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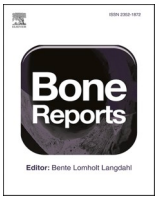

External training load is associated with adaptation in bone and body composition over the course of a season in elite male footballers

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ABSTRACT

This study examined the relationship between training load and changes in body composition and bone characteristics across a competitive season. Twenty senior male professional football players participated in this prospective longitudinal study. Participants underwent dual-energy X-ray absorptiometry (DXA) and peripheral quantitative computed tomography (pQCT) scans on four occasions across the study period, resulting in three phases of the season. Phase 1 (Scan 1-Scan 2: 6-weeks: pre-season), Phase 2 (Scan 2-Scan 3: 24-weeks: first part of the season), and Phase 3 (Scan 3-Scan 4: 13-weeks: second part of the season). External training load was quantified using GPS devices. In Phase 1 there was a significant increase (mean ± SE) in lean mass (from 66.0 ± 1.4 to 67.8 ± 1.4 kg) and a significant decrease in fat mass (from 11.5 ± 0.6 to 10.4 ± 0.6 kg). In Phase 2 there were significant increases in whole-body BMD (from 1.41 ± 0.02 to 1.43 ± 0.02 g/cm^2), leg (from 1563 ± 43 to 1572 ± 43 g) and whole-body BMC (from 3807 ± 100 to 3860 ± 100 g), tibial mass (14 % site) (from 3.72 ± 0.08 to 3.74 ± 0.08 g), tibial strength (SSI(POL)14 % site) (from 2331 ± 78 to 2378 ± 78 mm^3), and tibial density (4 % site) (from 382 ± 8 to 388 ± 8 mm^3). In Phase 3, there was a significant decrease in tibial mass (14 % site) (from 3.74 ± 0.08 to 3.72 ± 0.08 g). Bootstrapped (BCa 95 % CI) Pearson correlations showed that in Phase 2 there were significant positive relationships between the increases in leg BMC and total distance (r = 0.44, 0.01–0.80), accelerations (r = 0.45, 0.08–0.75), and decelerations (r = 0.49, 0.07–0.83), and between the increase in tibial strength (SSI(POL)14 % site) and accelerations (r = 0.53, 0.19–0.80). High magnitude dynamic actions, such as accelerations and decelerations were positively correlated with changes in bone characteristics during a professional football season and should be considered by practitioners when prescribing exercise to induce bone adaptation.

1. Introduction

Mechanical loading is a potent stimulator of osteogenesis (Kohrt et al., 2009). Exercise and physical activity that induce a high magnitude of mechanical loading have been associated with greater bone mass and strength than those that do not (Nilsson et al., 2013), while inadequate exercise volume has been associated with bone loss and osteoporosis (Daly et al., 2019).

A specific exercise program detailing the type, magnitude and volume of exercise required for optimised bone health is yet to be fully established, although activities that require multi-directional movement and high mechanical loads have been associated with increased bone mass (Vlachopoulos et al., 2017; Maïmoun et al., 2013; Seabra et al., 2017) stiffness (Vlachopoulos et al., 2017) and geometry (Maïmoun et al., 2013). Specific information related to the activity metrics that lead to beneficial bone adaptation are required for the accurate prescription of exercise to improve bone health. Football participation requires both multi-directional and high magnitude loading patterns (Clemente et al., 2019). Studies have associated football participation (Varley et al., 2022) with greater bone size, density and cortical

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Table 1
Total GPS training load in the three phases of a professional football season.

	Phase 1		Phase2		Phase 3	
	M	SD	*M*	SD	*M*	SD
TD (m)	185,060	47,671	536,604	135,957	272,083	147,169
HSD (m)	9705	3422	27,185	9481	12,416	7823
VHSD (m)	1793	1131	5908	3057	2644	2073
Accels	548	198	1677	732	847	545
Decels	515	177	1540	644	752	455

Note. TD = total distance, HSD = high speed (>5.5 m/s) distance, VHSD = very high speed (>7 m/s) distance, accels = accelerations (>0.5 m/s^2 for >0.5 s), decels = decelerations (>-0.5 m/s^2 for >0.5 s). *M* = mean, SD = standard deviation.

thickness compared to non-weight bearing sports (Greene et al., 2012). Specifically, we have previously (Varley et al., 2022) shown that bone mineral density (BMD), bone mineral content (BMC) and tibial bone mass and area increased across a competitive season in elite footballers. However, the specific football training stimulus (e.g., running, accelerating, decelerating) required to optimise bone health has not been quantified. Knowledge of the specific exercise variables that cause positive bone adaptations is important for practitioners acting to prevent or treat bone disorders. Insight into how specific exercise variables relate to bone adaption is also important in elite athletes as risk of stress fracture injury in elite footballers has been identified to relate to high-volume pre-season training (Ekstrand and Torstveit, 2012).

