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ORIGINAL INVESTIGATION

FUNCTIONAL BASIS OF ASYMMETRICAL LOWER-BODY SKELETAL MORPHOLOGY IN PROFESSIONAL AUSTRALIAN RULES FOOTBALLERS

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Short Title: *Functional morphology of professional footballers*

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ABSTRACT

Bone strength is a product of its material and structural properties and is highly responsive to mechanical load. Given the measureable and adaptable features of bone, and thus relevance to medical screening, injury prevention and injury management in athletes; this study describes the lower-body skeletal morphology of professional Australian Rules Footballers. Using a cross-sectional and quantitative study design, fifty four professional Australian Rules Football players (n = 54; age: 22.4 ± 3.8 years; height: 189.0 ± 7.5 cm; weight: 86.0 ± 8.6 kg; tibial length: 436.1 ± 29.2 mm; Body Fat: 9.9 ± 1.7 %) underwent tibiofibular pQCT scans for the kicking and support limbs, and a whole-body DXA scans. The support leg was significantly stronger than the kicking leg (bone strength: $p \leq 0.001$; $d = 0.47$) with significantly greater bone mass ($p < 0.001$; $d = 0.28$), cross-sectional areas ($p \leq 0.002$; $d = 0.20$), and greater cortex thickness ($p = 0.017$; $d = 0.20$), owing to significantly greater periosteal apposition ($p \leq 0.001$; $d = 0.29$) and endocortical expansion ($p = 0.019$; $d = 0.13$) despite significantly lower cortical density ($p = 0.002$; $d = -0.25$). Disparate skeletal morphology between limbs highlights context-specific adaptive responses to mechanical loads experienced during game-based tasks. Practitioners should concomitantly measure material and structural properties of musculoskeletal tissue when examining fragility or resilience to better inform medical screening, monitoring and injury risk stratification. Support leg axial loading highlights a potential avenue for interventions aiming to remediate or optimise bone cross-sectional area.

KEY WORDS: Bone, Adaptation, Asymmetry, Muscle, Imbalance.

Word Count: 249 (/250)

INTRODUCTION

Footballers seldom engage their lower limbs with equal preference within the tactical realm of their sport, selectively and often instinctively recruiting a dominant limb for most game-based activities. Indeed, footballers routinely plant and kick, jump and change direction sporadically through-out training and competition, often under highly dynamic and volatile conditions, all of which demonstrably lead to some level of subconscious and repetitious limb dominance on the basis of technical skill proficiency (i.e. kicking and support limbs) (15,16,18,20), or strength and power expression (i.e. jumping or changing direction) to yield desirable outcomes on command (23,38,47). Australian Rules Football (i.e. Australian Football) requires athletes to primarily utilise the kicking skill to deliver the ball to a desired location or intended target, which places considerably different demands on the preferred kicking and support limbs during task execution (1,16). Indeed, kicking requires footballers to adopt uni-pedal postures in order to powerfully strike the ball with the kicking limb while forcefully planting the support limb to provide stability, balance, and support (2-4,32). As such, the kicking limb experiences muscular forces in the absence of weight-bearing when swinging the limb (2,3,18); whereas the support limb experiences combinations of high-grade, impact and muscular forces simultaneously (4,20,32), often also used as the plant leg for single-leg jumping and changing direction (23,38,47). Consequently, the culmination of these differential loading patterns routinely expressed during training and competition may produce or exacerbate functional muscle and bone adaptations between the lower limbs.

