicking limb, 3) muscle–bone characteristics of the support limb, and 4) symmetry index. Independent *t*-tests were also conducted to determine whether significant differences were evident between the kicking and the support limbs within each group for all muscle–bone characteristics. A 2 × 2 MANOVA was conducted to examine differences between training age and limb function (less experienced: kicking leg, support leg; more experienced: kicking leg, and support leg) across all variables. Follow-up one-way ANOVA for each dependent variable was conducted to determine precisely where differences occurred between limbs across groups. Statistical significance was set at an alpha level of $P \leq 0.05$. Effect sizes were also calculated to determine the magnitude of difference between variables in accordance with Hopkins (17): $d \geq 0.2$ is small, $d \geq 0.6$ is moderate, $d \geq 1.2$ is large, and $d \geq 2.0$ is very large. Statistical computations were performed using a statistical analysis program (SPSS, Version 17.0; Chicago, IL).

RESULTS

Descriptive characteristics of less experienced and more experienced elite football athletes are provided in Table 1. More experienced players were significantly heavier ($P = 0.012$, $d = 0.71$) than less experienced players, despite no

evident difference in height or tibial length. When expressed relative to body weight, only bone mass was significantly higher in the more experienced group ($P = 0.013$, $d = 0.67$). Soft tissue masses (lean and fat) only exhibited small effects ($P \leq 0.316$, $d \geq 0.31$) with no significant difference between groups.

Training age. Musculoskeletal characteristics of the lower body for less experienced and more experienced elite football athletes are provided in Tables 2–4. More experienced players exhibited significantly higher skeletal properties, with greater tibial mass ($P \leq 0.001$, $d \geq 1.22$), trabecular vBMD ($P \leq 0.009$, $d \geq 0.79$), cortical vBMD ($P \leq 0.001$, $d \geq 1.57$), and total vBMD ($P \leq 0.001$, $d \geq 0.94$) of moderate to large effect across both limbs. More experienced players also exhibited higher structural properties than their less experienced counterparts, with significantly greater cortical area and cortical thickness ($P \leq 0.001$, $d \geq 0.92$) of moderate effect; higher trabecular, total, and periosteal areas of small effect ($P \leq 0.387$, $d \geq 0.21$); and lower endocortical area of small effect ($P \leq 0.406$, $d \geq 0.22$). The only material and structural components with no significant difference or notable effect with training age were marrow vBMD and marrow area ($P \leq 0.903$, $d \geq 0.02$).

Material and structural properties subsequently delivered significantly higher bone strength in more experienced players, with greater stress–strain indices ($P \leq 0.007$, $d \geq 0.69$) and absolute fracture loads ($P \leq 0.018$, $d \geq 0.57$) producing small to moderate effects across both limbs. Relative fracture load exhibited a small positive effect between training ages in the support leg only ($P = 0.158$, $d = 0.23$). Furthermore, DXA-derived areal measures of aBMC and aBMD of the shank segments were also significantly higher in more experienced players ($P \leq 0.001$, $d \geq 1.00$) of moderate to large effect,

TABLE 2. Lower-body skeletal values of the tibia (pQCT) for less experienced ($n = 27$) and more experienced ($n = 28$) elite football athletes.