Knowledge of the specific football training characteristics that are associated with bone accrual is key to improving the understanding of how exercise relates to bone adaptation. Cross-sectional studies show that moderate (Tobias et al., 2007) and vigorous (Gabel et al., 2017) intensity activity, measured via accelerometer-based activity monitors, is associated with increased bone strength (Tobias et al., 2007; Gabel et al., 2017). These studies did not, however, monitor the type of exercise performed and there are drawbacks to using accelerometers to assess exercise load (Maddison and Mhurchu, 2009). An alternative to monitoring exercise load is to use to use global positioning satellite (GPS) systems, which can provide accurate information on the distance, duration, and speed aspects of movement during exercise (Uth et al., 2016). Only one study has examined how bone characteristics respond to football participation that is quantified by GPS tracking (Uth et al., 2016). A 12-week football participation intervention involving small-sided games increased leg BMC in elderly males with prostate cancer (Uth et al., 2016), although it is not clear how translatable this might be to a young, healthy population. In addition, body composition, particularly lean mass, has been associated with increased bone mass (Vlachopoulos et al., 2017). Football participation has been shown to cause increases in lean mass (Varley et al., 2022; Uth et al., 2016) and, therefore, the change in lean mass could drive changes in bone characteristics.

The aim of the present study was to examine the relationship between GPS-derived training load markers and changes in body composition and bone characteristics, at key stages across a competitive season, in elite footballers.

2. Materials and methods

2.1. Participants

Twenty senior male professional football players volunteered to participate in this study as part of the Bone Health in Elite Athlete Cohort (BEA-C) (Varley et al., 2022). Participants were contracted to the same professional football club in England and were in full time training. Participants were included in the study if they were injury free, had no history of stress fracture injury and not taking any medication known to influence bone metabolism. Across the season, this typically consisted of four 120-minute training sessions incorporating football training, strength and conditioning, tactical and technical drills and one or two competitive matches per week. The study was approved by the National Health Service Research Ethics Committee (Reference 15/EM/0037) and conformed to Ionising Radiation Regulations. Participants provided informed consent to take part in the study.

2.2. Design

This was a season-long prospective longitudinal study. Participants underwent whole-body dual-energy X-ray absorptiometry (DXA) (iDXA, GE Healthcare, UK) and tibial peripheral quantitative computed tomography (pQCT) (XCT2000L, Stratec Medizintechnik) scans on four occasions across the study period. Scan 1 occurred at the start of the pre-season training period (n = 20). Scan 2 occurred after 6 ± 1 (mean ± 1SD) weeks, at the end of the pre-season period/start of competitive matches (n = 20). Scan 3 occurred at 30 ± 1 weeks, during the season (n = 20) and scan 4 occurred at 43 ± 1 weeks, at the end of the season (n = 17) (Supplementary information). This allowed changes in DXA and pQCT variables to be calculated during three stages of the football season that are practical and of importance to the applied practitioner: Phase 1 (Scan 1–Scan 2: a 6-week period of pre-season), Phase 2 (Scan 2–Scan 3: a 24-week period in the first part of the competitive season), and Phase 3 (Scan 3–Scan 4: a 13-week period in the second part of the competitive season). Players were monitored using GPS devices during training, which also allowed external training load to be quantified. In turn, this allowed relationships between training load indicators and changes in body composition/bone characteristics to be explored.

Table 2
Multilevel models showing changes in average weekly GPS training load across three phases of a professional football season.

	Weekly TD (m)		Weekly HSD (m)		Weekly VHSD (m)		Weekly accels		Weekly decels	
	Est	S.E.	Est	S.E.	Est	S.E.	Est	S.E.	Est	S.E.
Fixed part										
Phase 1	32,070	1150	1686	85	323	34	98	7	93	6
Phase 2	17,708[a]	1150	898[a]	85	195[a]	34	56[a]	7	51[a]	6
Phase 3	6290[b]	1212	277[b]	89	[54b]	35	19[b]	7	18[b]	6
Random part										
Intercept variance	–	–	62,856	29,585	10,210	4736	411	186	327	155
Residual variance	26,433,511	4,908,580	82,097	18,837	12,834	2947	472	108	438	101
−2LL	1156		844		737		547		540	

Note. TD = total distance, HSD = high speed (>5.5 m/s) distance, VHSD = very high speed (>7 m/s) distance, accels = accelerations (>0.5 m/s^2 for >0.5 s), decels = decelerations (>-0.5 m/s^2 for >0.5 s). Est = estimate. S.E = standard error. For the fixed part of the models, independent intercepts are displayed for each phase of the season. [a] indicates significant changes between Phase 1 and Phase 2, [b] indicates significant changes between Phase 2 and Phase 3. For the random part of the models, the intercept variance is the estimated between-player variance in intercepts. The residual variance is the estimated within-player variance −2LL = −2 * loglikelihood for the final model. $p < 0.05$.