Functional adaptations of muscular strength and power, commensurate with the development of functional asymmetries in muscle mass have been well-established in Australian Rules Football (2,16,20,24,39), and in skeletal tissue of tennis players (*upper limbs*) and jumpers (*lower limbs*) (14,26,27); though whether functional asymmetries extend to skeletal structures of Australian Rules Footballers has yet to be comprehensively quantified. Disparate skeletal morphologies likely develop as a consequence of diverse mechanical loading environments, whereby compressive, torsional, transverse, and tensile loads routinely applied to hard-tissue structures of each limb may expose the skeleton of footballers to mechanical stimuli that can lead to positive bone and site-specific adaptations or subsequent stress reactions and fractures (9,30,35). Accordingly, characterizing lower-body bone material, structure and strength of Australian Rules Footballers is pertinent; particularly owing to the adaptability of musculoskeletal tissue to mechanical load (11,17,43), providing strength and conditioning practitioners with important modifiable characteristics to screen, monitor, and target with exercise interventions. In particular, whether macroscopic asymmetries exist, and/or whether different levels of skeletal robustness or slenderness exist between limbs on the basis of functionality serves to inform medical screening for injury risk; interventional efficacy of primary, prophylactic or remedial programs; and provide insight into expectant morphological adaptations from various modes of exercise prescription and training loads accordingly.

Skeletal examinations and descriptive profiles of hard-tissue in professional Australian Rules Footballers are scarce (21,22,41), primarily using Dual-energy X-ray Absorptiometry (DXA) to provide two-dimensional whole-body and regional examinations of bone area, mineral content and mineral density. While such investigations provide basic insights into bone mass using areal bone mineral content (aBMC) and areal bone mineral density (aBMD) as surrogate measures of bone strength, these low-resolution uniplanar images are unable to examine bone structure (shape, size, geometry) or material (macroscopic composition, microscopic architecture); and are limited solely to frontal plane mass distribution. Given the complex array of morphological interactions (structural and material) present within hard-tissue structures; areal measures consequently explain ~50% of bone strength (11,17), highlighting the need for comprehensive assessment tools and procedures when quantifying skeletal properties to screen and monitor athlete robustness, training efficacy or injury risk.

Technological advancements have led to the development of peripheral Quantitative Computed Tomography (pQCT), a bone densitometry imaging device capable of producing higher resolution and three-dimensional measurements as an alternative to DXA. pQCT is particularly advantageous as it allows practitioners to concomitantly measure structural and material properties of bone in order to cross-sectionally estimate bone strength with greater precision (10) and longitudinally monitor morphological adaptations responsible for alterations in bone strength following prescribed interventions or periods of immobilization (17,21). Owing to its greater descriptive capabilities and improved measurement outcomes, pQCT has gained ascendency in clinical and research contexts, yet has received minimal attention in sporting contexts. Given the novelty of pQCT in athletic environments, limited normative or descriptive, cross-sectional and/or longitudinal studies exist. Of these studies, three describe the upper-limbs of tennis players (14,27,28), two describe the lower limbs of soccer players and rugby league players respectively (1,12), with only one study in Australian Rules Football (21) reported in the literature to date. This severely complicates musculoskeletal screening and monitoring procedures and interpretation in Australian Rules Football, as normative and comparative values are critically important and necessary to provide benchmarks and baseline information for comparison.

Owing to the absence of lower-body skeletal examinations in Australian Rules Football, and the adaptability of bone strength to mechanical loading programs (training) and demands (competition), this study comprehensively characterized lower-body bone strength and skeletal morphology of kicking and support limbs in professional Australian Rules Footballers using two-dimensional (DXA) and three-dimensional (pQCT) densitometry. Specifically, this study establishes the prevalence and extent of functional asymmetry inherent within the lower-limbs of Australian Rules Footballers; and so too the various and unique macroscopic material, structural and strength adaptations evident as a consequent of long-term exposure to differential loading patterns.

METHODS

Experimental Approach to the Problem

This acute, cross-sectional study commenced with anthropometric measures including height (cm), weight (kg) and tibial length (mm), followed by a series of bone densitometry scans performed at the commencement of preseason training. Specifically, whole-body and lower-body segmental mass (lean, fat, bone and total) was examined using DXA; while lower-body bone material, bone structure and bone strength was assessed for both limbs using pQCT. Differences between limbs were assessed using dependent t-tests for all musculoskeletal characteristics, symmetry indices and percent differences respectively.