	Less Experienced (≤ 3 yr)				More Experienced (> 3 yr)				Kicking Leg		Support Leg	
	Kicking Leg	Support Leg	Effect	Sig.	Kicking Leg	Support Leg	Effect	Sig.	Effect	Sig.	Effect	Sig.
Bone material												
Tibial mass ($\text{g}\cdot\text{cm}^{-1}$)	4.51 ± 0.3	4.57 ± 0.4	0.17	0.602	4.94 ± 0.4	5.06 ± 0.4	0.30 ^c	0.243	1.22 ^a	0.001**	1.22 ^a	0.001**
Tt.vBMD ($\text{mg}\cdot\text{cm}^{-3}$)	608.7 ± 35.2	607.0 ± 28.7	0.05	0.801	646.7 ± 45.4	645.7 ± 43.1	0.02	0.931	0.94 ^b	0.001**	1.06 ^b	0.001**
Tb.vBMD	279.4 ± 28.4	277.2 ± 25.9	0.08	0.711	303.9 ± 33.5	303.0 ± 33.4	0.03	0.919	0.79 ^b	0.009**	0.86 ^b	0.004**
Ct.vBMD	1102.7 ± 12.2	1099.9 ± 14.8	0.21 ^c	0.474	1127.2 ± 14.9	1122.9 ± 14.5	0.30 ^c	0.281	1.80 ^a	0.001**	1.57 ^a	0.001**
Ma.vBMD	21.0 ± 7.2	21.3 ± 8.7	0.04	0.793	22.2 ± 6.4	22.0 ± 6.1	0.03	0.917	0.18	0.491	0.09	0.797
Bone structure												
Tt.Ar (mm^2)	860.4 ± 78.6	870.5 ± 79.4	0.12	0.725	883.5 ± 91.5	906.8 ± 99.1	0.25 ^c	0.373	0.27 ^c	0.286	0.40 ^c	0.088
Tb.Ar	635.0 ± 70.7	638.9 ± 67.2	0.06	0.957	650.1 ± 72.8	665.5 ± 81.2	0.20 ^c	0.466	0.21 ^c	0.387	0.36 ^c	0.119
Ct.Ar	324.3 ± 25.3	331.6 ± 35.7	0.24 ^c	0.353	351.4 ± 29.6	361.9 ± 30.2	0.35 ^c	0.201	0.98 ^b	0.001**	0.92 ^b	0.001**
Ma.Ar	231.0 ± 66.1	235.2 ± 67.9	0.06	0.868	229.1 ± 89.7	230.2 ± 77.1	0.01	0.961	0.02	0.903	0.06	0.814
Ct.Th (mm^2)	4.73 ± 0.3	4.78 ± 0.4	0.14	0.618	5.17 ± 0.4	5.26 ± 0.4	0.23 ^c	0.459	1.24 ^a	0.001**	1.20 ^a	0.001**
Ps.Ar	85.6 ± 3.5	86.5 ± 3.7	0.25 ^c	0.445	86.9 ± 4.6	88.2 ± 4.8	0.28 ^c	0.327	0.31 ^c	0.248	0.40 ^c	0.108
Ec.Ar	55.7 ± 4.2	56.2 ± 4.0	0.12	0.726	54.4 ± 5.7	55.1 ± 5.8	0.12	0.649	0.26 ^c	0.300	0.22 ^c	0.406
Bone strength												
SSI (mm^3)	2458.8 ± 256.6	2564.6 ± 340.3	0.35 ^c	0.188	2673.0 ± 353.8	2836.3 ± 384.7	0.44 ^c	0.110	0.69 ^b	0.007**	0.75 ^b	0.002**
FL.Ab (N)	5691.7 ± 689.8	5773.0 ± 818.9	0.11	0.802	6156.6 ± 929.2	6284.4 ± 890.0	0.14	0.608	0.57 ^c	0.018*	0.60 ^b	0.006**
FL.Rel (N/N)	7.00 ± 0.5	7.10 ± 0.7	0.16	0.798	7.10 ± 0.7	7.26 ± 0.7	0.23 ^c	0.425	0.16	0.459	0.23 ^c	0.158
FL ratio (X/Y)	1.18 ± 0.1	1.20 ± 0.1	0.20 ^c	0.689	1.16 ± 0.1	1.18 ± 0.1	0.20 ^c	0.611	0.20 ^c	0.406	0.20 ^c	0.623

Values are presented as mean ± SD, Tt, total; vBMD, volumetric bone mineral density; Tb, trabecular; Ct, cortical; Ma, Marrow; Ar, area; Ct.Th, cortical thickness; Ps.Ar, periosteal area; Ec.Ar, endocortical area; SSI, stress–strain index; FL, fracture load; Ab, absolute; Rel, relative; Effect, effect size; Sig., significance.

^aLarge effect size ($d \geq 1.2$).

^bModerate effect size ($d \geq 0.6$).

^cSmall effect size ($d \geq 0.2$).

*Statistical significance ($P \leq 0.05$).

**Statistical significance ($P \leq 0.01$).

TABLE 3. Lower-body skeletal values of the shank (DXA) for less experienced ($n = 27$) and more experienced ($n = 28$) elite football athletes.