Table 3
Multilevel models showing changes in DXA across three phases of a professional football season.

	Fat mass (g)		Lean mass (g)		Legs BMD (g/cm^2)		Total BMD (g/cm^2)		Legs BMC (g)		Total BMC (g)		Legs area (cm^2)		Total area (cm^2)	
	Est	S.E.	Est	S.E.	Est	S.E.	Est	S.E.	Est	S.E.	Est	S.E.	Est	S.E.	Est	S.E.
Fixed part																
Scan 1	11,462	562	66,062	1353	1.64	0.03	1.42	0.02	1559	43	3802	100	947	17	2677	43
Scan 2	10430[a]	562	67773[a]	1353	1.64	0.03	1.41	0.02	1563	43	3807	100	949	17	2687	43
Scan 3	10,856	562	67,233	1353	1.64	0.03	1.43[b]	0.02	1572[b]	43	3860[b]	100	954	17	2692	43
Scan 4	10,766	568	67,370	1357	1.66	0.03	1.42	0.02	1569	43	3839	101	944	17	2689	43
Intercept variance	5,710,357	1,854,043	35,642,329	11,348,523	0.01	<0.01	0.01	<0.01	36,856	11,672	200,420	63,488	5510	1768	35,907	11,426
Residual variance	602,849	112,976	944,535	176,932	<0.01	<0.01	<0.01	<0.01	195	37	1330	249	323	61	861	161
−2LL	1316		1378		−253		−319		756		900		747		840	

Note. DXA = dual-energy X-ray absorptiometry. BMD = bone mineral density. BMC = bone mineral content. Est = estimate. S.E = standard error. For the fixed part of the models, independent intercepts are displayed for each scan of the season. [a] indicates significant changes between Scan 1 and 2, [b] indicates significant changes between Scan 2 and 3. For the random part of the models, the intercept variance is the estimated between-player variance in intercepts. The residual variance is the estimated within-player variance. −2LL = −2 * loglikelihood for the final model. $p < 0.05$.

2.3. Procedures

Body composition and bone characteristics were measured using whole-body DXA and tibial pQCT. Each participant completed a health status questionnaire prior to each testing session. Stature (Stadiometer, Seca, Hamburg, Germany) and body mass (Seca, Birmingham, UK) were recorded with participants wearing minimal clothing. The same manufacturer-trained operator performed all measures consistent with the manufacturer's guidelines. Calibrations of the DXA and pQCT were completed prior to scanning using phantoms of a known density. Participants were asked to wear minimal clothing or a cotton examination gown and remove any jewellery or metal prior to the scan to avoid measurement distortion. Participants fasted for at least 2 h, emptied their bladder immediately before and were asked to be euhydrated prior to the scan.

2.3.1. Dual-energy X-ray absorptiometry

Whole-body DXA scans assessed participant areal BMD, BMC, area, lean and fat mass. Participants were positioned supine on the DXA bed within the scanner range, with ankles and knees held in place by Velcro straps to minimise unintended movements. The participants laid with arms by their sides and were asked to remain motionless for the duration of the scan. Subsequent segmental analysis for all scans was completed by the same trained operator. Coefficients of variation for the model of scanner used 0.08–1.30 % (BMD) and 0.6 % (fat mass) (Norcross and Van Loan, 2004; Ward et al., 2007). If any movement artefacts (inaccuracies in the measurement caused by motion) were present following the scan, the image was classed as invalid, and a repeat measure was performed. To assess for artefacts, the image was initially visually inspected by the researcher performing the scan. If an artefact was thought to exist, the image was viewed by a second researcher that was also trained in the scanning procedure.

2.3.2. Peripheral quantitative computed tomography

pQCT assessed the following tibial characteristics and sites: mass (4 %, 14 %, 38 %, g), stress strain index polar (SSIPOL) (a bending strength estimator that accounts for torsional load) (14 %, 38 %, mm^3), trabecular area (4 %, mm^2), trabecular density (4 %, mg·cm^{-3}), cortical area (14 %, 38 %, mm^2), cortical density (14 %, 38 %, 66 %, mg·cm^{-3}) cortical thickness (14 %, 38 %, mm), periosteal circumference (14 %, 38 %, mm) and total area (14 %, 38 %, 66 %, mm^2). pQCT scans were taken of the dominant (preferred kicking leg) lower leg. pQCT has previously been shown to provide a reliable measurement of bone characteristics in humans (Izard et al., 2016). Each participant's tibial length was measured to the nearest 1 mm (manufacturer supplied rigid ruler), determined as the midpoint of the medial malleolus to the medial aspect of the tibial plateau. The tibial length recorded in scan 1 was used for all subsequent scans to ensure the same region of the tibia was being measured. The participant's leg was placed in the scanner with their foot secured in a purpose-built attachment. The leg was aligned with use of an integrated laser and a clamp was placed to the knee to reduce movement, with the participant instructed to remain as still as possible for the duration of the scan. A preliminary reference point locating scout-view scan was performed in the frontal plane to confirm the location of the middle of the distal end plate, which would act as a positioning line. Sectional images were then obtained at distal sites (4 %, 14 % of tibial length) and the diaphysis of the tibia (38 %, 66 % of tibial length) from the positioning line with a voxel size set at 0.5 mm and a slice thickness of 2.5 mm for all measurements. Contour mode 1, with a threshold of 180 mg·cm^3, was used to separate soft tissue and bone. Peel mode 1 was used to analyse trabecular bone, a constant default threshold of 711 mg·cm^3 was used to identify and remove cortical bone. The integrated XCT2000L software (6.20A) was used to analyse the images. If any movement artefacts (inaccuracies in the measurement caused by motion) were present following the scan, the image was classed as invalid, and a repeat measure was performed. In the present

