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Original Article

Side-to-side differences in bone strength in master jumpers and sprinters

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Abstract

Introduction: This study evaluated side-to-side difference in tibial bone structure, calf muscle cross-sectional area (CSA) and hopping force in master athletes as a result of training for sports with different magnitudes of inter-leg loading difference. **Methods:** Tibial bone parameters (at 4%, 14%, 38% and 66% tibial length proximal to distal end), muscle CSA (at 66% tibial length) and hopping forces of both legs of 51 master athletes (conditioned jumpers, conditioned triple jumpers, unconditioned jumpers, hurdlers and sprinters) were examined using pQCT. In epiphyseal 4% slice bone CSA (Ar.tot), total BMC (vBMC.tot), trabecular BMC (vBMC.tb) cortical BMC (vBMC.ct), and trabecular BMD (vBMD.tb) were measured. In diaphyseal slices, Ar.tot, vBMC.ct, cortical density (vBMD.ct), cross-sectional moment of inertia (CSMI) and calf muscle CSA (MuscA) were examined. **Results:** In conditioned jumpers, side-to-side differences in favour of take-off leg were found in 4% slice in vBMC.tb (+4.1%) ($P<0.05$). A side-to-side difference was found in 66% slice vBMC.ct and CSMI (both $P<0.05$), with conditioned jumper (+2.8% and 6.6%) and triple jumper (+2.7% and 7.2%) values higher than other groups. **Conclusion:** The results suggest that regular training in high-impact sports with uneven lower limb loading results in side-to-side differences in skeletal adaptation independent of age and gender, suggesting that high-impact exercise is effective in maintaining bone strength throughout human lifespan.

Keywords: Ageing, Exercise, Loading, pQCT

Introduction

Exercise is effective in improving and maintaining bone mineral content (BMC), bone mineral density (BMD), cross-sectional area (CSA) and moment of inertia (which relates to bone bending strength) of elderly subjects[17,38]. Comparing bone strength parameters of athletic populations with those of non-exercising control people introduces potentially confounding genetic, hormonal and nutritional factors[15], whereas allocating participants to exercise and control groups and studying them throughout their lifetime has certain logistical and ethical obstacles. However, these limitations are partially overcome when comparing the effect of differences in the loading of limbs, as occurs in (for example) jumping athletes, gymnasts and tennis players. Previous studies involving athletes participating in sports with uneven loading patterns have found side and loading pattern-specific differences in bone between the playing and non-playing arm (tennis)[10,15] and dominant and non-dominant leg (gymnastics)[39]. These side-to-side differences are similar to those observed in comparisons between exercising individuals and non-exercising controls[1,12,16]. In addition, side-to-side differences in bone parameters of tennis players were found to correlate with those in muscle mass and grip strength[7], supporting the idea of a strong relationship between muscle and bone.

In the leg, the forces experienced by the bone during exercise are a combination of ground reaction forces (GRFs) and the forces exerted by the muscles[30]. Accordingly, there seems to be a close anatomical relationship between the musculature and bone during growth. In addition, the osteogenic stimulus of muscular forces acting upon the bone seem to be a prerequisite to prevent immobilisation-induced bone losses[3,26,29,30]. Leg

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power output (as measured by jumping mechanography) reduces by ~50% between the ages of 20 and 80 in healthy, physically competent but non-athletic elderly people, with much more moderate changes in peak hopping force and no concurrent decrease in muscle CSA[35]. Even in master athletes, i.e. in people who train for and compete in running events beyond the age of 35, there is a progressive decline in running speed and ground reaction forces[18,32] along with muscle strength[17] with increasing age. Therefore, it is plausible that the age related decline in tibial bone strength in older athletes who continue to train[39] is an effect of the reduced musculoskeletal forces. Bone responds to dynamic rather than static loading[13], and high-impact sports (such as gymnastics or volleyball) produce more pronounced adaptations than participation in low-impact sports such as cycling[23]. The jumping disciplines within athletics offer an opportunity to study high-impact events with varying asymmetric loading patterns; hurdling, pole vault, long, high and triple jump have different magnitudes of inter-leg loading difference– e.g. ~10% in hurdling[5] and ~20% in triple jump[25], whereas in sprinting there is no significant level of inter-leg loading difference[19]. Regular training in these events will cause the legs to experience differing levels of inter-leg loading difference, and so differential adaptations should occur.