	Less Experienced (≤ 3 yr)				More Experienced (> 3 yr)				Kicking Leg		Support Leg	
	Kicking Leg	Support Leg	Effect	Sig.	Kicking Leg	Support Leg	Effect	Sig.	Effect	Sig.	Effect	Sig.
Areal bone mass												
Area (cm)	204.9 \pm 19.5	205.8 \pm 18.0	0.05	0.855	216.8 \pm 25.2	217.6 \pm 26.0	0.03	0.913	0.53 ^c	0.057	0.53 ^c	0.060
aBMC (g)	270.5 \pm 28.6	270.7 \pm 29.7	0.01	0.979	308.9 \pm 44.5	311.7 \pm 44.5	0.06	0.815	1.03 ^b	0.001**	1.08 ^b	0.001**
aBMD (g·cm ⁻²)	1.32 \pm 0.1	1.31 \pm 0.1	0.10	0.745	1.42 \pm 0.1	1.43 \pm 0.1	0.10	0.748	1.00 ^b	0.001**	1.20 ^a	0.001**

Values are presented as mean \pm SD. Area, bone area; Effect, effect size; Sig., significance.

^aLarge effect size ($d \geq 1.2$).

^bModerate effect size ($d \geq 0.6$).

^cSmall effect size ($d \geq 0.2$).

*Statistical significance ($P \leq 0.05$).

**Statistical significance ($P \leq 0.01$).

whereas whole bone area exhibited a small positive effect ($P = 0.057$, $d \geq 0.53$). Soft tissue measures were favorable toward more experienced players, with significantly higher muscle area ($P \leq 0.003$, $d \geq 0.86$) and significantly lower fat area ($P \leq 0.014$, $d \geq 0.69$) in more experienced players with moderate effect. This was similarly evident for lean mass ($P \leq 0.016$, $d \geq 0.68$) and fat mass ($P \leq 0.256$, $d \geq 0.31$) of the shank segments using DXA. Muscle density was lower in more experienced players, but with only a small magnitude of effect ($P = 0.168$, $d \geq 0.41$).

Limb function. Muscle–bone comparisons between kicking and support limbs within each training age category are also provided in Tables 2–4. Significant interaction effects were evident between training age and limb function for material ($F_{5, 102} = 0.141$, $P = 0.007$, Wilks $\Lambda = 0.993$), structural ($F_{7, 100} = 0.181$, $P = 0.013$ Wilks $\Lambda = 0.987$), and strength ($F_{4, 103} = 0.260$, $P = 0.010$, Wilks $\Lambda = 0.990$) components. A significant interaction was also prevalent with all variables combined ($F_{16, 91} = 0.182$, $P = 0.031$, Wilks $\Lambda = 0.969$). Indeed, skeletal asymmetries were observed between limbs for one material (cortical vBMD), two structural (cortical and periosteal areas), and two strength variables (stress–strain index and fracture load ratio) in less experienced players of small effect ($P \leq 0.689$, $d \geq 0.20$), whereas two material (tibial mass and cortical vBMD), five structural (trabecular area, cortical area, total area, periosteal area, and cortical thickness), and three strength variables (stress–strain index, absolute fracture load, and fracture load ratio) were notably different in more experienced players of small effect ($P \leq 0.611$, $d \geq 0.20$). In all cases, the support

leg exhibited favorable material, structural, and strength values over the kicking leg for less experienced and more experienced players alike, a general trend evident in all Australian footballers. Muscular differences were also evident between limbs, with lower muscle density in the support limb for less experienced and more experienced players ($P \leq 0.391$, $d \geq 0.23$), despite no clear differences detected using areal, DXA-derived measures of hard tissue or soft tissue between limbs for either group of footballers. This highlights the inadequacy of DXA to appropriately quantify morphological musculoskeletal adaptations within individual athletes.

Skeletal asymmetry between kicking and support limbs was notably higher in more experienced players, as conveyed in Figure 2. Tibial mass, total vBMD, total area, and stress–strain index were chosen as representative variables of material (mass and density), structure (cross-sectional area), and strength (bending resistance) to avoid repetitious reporting of similarly behaved variables. Significantly higher asymmetries were evident for tibial mass ($P \leq 0.044$, $d \geq 0.50$), cross-sectional area ($P \leq 0.039$, $d \geq 0.53$), and stress–strain indices ($P \leq 0.050$, $d \geq 0.42$) of small to moderate effect, with no asymmetrical difference in volumetric density ($P \leq 0.793$, $d \geq 0.07$). Interestingly, only total vBMD displayed no clear difference in asymmetry between limbs or training ages. Collectively, more experienced players exhibited higher asymmetries as a result of greater material, structure, and strength values in the support leg relative to the kicking leg of a higher magnitude compared with less experienced players. This trend of favorable adaptation to the support leg relative to the kicking leg

TABLE 4. Lower-body soft tissue characteristics of the shank (DXA) and tibia (pQCT) for less experienced ($n = 27$) and more experienced ($n = 28$) elite football athletes.