Subjects

Sixty (n = 60) professional Australian Rules Footballers competing in the national Australian Football League (AFL) were recruited for participation in this study. Athletes with any lower limb injuries or contraindications requiring immobilisation within six months prior to data collection; any major (partial or complete) lower-limb fractures within the past 24 months; or metallic surgical implants located beneath the trunk were excluded from analysis to eliminate any confounding factors. This rendered six professional players as unsuitable for inclusion, providing a total cohort of fifty-four AFL footballers (n = 54; age: 22.4 ± 3.8 years; height: 189.0 ± 7.5 cm; weight: 86.0 ± 8.6 kg; tibial length: 436.1 ± 29.2 mm; BMI: 24.0 ± 1.5; Body Fat: 9.9 ± 1.7 %; professional training age: 4.2 ± 2.1 years). Players wore their club-issued football shorts during the data collection process and were notified of the potential risks involved. All procedures conformed to the Code of Ethics (World Medical Association), Declaration of Helsinki, with ethics approval provided by the University Human Research Ethics Committee (HREC Approval: #9384).

Procedures

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 in triplicate for each participant, with the average retained for analysis. All measures were reliably performed by the same accredited exercise scientist (Exercise and Sport Science Australia; CV $\leq$ 0.23%; ICC $\geq$ 0.996).

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/re-scan coefficient of variation below 1% in our laboratory (16). Using the in-built scan analysis software (Version 12.4; QDR for Windows, Hologic, Waltham, MA), four sub-regions were created using the sub-region analysis tool in order to quantify the thigh and shank segments for each limb (19). Bone area

(BA), bone mineral content (aBMC), bone mineral density (aBMD), lean mass, fat mass and total mass for the shank segments were retained for analysis.

- FIGURE 1 -

Tibial scans were performed on each limb using pQCT (XCT-3000, Stratec Medizintechnik, Pforzheim, Germany), with coefficients of variation for lower limb pQCT precision reported elsewhere (37). 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 foot-hold attachment. Four pQCT scan slices were then measured at 4%, 14%, 38% and 66% of tibial length (distal-to-proximal). Prior to scan commencement, the central gantry was positioned at the base of the medial malleolus to acquire a 30mm image identifying the talocrural joint; used as the internal reference point from which the scan commenced. 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 above one (> 1.0) reflects greater strength in the sagittal plane and a value below one (< 1.0) reflects greater strength in the frontal plane.

Sectoral analyses of each slice (4%, 14%, 38% and 66%) for both limbs (kicking and support) and skeletal structures (tibia and fibula) were determined in accordance with prior studies (30,35,37). Specifically, images were automatically re-orientated according to a line between tibia and fibula bone area centers, thereby eliminating confounding variations due to subtle differences in limb positioning during each scan. Endocortical (14%, 38%, and 66% slices) and pericortical (all slices) radii were produced around the bone in 10° sectors with the first sector towards fibula (away from tibia for fibula). Sectors ran clock-wise for the left leg, and counter clock-wise for the right leg so that the sectors matched anatomically between limbs.

Symmetry index (SI) was determined for all musculoskeletal variables (5,13,24,25,36,40,48). The SI is a well-established unitless measure (index) of asymmetry, and the equivalent of a percent difference (in magnitude) appropriately normalised to the averaged summation of comparator values (i.e. kicking and support limbs). This approach is well-justified in the anthropometry, biomechanics and human movement literature as the most sensitive assessment of inter-limb symmetry (5,48), and elicits equivalent values to percent difference results as a natural logarithmic function (Ln(%D), as described in a recent editorial of the British Medical Journal by Professor Tim Cole and Professor Douglas Altman (6,7). As arranged in this paper, a negative score represents lateral dominance towards the kicking leg, while a positive score represents lateral dominance towards the support leg utilizing the SI and Ln(%D) equations below, to illustrate this concept as an index and percent difference accordingly.

$$\textit{(1)} \qquad SI = \frac{\textbf{Support Leg} - \textbf{Kicking Leg}}{\textbf{0.5 x (Support Leg + Kicking Leg)}} \textbf{ x 100}$$

$$\textit{(2)} \qquad Ln(\%D) = [\ \textbf{Ln(Support)} - \textbf{Ln(Kicking)}\ ] \textbf{ x 100}$$