Table 4
Multilevel models showing changes in pQCT across three phases of a professional football season.

	Mass 4 % (g)		Mass 14 % (g)		Mass 38 % (g)		SSIPOL 14% (mm^3)		SSIPOL 38 % (mm^3)		Area 4 % (mm^2)		Area 14 % (mm^2)	
	Est	SE	Est	SE	Est	SE	Est	SE	Est	SE	Est	SE	Est	SE
Fixed part														
Scan 1	5.31	0.12	3.71	0.08	5.11	0.11	2352	78	2477	65	1388	38	591	17
Scan 2	5.34	0.12	3.72	0.08	5.11	0.11	2331	78	2434	65	1404	38	593	17
Scan 3	5.34	0.12	3.74[b]	0.08	5.14	0.11	2378[b]	78	2478	65	1388	38	595	17
Scan 4	5.33	0.12	3.72[c]	0.08	5.21	0.11	2357	78	2530	66	1387	39	589	17
Random part														
Intercept variance	0.29	0.09	0.12	0.04	0.20	0.07	115,600	36,879	68,517	22,870	28,285	9041	5407	1720
Residual variance	0.01	<0.01	<0.01	<0.01	0.03	0.01	4943	927	14,810	2776	1258	236	120	23
−2LL	−69		−186		3		964		1017		857		690	

Note. pQCT = peripheral quantified computed tomography. SSIPOL = polar stress strain index, cortical thick = cortical thickness, perio circum = periosteal circumference, endo circum = endosteal circumference. Est = estimate. SE = standard error. For the fixed part of the models, independent intercepts are displayed for each scan of the season. [b] indicates significant changes between Scan 2 and 3. [c] indicates significant changes between Scan 3 and 4. For the random part of the models, the intercept variance is the estimated between-player variance in intercepts. The residual variance is the estimated within-player variance. −2LL = −2 * loglikelihood for the final model. $p < 0.05$.

study, no participants were removed from the analysis due to artefacts.

2.4. Training load

The study period was aligned with a full football season. Participants engaged in their normal training and competition practices associated with being senior professional footballers. The physical demands for all outdoor matches and training sessions were monitored using a 10 Hz GPS (Viper, STATSports, Ireland). This system has been validated for use by team sport players, demonstrating a bias of 1.80 ± 1.93 % in peak speed during a 20 m sprint, when assessed by GPS (26.3 ± 2.4 $km{\cdot}h^{-1}$) and radar gun (26.1 ± 2.6 $km{\cdot}h^{-1}$) (Beato et al., 2018). Each player wore a harness containing a GPS unit positioned between the shoulder blades. Post-session, each GPS unit was downloaded and analysed using commercially available software (Viper, STATSports, Ireland). The training variables assessed included: total distance covered (m), high speed (>5.5 m/s) distance covered (m), very high speed (>7.0 m/s) distance covered (m), number of accelerations above 0.5 m/s^2 for >0.5 s, and number of decelerations below −0.5 m/s^2 for >0.5 s. Totals of each of these variables for each player were calculated for each phase of measurement (Phase 1: Scan 1-Scan 2; Phase 2: Scan 2-Scan 3; Phase 3: Scan 3-Scan 4).

2.5. Data analysis

2.5.1. Examining change across the season

The present study represents a hierarchically structured data set, with repeated measures nested within players. Thus, changes in players' DXA, pQCT, and GPS variables across key points of the season were examined using multilevel modelling (MLwiN, v 3.05, Bristol, UK). Following Rasbash et al. (2017), random intercept models were developed, whereby a two-level structure was defined (assessment occasion (level 1) nested within players (level 2)), with a given DXA, pQCT, or GPS variable as the continuous response variable for each model. The (random) effect of allowing the intercept to vary was examined, which allowed between-player variation in the response variable to be modelled. The fixed effect of time point was examined, to determine whether the response variable changed across the season. To allow dose-response relationships to be subsequently examined, a major purpose of this analysis was to determine the change within consecutive phases of the season, e.g., changes in fat mass between Scan 1-Scan 2 (i.e., Phase 1), between Scan 2-Scan 3 (i.e., Phase 2) and between Scan 3-Scan 4 (i.e., Phase 3). Thus, while the main effect of time was included in each model, interest lies in the effect of consecutive time points on the response variable. Indeed, the delta in each variable was subsequently calculated for significant changes in DXA and pQCT variables between each time point. The assumption that variance in random effects followed a normal distribution with a mean of zero, was checked following each analysis. Statistical significance was accepted at the 95 % confidence level ($p < 0.05$).