	Less Experienced (≤ 3 yr)				More Experienced (> 3 yr)				Kicking Leg		Support Leg	
	Kicking Leg	Support Leg	Effect	Sig.	Kicking Leg	Support Leg	Effect	Sig.	Effect	Sig.	Effect	Sig.
Soft tissue characteristics												
Mu.Ar (mm ²)	8498.7 \pm 1059.6	8400.9 \pm 1108.9	0.09	0.746	9457.8 \pm 1177.1	9487.2 \pm 1094.5	0.03	0.925	0.86 ^b	0.003**	0.99 ^b	0.001**
Mu.Den (mg·cm ⁻³)	78.7 \pm 1.2	78.4 \pm 1.4	0.23 ^c	0.391	78.1 \pm 1.7	77.7 \pm 1.7	0.24 ^c	0.379	0.41 ^c	0.168	0.45 ^c	0.132
Lean mass (g)	3043.5 \pm 308.5	3056.1 \pm 321.9	0.04	0.886	3294.8 \pm 421.6	3300.3 \pm 396.0	0.01	0.960	0.68 ^b	0.016*	0.68 ^b	0.016*
Fat.Ar (mm ²)	1377.7 \pm 425.0	1319.2 \pm 419.4	0.14	0.620	1095.5 \pm 387.4	1012.9 \pm 456.0	0.20 ^c	0.476	0.69 ^b	0.014*	0.70 ^b	0.014*
Fat mass (g)	422.0 \pm 144.3	409.9 \pm 152.1	0.08	0.770	376.9 \pm 99.3	367.9 \pm 114.2	0.08	0.754	0.36 ^c	0.187	0.31 ^c	0.256

Values are presented as mean \pm SD. Mu, muscle; Ar, area; Den, density; Effect, effect size; Sig., significance.

^aLarge effect size ($d \geq 1.2$).

^bModerate effect size ($d \geq 0.6$).

^cSmall effect size ($d \geq 0.2$).

*Statistical significance ($P \leq 0.05$).

**Statistical significance ($P \leq 0.01$).

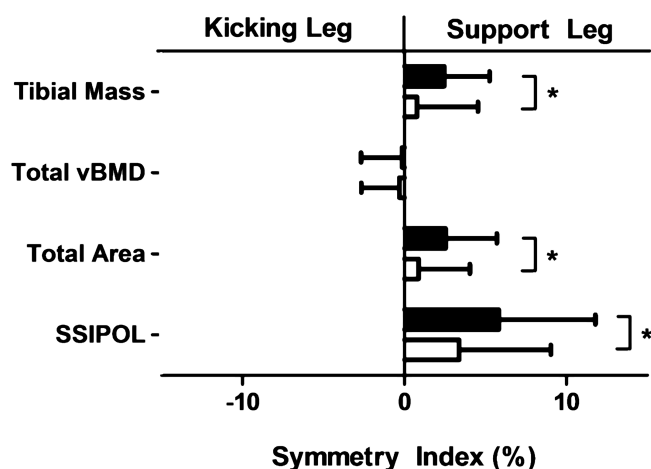


FIGURE 2—Symmetry index of more experienced (black bars) and less experienced (white bars) elite football athletes for material, structural, and strength measures between the kicking and support limbs. *Statistical significance between training age ($P \leq 0.05$).

within each group is further evident as training age increases, highlighting a chronic loading effect for musculoskeletal morphology.