The aim of this study was therefore to investigate side-to-side differences in the tibiae of master athlete sprinters, hurdlers and jumpers. We used pQCT to quantitatively measure side-to-side differences in trabecular and cortical bone structure and muscle cross-sectional area of athletes representing disciplines with different magnitudes of inter-leg loading difference - maximal hopping force was measured using a force platform. Similarly, data from jumpers who compete but do not regularly train would provide some additional insight into the importance of exposure volume[37]. Taken together, the outcome of the study provides information on how different magnitudes and types of bone loading are associated with muscle force, muscle CSA and bone strength parameters and if and how the association of high-impact exercise with bone strength parameters changes with age.

Participants and Methods

Participants

Fifty-one master athletes (23 male, 28 female – average age 54.9±12.4 yrs) competing at the World Masters Athletics Championships in Lahti, Finland in 2009 were recruited for this study. Subjects were included when they reported to be in good health and with no leg fractures within the preceding 24 months, which was ascertained by a short interview with a medical doctor. The study conformed to Declaration of Helsinki guidelines and was approved by both Manchester Metropolitan University's and the local Ethics Committee prior to the start of the study – informed written consent was obtained from all subjects prior to their participation.

Information was collected from each participant on their history of competing in various athletic events (high jump, long jump, triple jump, pole vault, hurdles and sprinting). More precisely, participants were asked the age they started and/or stopped competing and the number of hours training per week they routinely completed in each sprinting and jumping discipline. Participants were also asked for their preferred take-off leg in each jumping event (or hopping/starting block push-off leg in non-jumpers), which is subsequently referred to as their dominant leg. Age, height, body mass and their performances in the championships were also recorded, as well as their preferred event. Their performances during the Lahti championships were age-graded using the World Master Athletes (WMA) age-grading factors and Age-Graded Performance (AGP) calculator at http://www.howardgrubb.co.uk/athletics/wmalookup06.html. This grades performances as a percentage relative to the world record for their age in that event. The athletes were then grouped either as: i) pole vaulters, high or long jumpers who regularly completed jump-specific training as part of their weekly training schedule (subsequently referred to as 'conditioned jumpers', ii) triple jumpers who included jump training, (referred to as 'conditioned triple jumpers'), iii) hurdlers, iv) sprinters (who did not engage in jumping events) or v) unconditioned jumpers (i.e. those who competed regularly in jump events but did not complete regular training for this event). The latter group were typically people whose main events were sprinting competitions.

	ConJ N=21	**TriJ N=8**	**UncJ N=6**	**Hurd N=7**	**Sprt N=9**
ConJ	N/A	8	N/A	0	N/A
TriJ	5	N/A	N/A	0	N/A
Hurd	8	0	N/A	N/A	N/A
Sprt	18	4	6	1	N/A

(ConJ – Conditioned Jumpers, TJ – Conditioned Triple Jumpers, UncJ – Unconditioned Jumpers, Hurd – Hurdlers, Sprt – Sprinters).

Table 1. Number of athletes also training for events other than their main event (main event emboldened at top).

Bone measurements

Tibial scans were taken with a Stratec XCT-2000 or XCT-3000 pQCT scanner (Stratec Medizintechnik GmbH, Pforzheim, Germany) as outlined previously[35]. Scans were taken at four sites of the left and right tibia, corresponding to 4%, 14%, 38% and 66% tibial length, where 0% corresponds with the tibio-talar joint. The bone experiences mainly compressive force at 4% and 14% sites, whereas bending forces are a more important stressor of the bone at 38% and 66%[4] – muscle CSA measurements were examined at the 66% site to examine the muscle-bone relationship. Measurements were then exported using the Automated Analysis Tools in Version 6.00 of the software supplied with the machine. A peeling threshold of 650 mg·cm^3 was set for diaphyseal and metaphyseal sections of bone, with a threshold of 180 mg·cm^3 set for the epiphyseal 4% slice. Only the inner 45% of bone was selected for analysis in the epiphysis, and in all cases the default contour, peeling

