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ORIGINAL ARTICLE

Effects of age and starting age upon side asymmetry in the arms of veteran tennis players: a cross-sectional study

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Abstract
Summary While tennis playing results in large bone strength benefits in the racquet arm of young players, the effects of tennis playing in old players have not been investigated. Large side asymmetries in bone strength were found in veteran players, which were more pronounced in men, younger players and childhood starters.
Introduction Regular tennis results in large racquet arm bone and muscle strength advantages; however, these effects have not been studied in old players. The non-racquet arm can act as an internal control for the exercising racquet arm without confounding factors, e.g. genotype. Therefore, veteran tennis player side asymmetries were examined to investigate age, sex and starting age effects on bone exercise benefits.
Methods Peripheral quantitative computed tomography (pQCT) scans were taken at the radius, ulna and humerus mid-shaft and distal radius in both arms of 88 tennis players (51 males, 37 females; mean age 63.8±11.8 years). Thirty-two players began playing in adulthood, thereby termed 'old starters'; players were otherwise termed 'young starters'.
Results Muscle size and bone strength were greater in the racquet arm; notably, distal radius bone mineral content (BMC) was 13±10 % higher and humeral bone area 23±12 % larger (both $P<0.001$). Epiphyseal BMC asymmetry was not affected by age ($P=0.863$) or sex ($P=0.954$), but diaphyseal asymmetries were less pronounced in older players and women, particularly in the humerus where BMC, area and moment of resistance asymmetries were 28–34 % less in women ($P<0.01$). Bone area and periosteal circumference asymmetries were smaller in old starters (all $P<0.01$); most notably, no distal radius asymmetry was found in this group (0.4±3.4 %).
Conclusions Tennis participation is associated with large side asymmetries in muscle and bone strength in old age. Larger relative side asymmetries in men, younger players and young starters suggest a greater potential for exercise benefits to bone in these groups.

Keywords Ageing · BMD · Bone · Exercise · Muscle · pQCT

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Introduction

Upper limb bone mineral content (BMC, indicating bone strength in compression) decreases with age [1]. Whilst bone cross-sectional area (CSA) is greater in older people, there are more pronounced age-associated decreases in bone mineral density (BMD). Similarly, whilst periosteal and endocortical circumferences increase with age, BMD losses imply that torsional strength decreases [1]. Bone strength and fall incidence are independent predictors of fracture risk [2]. Therefore, loss of upper limb bone strength will likely contribute to the age-related increase in upper limb fracture rates [3, 4], their incidence being similar to that in the lower limbs [5].

Exercise can be effective in increasing upper limb bone and muscle size and strength throughout life [6–11]. However, the relative effectiveness of exercise on bone strength with increasing age is not fully understood. Age-related loss of muscle mass and strength [12] will result in a lower exercise stimulus to the bone. In addition, the osteogenic response of aged bone to mechanical stimuli appears to be reduced [13]. A previous study comparing master runners with normally

active controls suggested a diminished benefit of exercise on lower limb bone strength with increasing age [14]. However, in that study, the location of bone strength differences (i.e. whether they were based on BMD, CSA or geometrical differences) could not be established; also, differences between master athletes and less active counterparts could be due to self-selection bias [14].

Biases such as self-selection and nutritional influences can be circumvented in the study of tennis players, where the non-racquet arm acts as a quasi-sedentary control. Regular tennis playing results in large side asymmetries (e.g. 40 % greater distal radius BMC and humerus CSA [11]) in bone strength in favour of the racquet arm, these differences being 10–20 times greater than in sedentary individuals [6, 15]. Tennis is therefore a highly promising exercise modality for upper limb bone strength; however, bone strength in old tennis players has not been studied. It has been suggested that joint size adapts to peak loads at epiphyseal closure [16, 17]; if so, the effect of exercise on bone in children and adults could differ. In support of this, it has been observed that exercise benefits in bone strength are less pronounced in female tennis players who had begun playing in adulthood [15, 18]. However, use of dual-energy X-ray absorptiometry (DXA) in the former study prevented analysis of cortical/trabecular differences or bone geometry. In the latter study, old starters were ~20 years older—this factor was not included in analysis.