2.5.2. Dose-response relationships

To examine whether there was a dose-response relationship between changes in body composition/bone characteristics and training load in each phase of the season/study, significant delta change in DXA and pQCT variables were then correlated with total GPS training load indicators using Pearson correlations. R-values were used to indicate effect size. Due to deviations from normality, data were analysed using robust bootstrapped procedures. Bootstrapping allows confidence intervals to be accurately estimated empirically for a given test statistic and so correlation analyses were performed using bias corrected and accelerated bootstrap confidence intervals with a 95 % confidence level (95 % CI, BCa) and 2000 resamples. Instead of p-values, correlations were interpreted with regards to the bootstrapped confidence intervals and effect sizes as this method has greater validity when distributions deviate from normality (Field and Wilcox, 2017). Correlations were conducted using IBM SPSS (v. 26).

3. Results

At the start of the study, participants had a mean (±1SD) decimal age, body mass, and stature of 25.2 ± 4.7 years, 80.89 ± 7.68 kg and 1.82 ± 0.07 m. The total GPS training loads associated with Phases 1, 2, and 3 of the season are displayed in Table 1. Table 2 displays the multilevel models for changes in average weekly GPS training load across the three phases of the season. There were significant decreases in weekly average total distance, high-speed running distance, very-high-speed running distance, accelerations, and decelerations between Phases 1 and 2. Similarly, there were significant decreases in weekly average total distance, high-speed running distance, very-high-speed running distance, accelerations, and decelerations between Phases 2 and 3. There was significant random variation in the intercept for all models, except total distance (see Table 2).

Tables 3 and 4 show changes in DXA and pQCT variables across key time points in the season. Between Scan 1 and Scan 2 (i.e. in Phase 1) there was a significant decrease in total fat mass and a significant increase in total lean mass (see Table 3). Between Scan 2 and Scan 3 (i.e., in Phase 2), there were significant increases in total BMD, Legs BMC, and whole-body BMC. There was significant random variation in the intercept for all models (see Table 3).

Area 38 % (mm^2)		Density 4 % ($mg \cdot cm^3$)		Density 14 % ($mg \cdot cm^3$)		Density 38 % ($mg \cdot cm^3$)		Cortical thick 14 % (mm)		Cortical thick 38 % (mm)		Perio circum 14 % (mm)		Perio circum 38 % (mm)		Endo circum 14 % (mm)		Endo circum 38 % (mm)	
Est	S.E.	Est	S.E.	Est	S.E.	Est	S.E.	Est	S.E.	Est	S.E.	Est	S.E.	Est	S.E.	Est	S.E.	Est	S.E.
534	11	385	8	633	14	957	10	3.40	0.10	6.97	0.12	86.02	1.21	81.90	0.80	64.66	1.62	38.10	0.95
535	11	382	8	632	14	955	10	3.38	0.10	6.96	0.12	86.19	1.21	81.92	0.80	64.94	1.62	38.18	0.95
538	11	388[b]	8	635	14	956	10	3.40	0.10	6.95	0.12	86.28	1.21	82.19	0.80	64.93	1.62	38.49	0.95
549	12	386	8	636	14	953	10	3.42	0.10	6.96	0.12	85.84	1.21	82.85	0.83	64.34	1.62	39.23	1.00
1483	550	1267	404	3846	1220	1694	565	0.18	0.06	0.26	0.09	28.52	9.07	8.54	3.07	50.71	16.16	8.96	3.60
954	179	39	7	46	9	365	69	0.01	<0.01	0.03	0.01	0.62	0.12	4.35	0.81	1.45	0.27	8.93	1.67
786		597		629		732		−84		15		285		375		345		419	

Between Scan 2 and Scan 3, there were also significant increases in tibial mass (14 % site), tibial strength (SSI(POL)14 % site), and tibial density (4 % site) (see Table 4). Between Scan 3 and Scan 4 (i.e., in Phase 3), there was a significant decrease in tibial mass (14 % site). There was significant random variation in the intercept for all models (see Table 4).

For the significant changes in DXA and pQCT variables in Phase 1, the delta in each variable was calculated, and then correlated with total distance, high speed running, very high-speed running, accelerations and decelerations completed in Phase 1. This process was repeated for Phases 2 and 3. In Phase 1, there were no relationships between changes in fat mass and lean mass with any training load markers (Fig. 1).