	ConJ N=21	TriJ N=8	UncJ N=6	Hurd N=7	Sprt N=9	Total N=51
Number of males/females	9/12	2/6	3/3	6/1	4/5	**24/27**
Age, years	54.4 (10.8)	58.9 (12.9)	60.0 (16.8)	50.4 (12.7)	55.1 (13.3)	**54.9 (12.4)**
Height, m	1.71(0.10)*	1.57(0.08)	1.70(0.09)*	1.74(0.07)	1.76(0.13)*	**1.70(0.11)**
Weight, kg	63.0(10.9)	54.4(5.1)	70.0(12.1)	68.8(11.3)	69.7(10.1)	**64.0(11.0)**
Age Range, years	37-72	37-81	41-90	36-76	38-72	**36-90**
Event Start Age, years	25.7(16.1)	28.4(17.8)	30.8(13.3)	18.1 (4.4)	30.9 (17.6)	**26.4 (15.1)**
Max Hopping Force(kN)	2.26(0.55)	1.55(0.30)	2.16(0.62)	2.27(0.45)	2.51(0.51)	**2.13(0.56)**
AGP (Age-graded Performance)	82.9(8.2)	75.4(5.9)	88.8(3.6)*	84.7(9.5)	88.1(4.4)*	**83.3 (8.1)**
Jump event training hrs/wk	2.9(2.3)	3.7(3.7)	0.0(0.0)*	4.1(3.1)	0.0(0.0)*	**2.3(2.8)**
Sprint training hrs/wk	3.5(2.6)	2.1(1.9)	7.2(3.3)	4.4(3.4)	7.0(6.9)	**4.5(4.1)**
Total training hrs/wk	6.4(3.0)	5.8(3.7)	7.2(3.3)	8.6(3.8)	7.0(6.9)	**6.8(4.1)**

*(ConJ – Conditioned Jumpers, TJ – Conditioned Triple Jumpers, UncJ – Unconditioned Jumpers, Hurd – Hurdlers, Sprt – Sprinters. Differences between groups were evaluated with a one-way ANOVA and Tukey post-hoc test. * significantly different from TriJ at P<0.05).*

Table 2. Group gender, age, stature, age-graded performance and training volume given as mean(sd).

and cortical modes set in the machine software were used.

The nomenclature chosen for acronyms follows the suggestions for reporting high-resolution CT results (http://nomenclature.bb.asbmr.org) and in a recent publication[33], given that there is currently no standardized nomenclature for pQCT results. The parameters examined in the 4% slice were total bone area (Ar.tot, mm^2), bone mineral content (vBMC.tot, mg), cortical bone content (vBMC.ct, mg), trabecular bone content (vBMC.tb, mg) and trabecular density (vBMD.tb, $mg \cdot cm^3$). The parameters examined in the 14% slice were Ar.tot, vBMC.tot and cortical density (vBMD.ct, $mg \cdot cm^3$), and in the 38% slice Ar.tot, vBMC.ct, vBMD.ct and polar cross-sectional moment of inertia (CSMI, mm^4). In addition, in the 66% slice Ar.tot, vBMC.ct, CSMI and muscle cross-sectional area (MuscA, mm^2) were measured.

Hopping Force

A series of hopping trials were performed on a Galileo force platform (Stratec Medizintechnik GmbH, Pforzheim, Germany) as previously reported[35]. In brief, 3-5 hops were performed on each foot with stiff ankle, and stiff and almost straight knee, always bouncing on the forefoot, to assess the peak force on the tibia – the best jump (on the basis of maximum power) was selected. During the hopping test, great care was taken that the leg remained straight and the heel did not touch the ground. Thus, the hopping test gives an approximation of the peak Achilles tendon forces assuming a constant mechanical advantage of the Achilles tendon (forefoot system). Experience shows that the plantar flexion force during hopping is substantially greater than during isometric plantar flexion testing.