Whilst men have greater muscle size and bone strength than women of similar size [19], sex effects on exercise benefits in bone—particularly in older individuals—are not well explored. Whilst adolescent males were found to have more pronounced bone strength side asymmetries than females players [11], this was not true in adults [20]. Diaphyseal and epiphyseal bone and cortical and trabecular bone respond differently to exercise [11, 21], disuse [22] and ageing [1]; it may be that sex, age or starting age effects on bone benefits also differ between bone types.

Comparing upper limb bone strength in master tennis players of different ages (and players who began playing in childhood and adulthood) would provide valuable information on the potential of tennis for improving upper limb bone strength. Tennis players also allow examination of effects of sex, age and starting age of playing on exercise benefits in bone, where the racquet arm is compared with an 'internal control' (the non-racquet arm), thus circumventing any genetic/nutritional factors influencing comparisons of athletes and sedentary controls. As muscle is the greatest stressor of bone, analysis of muscle size and strength side asymmetries could help explain to what extent sex and age-related changes in the myogenic effect of exercise influence exercise benefits to bone.

Accordingly, a study was organized to assess for the first time muscle and bone size and strength in the arms of veteran tennis players of both sexes. Veteran tennis players continue to train for and compete in high-level tennis beyond the age of 35 years. It is hypothesised that bone strength indicators and muscle size and strength will be greater in the racquet than the non-racquet arms of master tennis players and also that asymmetries in muscle and bone size and strength (indicating the exercise benefit) will be less pronounced in women, older players and adult starters.

Methods

Participants

Eighty-eight competitive veteran tennis players (51 males, 37 females; mean age 63.7±11.8 years) competing at the British Open Veterans' Indoor Championships in Birmingham in January 2012 and the respective Clay Court Championships in Bournemouth in June 2012 were recruited. Participants were included if they played tennis for >3 h week^{-1}, reported to be in good health and had no leg or arm fractures within the preceding 24 months. The study complied with the Declaration of Helsinki guidelines and was approved by the Manchester Metropolitan University's Ethics Committee, and written informed consent was obtained from all participants prior to testing. Height and body mass were measured. Details of participants' preferred racquet arm, use of single or double-handed backhand/forehand and training and playing history in tennis and other sports were recorded during a structured interview with the first author. Participants were asked at what age they started to play tennis regularly, how many hours they played each week and if they regularly played other sports, in particular those where one arm is favoured over the other (cricket, hockey, etc.). Women only were also asked for their menarcheal and menopausal age (if applicable) and details of hormonal treatment or relevant surgery (e.g. hysterectomy). The governing body for English tennis (The Lawn Tennis Association) maintains a national ranking system where players are ranked in 5-year groupings (under 35, under 40, etc.) based on results in regional and national tournaments. The rankings are accessible at http://www2.lta.org.uk/Search/PlayerSearch/; the ranking of each participant at the time of testing was recorded.

Selection criteria for designation as old or young starter were required. Patterns of bone growth during adolescence differ between boys and girls. The growth in height and increase in periosteal circumference continue until the late teens in boys [23–25]. In our cohort, the men started playing tennis before the age of 16 or after the age of 22 and were considered as starting in childhood or adulthood, respectively. The growth in height and increase in periosteal circumference slow dramatically around the age of 14 in girls [23–25], coinciding with menarche [26]. Therefore, for the women, menarcheal status at time of starting tennis was used to determine child or adult starter status.