Statistical Analyses

Normality was assessed using the Shapiro-Wilk test, with the null hypothesis determining a normally distributed data-set. Accordingly, paired samples t-tests were conducted to determine whether significant differences were evident for muscle-bone characteristics between limbs (1). Sectoral analyses, post-alignment, were evaluated for leg x sector interactions using a repeated-measures analysis of variance, and adjusted using Bonferroni's post-hoc test between legs and sectors if a significant interaction was indicated for the given slice. Statistical significance was set at an alpha level of $p \leq 0.05$. Cohen's effect size (*d*) was also calculated to determine the magnitude of difference between limbs in accordance with Hopkins (25), and interpreted as: $d \geq 0.2$ is small; $d \geq 0.6$ is moderate; $d \geq 1.2$ is large; $d \geq 2.0$ is very large. Owing to small (2-fold) differences in bone material and bone structural parameters yielding exponentially large (100-fold) downstream differences in skeletal strength or fatigue resistance (15,17,43); and smaller differences in muscle mass (3%) yielding larger differences in muscle strength (8%) (20), we classified bone asymmetries ≥2 (SI) or ≥2% (Ln(%D), and muscle asymmetries ≥5 (SI) or ≥5% (Ln%D) as clinically noteworthy, given that asymmetry magnitudes are not equally meaningful across tissue types and strength expressions. Statistical computations were performed using a statistical analysis program (SPSS, Version 21.0; Chicago, IL).

RESULTS

Muscle-bone characteristics of the kicking and support limbs are provided in Tables 1 and 2 for pQCT and DXA variables respectively.

- TABLE 1 -

pQCT

Significant differences were observed for material, structural and strength properties of skeletal tissue, with the support leg exhibiting superior values. Specifically, the support leg reported higher hard-tissue mass ($p < 0.001$; $d = 0.28$; SI = 2.30; Ln(%D) = 2.30%), greater trabecular, cortical and total cross-sectional areas ($p \leq 0.002$; $d \geq 0.20$; SI ≥ 2.22; Ln(%D) ≥ 2.22%), and thicker cortices ($p = 0.017$; $d = 0.20$; SI = 2.00; Ln(%D) = 2.00%) due to greater periosteal apposition ($p < 0.001$; $d = 0.29$; SI = 1.38; Ln(%D) = 1.38%) and endocortical expansion ($p = 0.019$; $d = 0.13$; SI = 1.26; Ln(%D) = 1.26%). This culminates in superior bone strength for the support leg, exemplified by significantly greater stress-strain resistance ($p < 0.001$; $d = 0.47$; SI = 5.91; Ln(%D) = 5.91%) and higher fracture loads ($p = 0.026$; $d \geq 0.16$; SI ≥ 2.15; Ln(%D) ≥ 2.15%), despite having significantly lower cortical density ($p = 0.002$; $d = 0.25$; SI = 0.43; Ln(%D) = 0.43%), illustrating the potent contribution of bone structure and bone mass distribution to bone strength, additional to bone density acting as a poor surrogate measure. This relationship occurs as mass distributed over a larger area will measure as lower density despite conferring greater robustness and strength to tissue (17), evidenced in this examination.

- FIGURE 2 -

Sectoral analyses of bone structure across all tibial and fibular slices between the kicking leg and support leg are provided in Figure 1, with each limb interlaced over the other. Significant structural differences (leg x sector interaction $p \leq 0.05$) across all levels were evident, with notable cortex (periosteal and endocortical) expansion in the support leg relative to the kicking leg. Importantly, the largest differences were evident at the 14% and 38% slices of the tibia and fibula, which are most prone to stress-related injuries or syndromes from overuse or poor biomechanics. Lastly, no differences were evident between muscle cross-sectional area, muscle density and fat cross-sectional area between limbs.

DXA

Significant differences were observed for the femoral region only using DXA, with the thigh segment of the support leg exhibiting greater bone area and bone mineral content ($p \leq 0.002$; $d \geq 0.20$; SI $\geq$ 2.23; Ln(%D) $\geq$ 2.23%) with no significance difference noted in bone mineral density, further demonstrating the limitation of using bone mineral density as an isolated surrogate of bone strength or skeletal adaptation. Furthermore, no significant differences were observed in the tibiofibular region (shank segment) using DXA, despite the high significant differences seen in the same tissues when using pQCT (described above). However, DXA is in agreement with pQCT when quantifying soft-tissue mass (muscle and fat), with no significant differences noted in either thigh or shank segments.