Statistical Analysis

Data were examined using SPSS 16.0 (SPSS Inc, Chicago, Ill). To test the effect of athletic specialty on side-to-side differences, we used a repeated measures ANOVA with as within subject factor side (dominant vs. non-dominant leg) and between subject factors gender (male vs female) and group (4 levels: 1. conditioned jumpers (ConJ), 2. conditioned triple jumpers (TriJ), 3. hurdlers (Hurd) and 4. the combined unconditioned jumpers (UncJ) and sprinters (Sprt)) and age as a covariate. If a significant group x side interaction was found (meaning the ratio dominant:non-dominant side differed between groups) a one-way ANOVA with Tukey post-hoc test was used on the dominant:non-dominant ratios to detect the location of the differences. Similarly, one way ANOVA with Tukey post-hoc tests was used to determine any group difference in age, training habits, AGP and all bone, muscle and force parameters in both the dominant and non-dominant leg. Linear regression analysis was used to examine the relationship between measured bone parameters, muscle cross-sectional area and maximal hopping force in both the dominant and non-dominant leg. In addition, Generalised Linear Models were then used to establish any difference in these relationships between the dominant and non-dominant leg – the relevant bone parameter was set as dependent variable, group as a factor and muscle CSA or maximal hopping force as the covariate. Differences were considered significant at $P<0.05$. Data are shown as mean +/- SD.

Results

Table 1 shows that many of the jumpers also participated in sprinting, while there were no athletes with sprinting as their primary event that participated in jumping. Group characteristics are shown in Table 2. It can be seen that there were no significant differences in group training habits (aside from sprinters and unconditioned jumpers not completing any jump specific training) or age, however AGP was lower in the conditioned triple jumper group than in the unconditioned jumper and sprinter groups ($P<0.05$).

Overall, indicators related to bone strength and muscle

		ConJ N=21	**TriJ N=8**	**UncJ N=6**	**Sprt N=9**	**Hurd N=7**
4%Ar.Tot	D	1194.8(195.4)	1022.6 (208.0)	1266.7(202.0)	1292.6(194.0)	1215.6(177.6)
(mm^2)	_ND_	_1170.2(174.1)_	_1020.3(213.3)_	_1266.4(193.7)_	_1299.7(186.4)*_	_1210.1(169.2)_
4% vBMC.tot	D	404.1(83.2)	311.7(80.8)	416.3(69.8)	433.1(85.3)	399.8(89.4)
(mg)	_ND_	_393.8(72.0)_	_308.8(87.5)_	_415.1(59.0)_	_430.7(78,7)*_	_397.0(85.2)_