Bone measurements

Scans were taken with a Stratec XCT-2000 peripheral quantitative computed tomography (pQCT) scanner (Stratec Medizintechnik GmbH, Pforzheim, Germany) in both forearms of the radius at 4 and 60 %, of the ulna at 60 % distal-proximal ulnar length, and at 35 % distal-proximal humerus length in both upper arms. Using the Automated Analysis Tools in Version 6.00 of the software supplied with the machine, a peeling threshold (peeling mode 1) of 650 mg cm^{-3} was set for diaphyseal sections of bone, with a threshold of 180 mg cm^{-3} set for the epiphyseal 4 % slice. Only the inner 45 % of the bone was selected for analysis of trabecular bone in the epiphysis, using contour mode 1. Bone strength in compression is dependent upon total BMC (vBMC.tot, mg mm^{-1}); similarly, polar moment of resistance (R_p, mm^{-3}) indicates the bone's torsional strength. These parameters were therefore the focus of this study (although as compressive forces dominate at epiphyseal sites, only total BMC was considered at the 4 % radius site). To establish whether differences in these bone strength indicators were a result of differences in BMD, size and/or geometry, a number of secondary variables were also examined. In the 4 % epiphyseal radius slice, total bone area (Ar.tot, mm^2) and trabecular BMD (vBMD.tb, mg cm^{-3}) were examined. In diaphyseal bone, Ar.tot, cortical area (Ar.ct, cm^2) and cortical density (vBMD.ct, mg cm^{-3}) were examined, with adjustments made to the cortical density values to take into account the partial volume effect [27]. At diaphyseal sites, periosteal (PsC, mm) and endocortical circumferences (EcC, mm) derived from a circular ring model were also calculated. Gross muscle cross-sectional area (MuscA, mm^2, as a surrogate for maximal force) in the 60 % slice of the forearm and 35 % upper arm slice was obtained using a threshold of 35 mg cm^{-3}. Short-term error for repeated pQCT measurements was obtained in ten adult participants. Coefficients of variation (CV) for the majority of parameters were less than 1 %, exceptions being distal radius Ar.tot (1.57 %), proximal radius and ulna EcC (1.15 and 1.44 %, respectively) and R_p at the three diaphyseal sites (1.31–2.46 %). MuscA CV was 1.53 and 1.85 % in the forearm and upper arm, respectively. These results are in line with results in the lower limb obtained previously with the same machine [28].

Hand grip force

Hand grip force was measured using a dynamometer (Jamar+, Sammons Preston Inc., Bollingbrook, IL, USA). Participants completed three measures in each hand whilst standing, with the arm down by the side but not touching the hip; the highest force value on each side was recorded.

Statistical analysis

Data were examined using the R statistical environment (version 2.14.0, www.r-project.org). Multiple linear regression with side (dominant/non-dominant), sex and old/young starter as dichotomous variables and with age, height, body mass and weekly training hours as continuous variables was used to determine main effects on the bone. Where significant side asymmetries were found, a second multiple linear regression on the racquet/non-racquet ratio was used to examine the relative effects of age, sex, starting age, height, body mass and weekly training hours on the relative magnitude of side asymmetry. Interactions between side and other factors obtained from the initial regression were not used for this purpose. This was because these effects would relate to absolute, non-relative side-to-side asymmetries (e.g. despite both men and women having a 13 % greater side asymmetry in vBMC.tot at the 4 % radius site, the initial regression revealed a side× sex interaction as the absolute difference between the two arms was greater in men). As seven primary variables (total BMC at all four sites and R_p at the three diaphyseal sites) were considered, Bonferroni correction was applied to resulting P values to correct for multiple comparisons. In both regressions, non-significant factors were removed by order of highest P value until a model containing only significant factors was established.

Twenty-seven female players (73 %) were post-menopausal, with 13.3±9.5 years having passed since menopause; eight women were either on hormone replacement therapy (HRT), had a hysterectomy or both. When age was considered, no significant effect of menopause or HRT/hysterectomy on bone/muscle parameters or side asymmetry was found; hence, all women were included in analysis. Whilst there were some minor effects of training years, there is a clear overlap between this parameter and old/young starting status. When only young or only old starters were considered, there were no effects of training years; hence, this was not included in the final analysis. Finally, as ranking is an ordinal scale and the number of registered players differs with age and sex, this was not considered in analysis.

Where there was a significant age effect, regression coefficients were used to calculate values at 40 and 80 years of age (>90 % of participants lay within this range) to quantify age associations. Differences were considered significant at $P<0.05$. Data are shown as mean±SD.