DISCUSSION

Musculoskeletal responsiveness to mechanical loading provides practitioners with important modifiable characteristics to screen, monitor, and target with exercise interventions. As such, this study sought 1) to provide a descriptive set of normative and comparative material, structural, and strength values of lower-body musculoskeletal properties in elite football athletes; 2) to identify the influence of training exposure (training age) on lower-limb muscle and bone morphology; and 3) to establish whether developmental laterality exists as a result of limb function during sport participation. Given that muscle and bone are highly adaptive to mechanical loads, normative values were stratified by training age and limb function to account for the influence of training exposure and asymmetrical loading on bone strength and its derivatives. Accordingly, we were able to describe the characteristically different musculoskeletal profiles of more experienced and less experienced players, such that higher training ages exhibited greater relative whole-body skeletal mass proportional to body mass and greater lower-body bone strength commensurate with greater exposure to mechanical loading over longer periods of time. Similarly, we were able to successfully demonstrate the existence of unique and distinct morphological adaptations prevalent between the kicking and support limbs of football athletes in response to repetitious asymmetrical loading patterns experienced as a consequence of their functional differences within the context of their sport.

Training age. Dose–response, load adaptation relationships between external stimuli and biomaterial properties implies that football athletes with greater acute and chronic exposure to training and competitive loading regimens should have proportionally higher magnitudes and broader ranges of

favorable musculoskeletal adaptations than those with lower exposure (9,26,33,37,38). Predictably, the relationship between training age and muscle–bone development was positive toward more experienced players in this study. In particular, more experienced players exhibited greater tibial masses and cross-sectional areas, a stimulatory characteristic of deterministic modeling and remodelling processes afforded through mechanical loading (4,8,10,11,34,35,37,41), delivering higher bone strength than less experienced players. Similarly, muscle cross-sectional area and lean mass were also significantly higher in more experienced players, an important protective coadaptation to assist managing load dispersion through the skeleton while neutralizing repetitious bending moments in the lower limbs during sports participation (4,5,10,21,35). Although biological age is a known confounding factor, bone size and strength only marginally change in the absence of dynamic and evolving (i.e., nonhabitual) mechanical load environments over time (3,25), whereas the cohorts of athletes in this study were provided with individually tailored and periodized mechanical loading programs (training) in addition to their mechanical loading demands (competition) thrice weekly across each season for the duration of their involvement at the elite level. Given that less experienced Australian footballers (<3 yr) have markedly higher injury susceptibility (9) than more experienced Australian footballers (≥ 3 yr), training age stratifications in this study provide an insight into the developmental musculoskeletal trajectory of Australian footballers, while also providing unique normative and comparative information for practitioners to utilize when medically screening athletes, stratifying injury risk, benchmarking athletes against criterion, or producing baseline examinations that underpin prophylactic or rehabilitative programs.

Limb function. Morphological adaptations respond differently to varying combinations of muscular, impact, and gravitational forces (6,11,22,29,43). Consequently, the dampened osteogenic stimulus afforded to the kicking limb relative to the support limb from low-grade impacts and absent gravitational loads during the kicking skill will likely develop asymmetrical osteogenic adaptations in favor of the support limb when extrapolated over time. Expectantly, in this study, musculoskeletal asymmetries were observable between limbs in Australian footballers, with the support limb exhibiting greater bone strength (stress–strain index, absolute fracture load, and relative fracture load) and higher bone mass relative to the kicking limb. In particular, the increased strength of the support limb is symptomatic of its structural superiority, developing thicker cortices with wider cross-sectional areas than the kicking limb. The support limb did exhibit slightly lower density values; however, this was not detrimental or unsurprising, as equivalent materials dispersed over larger areas are considered less dense despite delivering greater aggregate strength benefits, as was the case in the support limb for this cohort. This also highlights an evident limitation of using BMD as a surrogate measure in isolation (4,5,8,10,36). Indeed, cross-sectional area was the

primary morphological adaptation afforded to the support limb, a potent adaptation that improves load tolerance proportional to the fourth power of material distance from its neutral axis, such that a twofold increment in cross-sectional area would yield an eightfold increment in bone strength, notwithstanding other changes in mass or density parameters (5,34,35,41).