4% vBMC.ct	D	63.6(25.1)	41.4(27.3)	62.6(39.1)	78.6(37.4)	61.1(42.4)
(mg)	_ND_	_64.4(27.7)_	_38.2(23.9)_	_63.5(36.0)_	_74.0(32.7)_	_54.5(39.1)_
4% vBMC.tb	D	143.9(34.2)	105.6(37.6)	146.7(20.5)	147.4(34.2)	141.4(36.2)
(mg)	_ND_	_137.7(29.5)_	_105.8(38.4)_	_144.1(16.3)_	_149.1(29.1)_	_141.3(34.0)_
4% vBMD.tb	D	266.8(38.1)	225.3(46.4)	257.6(33.7)	269.8(54.4)	264.1(71.1)
(mg.cm^3)	_ND_	_244.7(35.9)_	_272.4(38.5)_	_253.2(34.9)_	_296.1(65.6)_	_257.3(60.7)_
14% Ar.Tot	D	491.8(94.4)	445.2(65.3)	524.4(95.9)	547.2(92.7)	534.3(92.7)
(mm^2)	_ND_	_479.9(91.6)_	_440.6(72.7)_	_524.7(97.6)_	_549.4(101.7)_	_528.6(83.0)_
14% vBMC.tot	D	289.6(55.4)	226.2(40.0)	297.8(62.0)	317.4(41.0)*	297.2(76.7)
(mg)	_ND_	_285.8(53.8)_	_223.1(50.6)_	_297.3(53.8)_	_317.9(49.5)*_	_288.7(65.5)_
14% vBMD.ct	D	1098.7(41.0)	1085.4(61.5)	1098.0(28.8)	1131.1(29.7)	1090.0(53.7)
(mg.cm^3)	_ND_	_1101.5(39.0)_	_1084.0(58.3)_	_(1098.3(34.7)_	_1119.1(43.1)_	_1085.1(65.9)_
38% Ar.Tot	D	466.5(94.3)	379.2(58.4)	473.2(116.0)	496.7(49.4)	463.9(84.4)
(mm^2)	_ND_	_438.3(90.0)_	_367.8(64.3)_	_477.8(106.1)_	_495.3(42.7)**_	_457.9(73.6)*_
38% vBMC.ct	D	426.8(78.8)*	319.6(37.8)	445.6(100.7)*	470.0(49.1)**	421.8(92.3)
(mg)	_ND_	_420.6(73.7)**_	_309.1(32.0)_	_458.5(95.2)**_	_467.0(53.5)**_	_418.1(78.0)*_
38% vBMD.ct	D	1159.0(41.0)	1155.8(46.3)	1156.4(29.5)	1169.8(27.9)	1167.3(41.4)
(mg.cm3)	_ND_	_1161.7(42.4)_	_1154.8(47.0)_	_1154.3(25.7)_	_1174.7(23.0)_	_1163.6(41.7)_
38% CSMI	D	35796(15410)	23867(7052)	40116(20883)	34000(7041)	35458(14063)
(mm^4)	_ND_	_34328(13834)_	_22830(8490)_	_40586(18405)_	_34268(8555)_	_34269(11954)_
66% Ar.Tot	D	663.1(176.1)	550.2(82.6)	673.6(177.0)	719.8(104.0)	670.8(106.3)
(mm^2)	_ND_	_640.4(156.0)_	_549.7(104.3)_	_667.3(169.2)_	_726.4(123.4)_	_683.9(102.7)_
66%vBMC.ct	D	457.5(84.7)*	349.2(60.7)	480.3(98.7)*	498.2(35.2)*	452.8(107.7)
(mg.cm^3)	_ND_	_445.6(81.0)*_	_342.4(73.3)_	_487.7(97.7)*_	_507.9(47.2)**_	_453.3(101.4)_
66%CSMI	D	68435(31865)	43224(13699)	72639(34466)	76838(17083)	66019(23876)
(mm^4)	_ND_	_63747(27721)_	_41842(19314)_	_72806(32523)_	_78325(18848)_	_66689(22084)_
66%MuscA	D	8342(1318)*	6853(1062)	9150(1555)*	8908(1052)*	8487(1819)
(mm^2)	_ND_	_8241(1271)_	_6762(1154)_	_8987(1237)*_	_9041(1371)*_	_8377(2058)_
HopForce	D	2.26(0.55)*	1.55(0.30)	2.16(0.62)	2.27(0.45)	2.51(0.51)*
(kN)	_ND_	_2.25(0.60)*_	_1.47(0.27)_	_2.16(0.56)_	_2.36(0.41)*_	_2.46(0.57)*_
HopPower	D	25.65(3.36)	18.78(4.82)	21.22(2.52)	25.80(5.59)	31.85(8.68)**
(W/kg)	_ND_	_25.28(4.27)_	_17.81(4.28)_	_21.15(1.98)_	_26.65(5.13)*_	_32.18(8.67)**_