Results

Cohort characteristics

There were no sex differences in age, tennis starting age or training volume (Table 1); men were heavier and taller than

Table 1 Cohort characteristics with groups separated by sex, age and starting age

Variable/group	Sex		Age			Starting age		Main effects (*P* values)		
	Male	Female	<55	55–69	70+	Young starter	Old starter	Sex	Age	Start age
n	51	37	21	37	31	56	32	–	–	–
Age (years)	65.0 (13.1)	62.3 (9.7)	48.3 (5.3)	62.2 (4.3)	76.3 (4.9)	61.2 (12.2)	65.1 (9.9)		–	0.013
Mass (kg)	78.2 (9.3)	62.9 (10.8)	71.8 (11.6)	69.5 (13.0)	74.3 (12.2)	71.5 (12.1)	72.0 (0.1)	<0.001		
Height (m)	1.76 (0.06)	1.65 (0.07)	1.75 (0.08)	1.69 (0.09)	1.71 (0.07)	1.73 (0.08)	1.69 (0.10)	<0.001	0.001	
National ranking	23.9 (28.3)	11.0 (9.9)	22.2 (33.3)	19.8 (20.6)	13.8 (14.9)	17.1 (9.3)	21.3 (15.3)	0.012	0.048	
Starting age (years)	20.2 (15.4)	20.6 (14.7)	14.7 (10.4)	19.1 (13.4)	25.6 (17.8)	10.9 (2.5)	36.6 (13.5)			<0.001
Training volume (h week^{-1})	7.4 (5.2)	7.4 (4.4)	7.4 (6.5)	7.2 (4.5)	7.2 (4.7)	6.6 (4.4)	8.8 (5.4)			0.038

women (both $P<0.001$) but had a lower national ranking ($P=0.012$). Older players were shorter ($P<0.01$), but there was no age effect on body mass or training volume. Whilst older players had a higher ranking ($P=0.048$), the number of registered players in the ranking system decreases with age.

Thirty-two players (16 men, 16 women) were classified as 'old starters'. There was no effect of starting age on height, body mass or ranking. However, young starters were younger ($P<0.05$), had a lower training volume ($P<0.05$) and had played tennis for longer ($P<0.001$).

Athletic history

Twenty-eight players participated in other sports (including running, cycling and swimming) on a weekly basis. Twenty-one players played sports which favoured one arm over the other on a weekly basis, including squash, golf, table tennis, hockey and badminton. In no case did the player play these sports with their non-racquet arm, and the vast majority played for less than 2 h per week, the exception being a badminton player playing for 3 h per week and a number of golfers who played for up to 8 h per week. When included as a factor in analysis, there was no effect of participation in other unilateral sports (or in use of a double-handed backhand stroke) on side asymmetry; these players were therefore retained in the final analysis (Table 2).

Effects of sex, body mass, height and starting age

The majority of bone parameters and all muscle and force parameters were positively associated with body mass; similarly, there were positive associations between height and several bone parameters. Even when body mass and height were considered as covariates, all measured bone, muscle and force parameters (with the exception of proximal ulna and humerus cortical BMD and endocortical circumference at all diaphyseal sites) were higher in men (Table 3) at $P<0.001$. There was no effect of starting age or training volume on any muscle, bone or force parameter.

Age effects

Total bone area at all sites, periosteal/endocortical circumference at diaphyseal sites and proximal radius and ulna R_p were all positively associated with age (all $P<0.001$ except proximal ulna R_p). Conversely, upper arm muscle CSA, grip force, distal radius trabecular BMD and cortical BMD at all diaphyseal sites (all $P<0.05$) were lower in older than young players.

Side asymmetries

Side asymmetries in total BMC and total bone CSA in favour of the racquet arm were found at all sites (all $P<0.001$ except distal radius and proximal ulna CSA $P=0.05$). At all diaphyseal sites, racquet arm cortical CSA, periosteal circumference and R_p were greater (all $P<0.01$). There were no significant side asymmetries in cortical BMD or endocortical circumference at diaphyseal sites, although racquet arm trabecular BMD was greater ($P>0.01$). Forearm and upper arm muscle CSA and hand grip force were greater in the racquet arm (all $P<0.001$) (Table 3). The most pronounced side asymmetries were in humeral vBMC.tot (22.9±11.8 %) and Ar.ct (23.8±12.6 %), although forearm MuscA (15.5±9.4 %) and grip force (14.8±11.6 %) side asymmetries were also considerable.