- TABLE 2 -

DISCUSSION

Lower-body skeletal examinations of Australian Footballers are scarce (21,22,41). Given the high (and incremental) prevalence of lower-limb fractures (stress and traumatic) in the AFL (31), in addition to the adaptability of bone strength to mechanical loading programs (training) and demands (competition); such examinations provide crucial data for practitioners to make informed decisions and be effective when medically screening athletes (i.e. what is normal versus abnormal?, and where do potential weaknesses reside?); stratifying injury risk (i.e. who is relatively fragile versus resilient?); benchmarking athletes against criterion (i.e. comparative to other sports, or to previously injured versus non-injured footballers); or producing baseline examinations which underpin the assessment of efficacy for prophylactic or rehabilitative programs. Accordingly, we report normative lower-body musculoskeletal data of the kicking and support limbs for elite Australian Footballers using segmental DXA and pQCT, providing a novel insight into the individuality of musculoskeletal adaptation between limbs of Australian Footballers, and a unique insight into the suitably of these techniques for skeletal examinations within this population, in particular.

Distinct differences in morphology between kicking and support limbs at all cross-sections were apparent, illustrating the effect of asymmetrical, unilateral loading patterns afforded to each limb as a result of routine functional demands in elite Australian Footballers. Indeed, differential loading patterns are commonplace in Australian Football during routine physical tasks such as kicking, jumping and changing direction (15,20,23) generated greater bone strength in the axially loaded and impact dominant support leg relative to the kicking leg, primarily through improved bone structure. Specifically, support leg loads resulted in higher periosteal apposition and moderately higher endocortical expansion leading to increased cross-sectional area and increased cortex thickness; as evidenced by its prolonged and disparate loading environments which have been shown to generate morphological asymmetry over time (21), as demonstrated in jump athletes and soccer players (lower-body) as well as tennis players (upper-body) comparative to athletic controls (1,27,46); an effect noted in this cohort of footballers.

Skeletal phenotypes have also been identified across sports containing particular types of mechanical load profiles, identifying clear structural differences in athletes who are chronically exposed to various magnitudes and frequencies of muscular and impact forces, with football resembling sports of high- and odd-impact dominance (30,35,42). However, in Australian Football, neither the kicking leg or support leg are exposed to mechanically exclusive or consistent loading environments due to the volatility and reactivity of the sport (i.e. each limb encounters combinations of magnitudes and modalities at various frequencies), thus do not fall neatly into a given phenotypical category. Indeed, the habitual and preferential recruitment of limbs to produce differential loading patterns in Australian Footballers led to the development of two unique morphological responses between limbs which extended beyond the tibia, to the fibula (a non-articulate bone with the foot, less influenced by impact transmission) (42), evident at all slices. While it is not unusual to see structural differences in the tibia and fibula between athletes of different sports on the basis of disparate exercise loading (21,33,34), it is practically relevant to note this extends to limb-specific, chronic loads within athletes of the same sport (and not just between athletes of different sports), thereby eliminating many confounding issues such as differences in genetics, general health, physical growth and maturation, or nutrition as examples. Most importantly, the largest structural differences were evident at the 14% and 38% slices of the tibia and fibula; noted as the most common regions for stress-related syndromes or fractures that may be prophylactically targeted, should practitioners wish to include more high-impact, odd-impact axial loading to athletes or limbs at risk.