In Phase 2 there were significant positive relationships between the increases in leg BMC and total distance (r = 0.44, BCa 95 % CI: 0.01 to 0.80), accelerations (r = 0.45, BCa 95 % CI: 0.08 to 0.75), and decelerations (r = 0.49, BCa 95 % CI: 0.07 to 0.83) (Fig. 1). There was a significant positive relationship between the increase in tibial strength (SSI(POL)14 % site) and accelerations (r = 0.53, BCa 95 % CI: 0.19 to 0.80) (Fig. 1). However, there was no relationship between changes in whole-body BMD, whole-body BMC, tibial mass (14 % site) and tibial density (4 % site) with any training load markers (Fig. 1). In Phase 3, there was no relationship between the change in tibial mass (14 % site) with any training load markers (Fig. 1).

4. Discussion

The present study was the first assessment of the relationship between GPS-derived training load markers and changes in bone and body composition characteristics of elite footballers during a competitive season. Significant positive correlations were shown during the first part of the season (Phase 2) between total distance, number of accelerations and decelerations with change in BMC of the legs. The number of accelerations was also positively correlated with change in tibial strength (SSIPOL 14 %) during the first part of the season (Phase 2). This suggests that seasonal time-point and distinct exercise characteristics have divergent effects on bone adaptation in elite athletes.

The relationships shown between GPS-derived performance variables and changes in bone characteristics provide an insight into the specific components of football training that cause bone adaptations to occur. The positive correlations between accelerations and decelerations with change in BMC (legs) and tibial strength (SSIPOL 14 % - accelerations only) may be the results of the high magnitude of mechanical loading that results from these actions. For example, decelerations have been shown to cause a greater amount of force and assumed mechanical loading to the bone in comparison to continuous activities (Dalen et al., 2016). This premise may be one of the factors, in addition to aspects such as energy availability, that explain the findings of Fredericson et al. (2007) who showed a greater whole-body BMD in football players compared to long-distance runners whose sport doesn't necessitate a high number of high magnitude activities, such as decelerations. Studies assessing high magnitude movements, such as jumping, have shown also shown increases in BMD (Vlachopoulos et al., 2017), area (Nilsson et al., 2010) and BMC (Gunter and Almstedt, 2012). Furthermore, the number

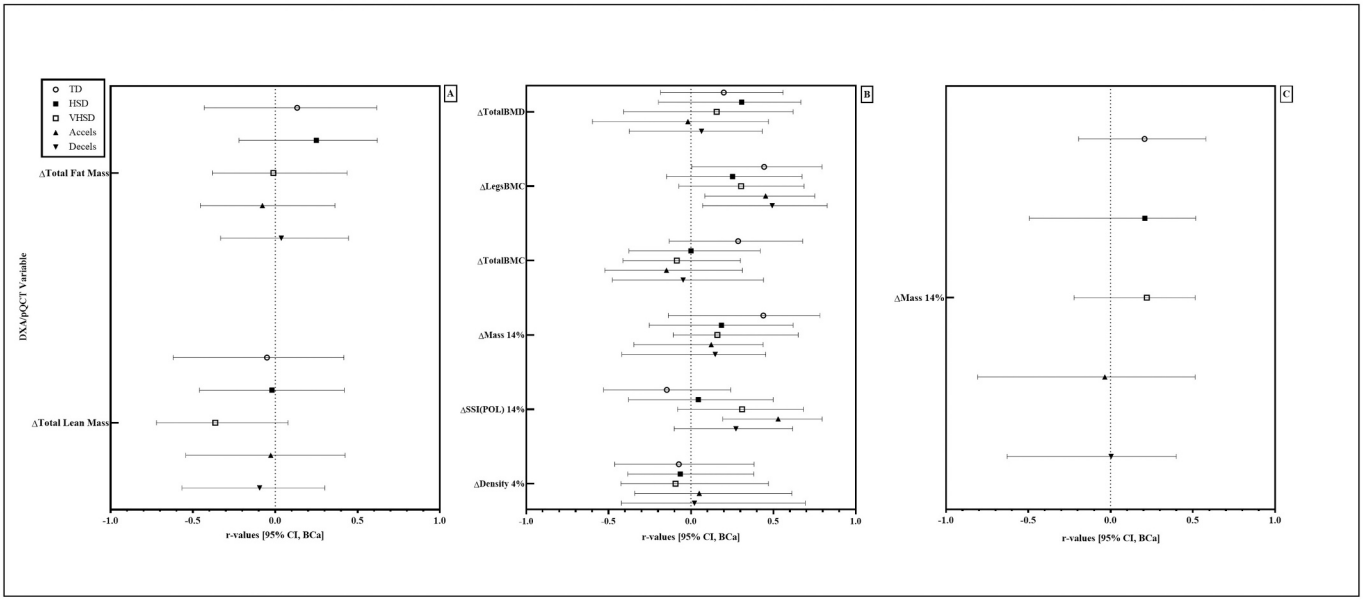

Fig. 1. Relationships at the BCa 95 % CI between changes in DXA and pQCT markers and training load markers during Phase 1 (a), Phase 2 (b) and Phase 3 (c).