(ConJ – Conditioned Jumpers, TriJ – Conditioned Triple Jumpers, UncJ – Unconditioned Jumpers, Hurd – Hurdlers, Sprt – Sprinters. Differences between groups were evaluated with a one-way ANOVA and Tukey post-hoc test. *significantly different from TriJ group mean at P<0.05, **significantly different from TriJ group mean at P<0.01 D-Dominant leg values, ND – Non-dominant leg values. Ar.tot – Total bone CSA, vBMC.tot – Total BMC, vBMC.ct – Cortical BMC, vBMC.tb –Trabecular BMC, vBMD.tb – Trabecular BMD, vBMD.ct – Cortical BMD, vBMC.ct – Cortical BMC, CSMI – Cross-sectional moment of inertia, MuscA – Muscle CSA.

Table 3. Group means for dominant and non-dominant leg tibial bone, muscle and force parameters measured as mean (sd).

cross-sectional area were lower in the conditioned triple jumpers than in the other groups (Table 3). However, these differences can be explained by differences in group stature as there were no significant group differences in absolute values when weight was controlled for (data not shown).

T-test results showed no difference in magnitude of side-to-side difference between the UncJ and Sprt groups, and so they were grouped together in the subsequent ANOVA analyses. Figure 1 shows side-to-side differences for the bone parameters in the 4% and 66% slices for which significant differences were found – no side-to-side differences were found for any bone parameter in either the 14% or 38% slices. A group x leg interaction was found (*P*=0.032) for vBMC.tb in the 4% slice indicating that the side-to-side difference differs between the

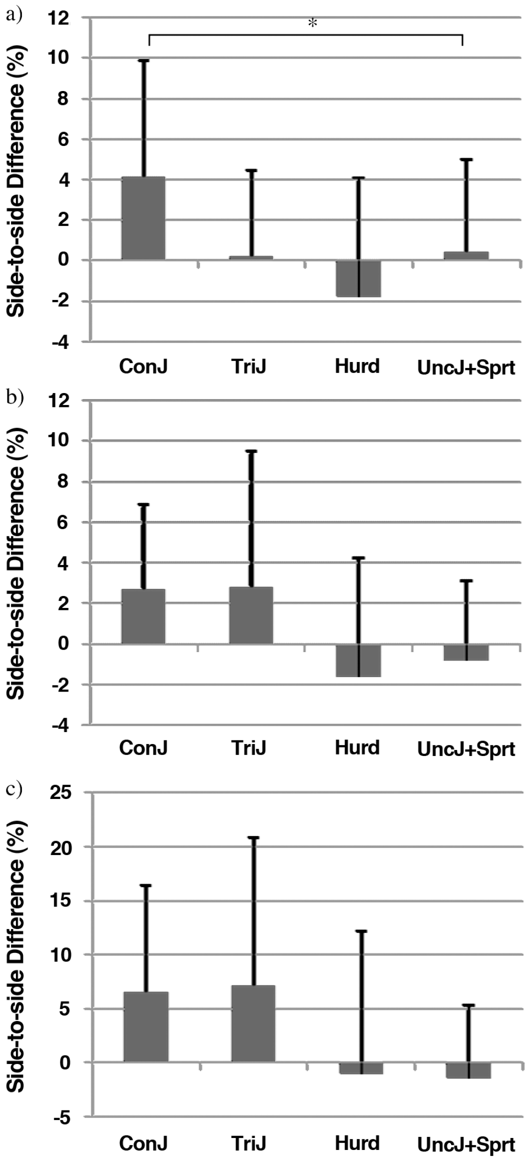

Figure 1. Group side-to-side differences in in: a) 4% slice trabecular bone mineral content, b) 66% slice cortical bone mineral content, c) 66% slice polar cross-sectional moment of inertia. *(ConJ – Conditioned jumpers, TriJ – Conditioned triple jumpers, Hurd – Hurdlers, UncJ+Sprt – Unconditioned jumpers and sprinters. Asterisks indicate significant difference between group side-to-side difference - *P<0.05).*

groups. A subsequent ANOVA on the percentage difference between the dominant and non-dominant legs showed that the side-to-side difference in the ConJ group (+4.1% in favour of the dominant leg) was larger than that of the combined UncJ+Sprt group. (P=0.033; Figure 1). A similar group x leg interaction was found in the 66% slice for CSMI (P=0.041), and vBMC.ct (P=0.016). Although a subsequent ANOVA on the ratios did not reveal the location of the differences, it can be seen in Figure 1 that the side-to-side difference was larger in the ConJ and TriJ than the other groups.

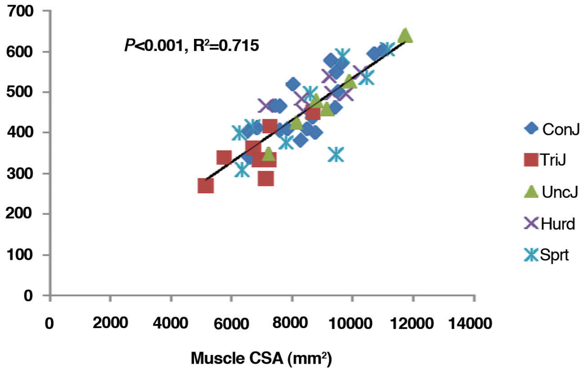

Figure 2. Linear regression (R-squared= .715; P<0.001) showing relationship between total calf muscle CSA and cortical BMC in the 66% slice (Regression line, R-squared and P values are for cohort as a whole).*(ConJ – Conditioned Jumpers, TriJ – Conditioned Triple Jumpers, UncJ – Unconditioned Jumpers, Hurd – Hurdlers, Sprt – Sprinters).*

There were no significant side-to-side differences in any of the bone parameters, muscle cross-sectional area or hop force at any of the measured sites in the hurdlers or combined unconditioned jumpers and sprinters groups. There was also no effect of age or gender on magnitude of side-to-side difference for any bone parameter at any of the measured sites. Due to the potential difference in forces experienced during bend running, the left and right legs of sprinters and unconditioned jumpers were also examined for side-to-side differences – none were found.