Increasingly, it is evident in the literature and in clinical practice that skeletal examinations aiming to establish fracture risk or quantify bone strength almost exclusively rely on DXA and its areal BMD surrogate as the key stratification marker. However, our results clearly indicate why this is a flawed approach: [1] the significantly stronger limb has significantly less density despite having significantly more mass; and [2] DXA could not detect significant differences in the tibiofibular segment between limbs despite numerous significant differences evident using pQCT. Indeed, structural properties of bone are potent drivers of bone strength yet have an inverse relationship with bone density (i.e. as cross-sectional area increases, the density of an equivalent mass decreases, all while bone strengthens), and cannot be quantified using the low-resolution and two-dimensional capability of DXA. Even small changes in bone structure generate exponential improvements in skeletal fatigue resistance (8,17,43) (a key determinant of stress-related bone injuries (44,45)), such that bone structure should be a principal focus of medical screening, and predominant target of prophylactic and remedial interventions; a skeletal feature responsive only to mechanical stimulation (8,17).

To conclude, functionally different morphological adaptations between limbs were identified, highlighting superior bone structure (and by extension, bone strength) of the support leg at all measured pQCT sites, predominantly in response to more frequent high-impact and odd-impact axial loading relative to the kicking leg. In contrast, the insufficiency of DXA was also demonstrated with its low-resolution, uni-planar images unable to detect significant differences between shank segments. Future research should explore differences between training ages and development stages in Australian Football; and should consider producing normative mid-femoral musculoskeletal data using pQCT (owing to detectable differences in this segment using DXA). Future research should also consider sectoral analyses for injured and non-injured footballers with- and without- stress fractures or associated syndromes.

PRACTICAL APPLICATIONS

Practitioners should use pQCT or an equivalent device to quantify skeletal parameters to better inform medical screening, improve player monitoring and optimise injury risk stratification in football athletes; avoiding an over-reliance on DXA for skeletal examinations. Specifically, muscle-bone measurements in clinical or academic contexts should concurrently quantify and report material, structural and strength variables where possible to be informative and effective for researchers, practitioners and athletes alike, particularly as neither material or structural components can predict bone strength independently and should not be used as surrogate measures in isolation. While DXA is more readily available to practitioners across the world, pQCT machines are increasingly more commonplace in hospital and academic institutions, and are recommended for preferential use where available, with comparable costs per limb scanned (pQCT) relative to a whole-body scan (DXA) depending on providers and their cost structures. However, the increased information and utility of data obtained through pQCT, as evidenced in this (and other) papers, justifies its use within elite or professional sporting bodies.

Lastly, athletes at risk of stress fracture (particularly due to slenderness), or athletes rehabilitating from stress-related syndromes or fractures should consider an exercise program inclusive of controlled high-impact and odd-impact axial loads (akin to the support leg) to target bone structure at potentially susceptible regions of the tibiofibular complex. These may include externally loaded lower-body exercises such as bilateral back squats, front squats and/or deadlifts, prior to graduating to bilateral weightlifting exercises (clean, jerk, snatch) and their derivatives. Externally loaded unilateral exercises such split squats, lunges and step-ups may also be used primarily in the sagittal plane, prior to graduating to multiple directions as tolerated. Bilateral and unilateral plyometric exercises such as jumping, bounding, hopping and unloaded-to-loaded drop jumps may be considered in more advanced footballer. Practitioners should consider the rate at which bone loses mechanosensitivity following repeated bouts of mechanical load, and insert rest periods where appropriate, to ensure skeletal adaptation occurs in the absence of unnecessary skeletal microdamage or fatigue.

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CONFLICT OF INTEREST:

[REDACTED FOR REVIEW] declare no conflicts of interest.

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LEGEND OF TABLES AND FIGURES

Table 1. Lower-body musculoskeletal shank values of the kicking and support limbs for professional Australian Rules Footballers using pQCT.

Table 2. Lower-body musculoskeletal shank values of the kicking and support limbs for professional Australian Rules Footballers using DXA.

Figure 1. Presentation of the DXA (bottom, left), and pQCT (top, left) with the talocrural joint PQCT reference line identified (top, right) and four PQCT tibial slices imaged (bottom, right).

Figure 2. Cross-sectional comparisons of fibular (top) and tibial (bottom) skeletal morphology from proximal (left) to distal (right) at 66%, 38%, 14% and 4% levels. The support leg (dotted line) is superimposed over the kicking leg (solid line), with areas of statistically significant differences outlined (dashed line) at periosteal (outer) and endocortical (inner) circumferences.

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