of decelerations performed has been correlated with increases in leg BMC following a 12-week small-sided game football intervention in elderly men with prostate cancer (Uth et al., 2016). Total distance was positively associated with the increase in legs BMC during the first part of the season (Phase 2). These associations could be due to the assumed increase in site-specific osteogenic high magnitude loading (i.e., jumping/landing, change in direction (Daneshjoo et al., 2015; Condello et al., 2016)) that likely to have occurred in players covering a greater distance and/or the ability of the pQCT to detect small changes relative to the measurement error. The positive correlation of high magnitude GPS-derived variables with bone characteristics in the present study underpins the important role for high magnitude activities in the osteogenic effect of football participation.

Although, changes in bone characteristics were evident, the changes shown were not uniform across all skeletal sites measured. The divergent changes shown may be due to bone adapting in a site-specific manner, with differing responses in, for example, bone geometry and mass occurring simultaneously at different segmental regions of the same measurement site. It can be speculated that bone may accrue in a specific area (e.g., anteriorly) in line with the loading applied, but decreased in another (e.g., posteriorly) causing no net change in the aspect of bone that is being measured (Weatherholt and Warden, 2016). Football participation typically involves multi-directional movement patterns, although the direction of activity and segmental analysis was not measured in the current study, so these assertations are speculative. It is, however, advised that segmental analysis of tibial structures is conducted in future studies to gain a greater insight into the site and direction specific bone adaptions.

The present study showed correlations between bone characteristics and GPS-derived performance variables to be phase of the season specific. Studies have previously reported increases in bone characteristics during a competitive season (Varley et al., 2022; Weidauer et al., 2014; Minett et al., 2017); BMD, BMC, and tibial bone mass and area increased across a season in elite male footballers (Varley et al., 2022). Similarly, Weidauer et al. (2014) showed increases in tibial cortical area and thickness (20 % site) from pre- to post-season and Minett et al. (2017) reported increases in tibial cortical area, cortical BMC and periosteal circumference (20 % site) between pre and post-season in female collegiate footballers. Unlike the present study, none of these studies monitored training volume, and only pre- and post-season scans were conducted, which meant that the specific activities causing increases in bone characteristics and seasonal fluctuations could not be established. The difference in bone adaptations shown between the present study and previous studies could be due to contextual variables, such as the playing surface (Miyamori et al., 2019) and the type of training undertaken by participants. As previous studies have not reported their training characteristics, however, the reason for the differences in findings remains speculative.

Specific physical performance variables have been associated with bone adaptations in a population of elderly men with prostate cancer undergoing androgen deprivation therapy. Uth et al. (2016) showed positive correlations between legs BMC and total distance covered, number of accelerations and decelerations performed following 12-weeks of playing small-sided football matches. The effects of androgen deprivation therapy (Smith et al., 2002) and prostate cancer (El Badri et al., 2019) on bone are, however, likely to influence the outcomes of this study, that might not necessarily be expected in a healthy population. Exercise and androgen deprivation and/or prostate cancer interactions and its effect on bone are likely to be complex and are not fully understood, although, despite this, the findings of the present study and those of Uth et al. (2016) are similar. In line with Uth et al. (2016), the present study showed positive relationships between changes in legs BMC and total distance, accelerations, and decelerations during the season. The current study extends the work of Uth et al. (2016) by showing that as well as relationships between GPS-derived training load and changes in DXA-derived measures, relationships exist between training load and changes in pQCT variables. Taken together, the positive correlations between GPS-derived training load markers and changes in bone characteristics in elite footballers in the present study and in elderly, prostate cancer sufferers (Uth et al., 2016) further underpins the importance of high magnitude dynamic actions for osteogenesis (Turner and Robling, 2003).