Side asymmetry—sex effects

There were no significant sex effects on side asymmetry in distal radius bone parameters (Table 4). The only sex effect found in proximal radius or ulna was a greater side asymmetry in proximal ulna cortical BMD in women ($P=0.007$). In the humerus, side asymmetries in BMC ($P<0.05$), total and cortical bone CSA, periosteal circumference and R_p (all $P<0.01$) were all 28–38 % greater in men. There were no sex effects on muscle or force side asymmetries. In addition, there were no significant age by gender or starting age by gender interactions on side differences for any bone, muscle or force parameter.

Table 2 Mean values for racquet and non-racquet arm muscle, bone and force parameters—cohort separated both by sex and age groupings. Mean values for old and young starters are not shown, as no significant effect of starting age was found for any muscle, bone or force parameter

Site	Measured variable	Sex				Age					
		Males		Females		<55		55–69		70+	
		Racquet arm	Non-racquet arm	Racquet arm	Non-racquet arm	Racquet arm	Non-racquet arm	Racquet arm	Non-racquet arm	Racquet arm	Non-racquet arm
4 % radius	Total BMC (mg mm^{-1})	181 (23)	161 (22)	117 (17)	104 (19)	159 (36)	142 (33)	146 (42)	128 (36)	160 (33)	144 (33)
	Total CSA (mm^2)	522 (57)	494 (73)	389 (55)	383 (48)	542 (69)	421 (56)	447 (90)	433 (83)	499 (86)	483 (90)
	Trabecular BMD (mg mm^{-3})	225 (39)	207 (39)	187 (32)	164 (33)	219 (46)	210 (48)	202 (39)	177 (38)	211 (37)	190 (38)
60 % radius	Total BMC (mg mm^{-1})	142 (15)	130 (14)	98 (14)	90 (14)	131 (22)	117 (21)	116 (29)	106 (27)	129 (24)	120 (22)
	Total CSA (mm^2)	163 (17)	151 (19)	121 (16)	115 (16)	145 (26)	129 (21)	136 (24)	127 (23)	157 (26)	150 (24)
	Cortical CSA (mm^2)	118 (13)	107 (12)	80 (11)	74 (11)	107 (19)	95 (17)	95 (23)	86 (21)	107 (21)	100 (19)
	Cortical BMD (mg mm^{-3})	1,159 (29)	1,160 (35)	1,148 (45)	1,138 (43)	1,174 (29)	1,182 (20)	1,158 (37)	1,150 (44)	1,137 (34)	1,131 (31)
	Periosteal circumference (mm)	45.0 (2.4)	43.4 (2.7)	38.9 (2.6)	38.0 (2.6)	42.5 (3.8)	40.1 (3.4)	41.1 (3.8)	39.9 (3.7)	44.3 (3.7)	43.3 (3.5)
	Endocortical circumference (mm)	23.6 (3.7)	23.2 (4.0)	22.4 (4.0)	22.0 (4.0)	21.7 (3.3)	20.5 (2.9)	22.4 (3.6)	22.5 (3.7)	24.8 (3.9)	24.9 (4.1)
	Polar moment of resistance (mm^4)	445 (69)	411 (73)	278 (50)	265 (48)	375 (88)	328 (80)	337 (92)	320 (91)	418 (112)	396 (99)
60 % ulna	Total BMC (mg mm^{-1})	178 (21)	167 (22)	124 (14)	115 (14)	158 (33)	141 (30)	147 (34)	137 (30)	164 (30)	157 (32)
	Total CSA (mm^2)	184 (22)	174 (24)	133 (19)	125 (18)	157 (35)	143 (31)	154 (30)	145 (27)	177 (31)	170 (33)
	Cortical CSA (mm^2)	146 (17)	136 (18)	100 (11)	94 (11)	127 (28)	115 (24)	120 (27)	111 (24)	134 (25)	129 (27)