Loading exposure over longer periods was shown to exacerbate identified asymmetry between limbs, with more experienced players containing larger morphological asymmetries than less experienced players, with higher magnitude benefits afforded to the support limb. This interlimb difference in adaptation provides a useful loading model, as it uses individual athletes as their own internal control to establish which loading profiles promote particular morphological, musculoskeletal changes over time. In this regard, repetitious high-impact gravitational loading evidently favors cross-sectional area as a morphological adaptation to potentially enhance skeletal robustness, bone strength, and fatigue resistance (22,28,32,40,41,43,44), with bone density exhibiting no discernible additional benefit between limbs irrespective of training age effects (11) (Fig. 2). Although biological age and body mass differed between groups, asymmetry between limbs would not increase because of these factors; aging is a uniform process across the body, and increases in body mass will affect both limbs equally in the absence of disparate loading profiles. Indeed, it is precisely these disparate loading profiles exposed to the kicking and support limbs that generate and exacerbate these morphological asymmetries over time, as demonstrated by several other studies using jump athletes with athletic controls (19,42). Similarly, Nikander et al. (28) and Rantalainen et al. (32) illustrated clear structural differences in athletes participating in sports with different chronic loading profiles: high magnitude versus high impact versus low impact versus no impact versus control. Intriguingly, our study illustrates this same relationship within athletes and within sports for Australian footballers; the kicking leg conforms with a high magnitude (muscle contraction) phenotype, whereas the support leg conforms with a high impact (gravitational) phenotype, two uniquely distinct morphology responses to common loading patterns specific to football. This presents practitioners with an opportunity to counterbalance physical development by targeting the kicking leg with high-impact, gravitational loading in controlled settings to promote physical resilience bilaterally.

Areal measures supplied by DXA were unable to identify asymmetry between limbs within each group despite clear material, structural, and strength differences identified by pQCT. This was expected, given that DXA is uniplanar, measures only frontal plane mass distribution, and is unable to measure bone structure or bone strength as primary asymmetrical adaptations and significant contributors to musculoskeletal resilience. Accordingly, practitioners are strongly encouraged to concomitantly measure structural and material properties of musculoskeletal tissues when examining factors that contribute to musculoskeletal resilience. This serves to

better inform medical screening, player monitoring, and injury risk stratification protocols for football athletes.

Strengths and limitations. Musculoskeletal differences evident between training ages in this study are confounded by biological age, with morphological variations partially influenced by differences in skeletal maturity. Regardless of this, mechanical loading programs confer additional bone material, structural, and strength benefits to the skeleton beyond those evident during ageing and maturation; thus, the findings of this study must be considered in context. To consolidate this relationship between training exposure and musculoskeletal development examined in the current study, differential adaptations evident between limbs were examined using a within-subject design to compare the kicking and support limbs between training ages. This internal comparison supported the influence of context-specific loading exposure, highlighting the developmental effect of asymmetrical loads unique to football sports, with larger differences in musculoskeletal adaptations evident in athletes of higher training age. Further strengths of this study also include the large sample size and use of elite level athletes often scarce in research contexts, the novel application of pQCT to elite Football athletes, and the unique comparison of lower-body musculoskeletal adaptations between limbs based on differential function. This is also the first study to quantify and report lower-body musculoskeletal morphology in Australian Football athletes of differing training ages.

CONCLUSION

Relationships between levels of training exposure (less experienced vs more experienced) and asymmetrical loading exposure (kicking limb vs support limb) were evident, with distinct morphological adaptations noted between limbs. In particular, greater training exposure led to greater material, structural, and strength adaptations of lower-body musculoskeletal properties commensurate with controlled multi-modal exercise interventions and participation in high-impact, odd-impact sporting competitions over time. Similarly, longer-term exposure to asymmetrical loading between limbs developed different morphological features for the kicking limb relative to the support limb; emphasizing the potent benefit of cross-sectional area as a key attribute to deliver greater bone strength in response to routine, high-impact gravitational loads within the support limb. Future research should consider quantifying seasonal adaptations in response to mechanical loading programs (training) and demands (competition) across a football season to examine whether asymmetrical changes are evident, which may underpin a footballer's developmental trajectory over time.

To increase musculoskeletal resilience in football athletes, practitioners may use exercises that frequently use combinations of high-impact, gravitational, and muscular loads to increase muscle and bone cross-sectional area, an evidently potent contributor to biomaterial strength. It is also strongly

recommended to measure and monitor structural and material properties of the musculoskeletal system to appropriately examine various factors that contribute to mechanical load tolerance in sport, to better inform medical screening, player monitoring, and injury risk stratification protocols for football athletes.

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