The present study used GPS to monitor player performance variables over a 9-month period. Physical performance training characteristics are not commonly recorded in studies assessing bone adaptations in relation to exercise (Carling and Orhant, 2010; Milanese et al., 2015). Previous studies assessing how quantified physical activity influences bone characteristics have typically monitored activity status using training volume (Varley et al., 2017; Lorentzon et al., 2005), and hip-mounted accelerometer-based activity trackers over a period of 3–7 days (Sayers et al., 2011; McMillan et al., 2018). Due to the inability of volume or accelerometer-based activity trackers to quantify football-based movement characteristics the specific physical performance variables that optimise bone characteristics cannot be elucidated (Maddison and Mhurchu, 2009). Conversely, in the present study GPS allowed aspects of football specific training, such as speed of running, number of accelerations and decelerations to be captured. The correlations between GPS derived performance metrics and changes in bone characteristics in the present study provide a more tangible resource for those looking to produce osteogenic exercise programmes. Likely due to imprecise measurement methods and the short time scale of previous studies, ambiguity exists in the quantification of exercise and resultant bone adaptations. While increasing the volume of football specific training has been shown to increase bone area and BMD (Varley et al., 2017) and 4 h of physical activity per week was associated with a greater cortical bone size (Lorentzon et al., 2005), the number of steps taken per day has been negatively associated with BMD (McMillan et al., 2018) and light and moderate physical activity was unrelated to cortical mass in adolescence, regardless of time spent exercising at this intensity (Gabel et al., 2017; Sayers et al., 2011) The present study clarifies the specific aspects of football training that result in a bone adaptive response by using a more objective measures of exercise, namely GPS.

Independent of GPS-derived training characteristics, BMC (legs and whole-body), BMD (whole-body, 4 % of tibia), tibial strength (SSIPOL) (14 %) and tibial mass (14 %) increased during the first part of the season (Phase 2). No changes in bone characteristics were shown in pre-season (Phase 1) and only tibia mass (14 %) changed in the second part of the season (Phase 3). These changes are in line with previous findings showing that bone characteristics increased following an increase in training load (Varley et al., 2017). The increase in the aforementioned bone characteristics is likely to be a result of the increased training load experienced between the off season (prior to Scan 1) and (Scan 3) in the first part of the competitive season (30-weeks). This time-period is sufficient for the bone to respond from the training stimulus that occurred during the early season.

The contrasting findings related to the stage of the season and the changes in bone characteristics could be due to the seasonal time-point at which the scans were conducted, the nature of activity at that part of the season, and the time difference between each scan. The lack of changes in bone characteristics during Phase 1 may be due to the short time-period between scans. Body composition changes were shown, however, as there was only 6-weeks between the scans conducted in Phase 1, a complete bone remodelling cycle will not have taken place (Watts, 1999). The limited changes during Phase 3 may reflect the decrease in training volume between Phase 2 and Phase 3 (Tables 1 and 2). Also, the increases in bone characteristic during Phase 2, may have reduced the potential for the bone to adapt. The difference in the response of bone characteristics to football training activity at different seasonal time points highlights the importance of monitoring bone health at multiple season periods rather than at pre- and post-season time points only.

The present study showed that fat mass decreased, and lean mass

increased during Phase 1, although there were no correlations with specific GPS derived performance variables. There were no changes at the other phases of the season. Seasonal changes in body composition have been shown in footballers but have not been related to specific aspects of training (Varley et al., 2022; Carling and Orhant, 2010; Milanese et al., 2015). Footballers' lean mass has been shown to increase during pre-season and then be maintained for the rest of the season (Carling and Orhant, 2010; Milanese et al., 2015). This is likely to be due to the increased training taking place during the pre-season period in comparison to the off-season. The findings of the present study may reflect that those changes in body composition are derived from multiple factors including diet and other, unobserved training markers.

4.1. Limitations

The present study was not without limitation. External loading derived from GPS can only be used as an estimate of bone loading and may not reflect the ground reaction forces and internal loading experienced by the bone. However, daily monitoring of ground reaction force and internal bone loading in a population of elite athletes over the course of a season is not yet practically possible. It is acknowledged that the participants would have experienced loading during match-play, which was not assessed during the present study. At the time of data collection, GPS units were not permitted to be worn during match-play. The training characteristics a player demonstrates in training are likely to be similar to those during match-play, and the authors are confident that the training data captured is an accurate representation of the loading the players experienced. The loading players experienced before the study commenced may have influenced the participants bone characteristics and subsequent bone adaptations. As all participants in the study were professional footballers and had been training with professional football clubs for 10+ years, the pre-study loading experienced by each player is likely to have been of a similar type and volume.

5. Conclusion

High magnitude dynamic actions, such as accelerations and decelerations were positively correlated with changes in bone characteristics. These finding suggest that high magnitude dynamic actions are key to the osteogenic effect of football training, which is likely the result of a greater mechanical loading stimulus. Due to this, acceleration and deceleration actions should be considered by practitioners when prescribing exercise to induce osteogenic actions.

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CRediT authorship contribution statement

Ian Varley: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Supervision, Project administration. **Marcus Ward:** Investigation, Writing – review & editing. **Chris Thorpe:** Investigation, Writing – review & editing. **Nathan Beardsley:** Investigation, Writing – review & editing. **Julie Greeves:** Resources, Writing – review & editing. **Craig Sale:** Methodology, Writing – review & editing. **Chris Saward:** Formal analysis, Investigation, Writing – review & editing, Project administration.

Declaration of competing interest

None.

Data availability

Data will be made available on request.

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