Muscle cross-sectional area in both legs was correlated with all bone parameters plus maximal hopping force and power (Figure 2 shows vBMC.ct at 66% slice, other figures not shown), except trabecular density at 4% slice and cortical density at 16% and 38% slices (Table 4). There was no difference in these relationships between the dominant and non-dominant legs.

Discussion

Mechanical loading through participation in exercise and sports can positively affect bone parameters associated with bone strength[6,10-12,20]. One of the aims of this study was to examine how the increased load on the dominant leg in sports with inter-leg loading differences relates both with trabecular and cortical bone structure. The data collected supports existing research, that there are site-specific bone adaptations to exercise loading[1,11]; here we observed side-to-side differences in the 4% and 66% slices, but not the 14% or 38% slices. These site-specific bone differences may be related to the different types of stress at each site within the bone[11,12], where the bone adapts to large compressive forces (in this case those found in long jump take-off) by increasing trabecular BMC in the 4% slice and to the large bending forces in the tibial shaft (caused by muscular contraction and again experienced during long

Site	Parameter correlated with muscle CSA	Coefficient of determination
4%	Ar.Tot	0.595**
	vBMC.Tot	0.720**
	vBMC.Crt	0.240**
	vBMC.Tb	0.592**
	vBMD.Tb	0.121*
14%	Ar.Tot	0.573**
	vBMC.Tot	0.702**
	vBMD.Crt	0.009
38%	Ar.Tot	0.681**
	vBMC.Tot	0.683**
	vBMD.Crt	0.002
	CSMI	0.632**
66%	Ar.Tot	0.554**
	vBMC.Tot	0.715**
	CSMI	0.667**
	HopForce	0.531**
	HopPower	0.385**

(*relationship significant at $P<0.05$ **relationship significant at $P<0.001$. Ar.tot – Total bone CSA, vBMC.tot – Total BMC, vBMC.ct – Cortical BMC, vBMC.tb –Trabecular BMC, vBMD.tb – Trabecular BMD, vBMD.ct – Cortical BMD, vBMC.ct – Cortical BMC, CSMI – Cross-sectional moment of inertia).

Table 4. Regression coefficients of determination for muscle CSA – bone and muscle CSA-force/power relationships in dominant leg.

jump take-off) by increased cortical BMC in addition to changes in the distribution of bone mass in the 66% slice.

Some studies have found that primarily trabecular bone is lost during ageing[27,34] whereas others have found that particularly cortical bone is affected by age[9,41]. The latter study argues that cortical bone loss may be underestimated due to misidentification of porous aged cortical bone as trabecular bone. A conclusion to this argument (when it arrives) will be useful when prescribing types of exercise to the elderly that induce predominately cortical or trabecular changes. This study supports the notion that regular loading of the bone is required to induce and maintain changes in bone structure[37], as side-to-side differences were only seen in groups who trained regularly specifically for jumping.

There is currently no other study comparing the effects on side-to-side difference in bone parameters of athletes competing and training for a variety of high-impact sports with varying degrees of differences in side-to-side loading. Differences in loading magnitude experienced by the bone as a whole result in a change in strain as detected by the bone cells, which then dictate the modelling or remodelling response in order to control stiffness and hence in the organ as a whole, strength. In the sprinters there was no significant side-to-side difference in any bone parameter and the slight side-to-side differences in leg loading during hurdling were also insufficient to produce significant inter-leg differences in bone structure. The larger side-to-side loading differences usually found in triple jump were associated with higher bone strength parameters in diaphyseal but not epiphyseal bone, although it is initially unclear why this area should be more readily affected. Given that typical side loading differences in the hurdles are ~10%[5] and those in the triple jump (which did see site-specific side differences) are 15-20%[25] it does appear that the threshold for adaptation (at least in certain parameters) lies between these two figures. This threshold for bone adaptation may vary along the length of the bone according to regular, grouped loading patterns (as occur in athletic training), with work demonstrating strain-dependent adaptation thresholds ranging from approximately 1300 to 3000 µstrain[14]. Perhaps these differences in thresholds for adaptation at different locations of the bone are responsible for the site-specific adaptations seen in triple-jumpers (as well as explaining the lack of any significant side differences found in the 14% and 38% sites in any group) – in that the strains determined by the compressive force in triple jumping may be lower than the threshold strain at the 4% site, but that the strains caused by bending forces are higher or equal to the threshold at the 66% site.

Another observation is that although the AGP values of the triple jumpers were significantly lower than those of the other groups (as were the majority of the bone measures – likely because there were significantly more females than males in the group), this did not affect the amount of side-to-side difference recorded. This is because the relevant vertical and horizontal ground reaction forces in the different phases (hop, step, jump) should retain their relative proportions[25] and hence retain the relative magnitude of the force side-to-side difference.

Contrary to previous work[3] there was no side-to-side difference in muscle cross-sectional area in any of our athletic groups. This may be due to the fact that it is knee extension rather than ankle plantarflexion that generates most of the force during jumping[22]. One thus might argue that the knee extensor muscles form the muscle-bone unit with the tibia in jumping and consequently one expects changes in these muscles rather than the calf muscles. The changes in the knee extensors in that case may correlate with tibial bone adaptations. However, the strength of the muscle-bone relationship in both the dominant and non-dominant limb support further the case that the action of the musculature is at least as important as the ground reaction forces experienced during exercise in determining bone traits. Whilst some of this relationship can be explained in terms of differing stature, the high correlation obtained even with weight-adjusted bone and muscle values indicates a strong stature-independent muscle-bone relationship regardless of the type of physical activity performed.

There are however some limitations within this study. Firstly, the nature of these master athletics meetings means that obtaining even subject numbers within different groups is difficult, and as such (particularly in the conditioned triple jumpers group) some group sizes may have been too small to reveal the relatively small effects of jumping exercise (above that of training regularly in sprinting) on bone. It was also difficult to isolate groups who competed purely in one discipline, and so as shown in the results section there were many athletes (particularly in the conditioned jumping groups) who – whilst not training regularly in other events – still competed in events outside their allotted discipline. There will also be some self-selection bias in athletes choosing to take part in jumping events. It is commonly assumed that joint size is determined by the end of puberty[8], and it seems logical that greater joints can transfer greater forces and thus better jumping performance. Hence, our finding of epiphyseal bone size asymmetry in conditioned jumpers may reflect such a self-selection bias. On the other hand, bone mineral content was also elevated on the dominating side in these jumpers, and bone mineral content readily adapts to habitual loading patterns[28,29], suggesting a true effect of jumping-associated forces upon bone. In addition, the lack of significant side-to-side differences in jumpers who did not complete jump-specific training regularly (despite no difference in their level of performance as assessed by AGP from conditioned jumpers as previously mentioned) also suggests that limb bone asymmetry is not a self-selection bias criterion in jumpers. We did not control for participation in other events with leg loading differences – football, gymnastics, etc. which may influence side-to-side difference in bone structure[37].

This study provides support for the importance of muscular action on bone health, whilst controlling for the natural anthropometric and allometric associations which can confound such studies. The side-to-side differences in bone strength parameters as a result of regular unequal loading (as occurs during jumping training) were also independent of age. This builds on existing knowledge that people training for higher impact sports have higher bone mineral content, cortical area and geometrical parameters than those in lower-impact sports and controls. This applies to both master athletes[38] and non-athletic subjects assigned to high and low-impact exercise groups[2], while sports popular with elderly people such as swimming and cycling are ineffective in increasing bone strength parameters above those of non-exercising controls[22]. Although the observed side differences were relatively small (4.1% in epiphyseal bone, and 2.7-7.2% in diaphyseal bone), it must be reiterated that these side differences are on top of the changes caused by sprinting, which itself is a high-impact activity. Whilst the risks for the elderly in competing in high-impact sports need to be examined, the present data suggest that training regularly in high-impact sports is an effective method of maintaining and possibly even improving bone health at old age.

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