	Cortical BMD (mg mm^{-3})	1,178 (31)	1,180 (30)	1,178 (37)	1,168 (32)	1,198 (25)	1,192 (23)	1,178 (34)	1,176 (32)	1,163 (33)	1,162 (30)
	Periosteal circumference (mm)	48.0 (2.9)	46.6 (3.2)	40.8 (2.9)	39.5 (2.8)	44.2 (4.9)	42.2 (4.5)	43.8 (4.3)	42.5 (3.9)	47 (4.2)	46.1 (4.6)
	Endocortical circumference (mm)	21.8 (3.2)	21.6 (3.3)	19.9 (3.9)	19.5 (3.6)	19.2 (3.0)	18.7 (3.0)	20.5 (3.5)	20.3 (3.1)	22.9 (3.4)	22.6 (3.5)
	Polar moment of resistance (mm^4)	572 (103)	513 (104)	352 (71)	316 (70)	459 (145)	396 (126)	441 (132)	394 (111)	537 (138)	495 (144)
35 % humerus	Total BMC (mg mm^{-1})	359 (42)	287 (37)	229 (34)	193 (28)	324 (66)	252 (49)	284 (82)	230 (59)	311 (71)	261 (58)
	Total CSA (mm^2)	382 (38)	321 (37)	275 (35)	246 (33)	338 (64)	279 (49)	317 (65)	273 (47)	359 (59)	317 (51)
	Cortical CSA (mm^2)	292 (36)	232 (31)	183 (27)	154 (22)	263 (58)	201 (42)	228 (67)	184 (47)	254 (60)	211 (49)
	Cortical BMD (mg mm^{-3})	1,187 (28)	1,190 (29)	1,184 (31)	1,183 (35)	1,197 (27)	1,207 (28)	1,190 (28)	1,187 (31)	1,172 (27)	1,170 (24)
	Periosteal circumference (mm)	69.2 (3.4)	63.4 (3.7)	58.7 (3.7)	55.5 (3.7)	64.9 (6.2)	59 (5.1)	62.8 (6.5)	58.3 (5.0)	66.9 (5.7)	62.9 (5.2)
	Endocortical circumference (mm)	33.1 (5.5)	33.3 (4.8)	33.5 (5.9)	33.7 (5.4)	30.4 (4.8)	30.9 (4.5)	32.9 (5.7)	33.0 (4.8)	36.0 (4.8)	36.1 (4.5)
	Polar moment of resistance (mm^4)	1,751 (271)	1,324 (230)	1,005 (182)	823 (154)	1,494 (442)	1,085 (320)	1,312 (463)	1,011 (294)	1,540 (399)	1,242 (320)
Forearm MuscA (mm^2)		4,821 (592)	4,239 (545)	3,275 (375)	2,791 (380)	3,460 (954)	3,124 (921)	3,080 (857)	2,817 (801)	3,270 (783)	3,040 (759)
Upper arm MuscA (mm^2)		3,838 (549)	3,535 (524)	2,388 (324)	2,166 (325)	4,276 (951)	3,645 (933)	4,060 (932)	3,520 (859)	4,243 (905)	3,762 (834)
Hand grip force (N)		450 (89)	399 (74)	305 (54)	260 (50)	431 (123)	364 (107)	376 (102)	327 (94)	374 (89)	341 (85)

Table 3 Main effects of side, age, sex, height and mass on bone strength indicators, muscle size and maximal hand grip force for racquet and non-racquet arms. Effect 'side' indicates significant difference between racquet and non-racquet arm values. We observed no sex×age interactions for any of the parameters. SE(β), standard error of the regression coefficient. *P* values relate to model including all significant factors. For all models, $P<0.001$

Site	Measured variable	Prediction of relevant parameter by multiple regression											R^2
		Intercept	Side		Sex		Age		Mass		Height		
		β (SE(β))	β (SE(β))	*P*	β (SE(β))	*P*	β (SE(β))	*P*	β (SE(β))	*P*	β (SE(β))	*P*	
4 % radius	Total BMC (mg mm^{-1})	33.8 (9.1)	16.6 (2.74)	<0.001	41.7 (3.51)	<0.001			1.09 (0.14)	<0.001			0.77
	Total CSA (mm^2)	175 (37.8)	20.5 (8.46)	<0.001	84.7 (10.9)	<0.001	1.33 (0.37)	0.003	1.91 (0.43)	<0.001			0.57
	Trabecular BMD (mg mm^{-3})	158 (24.3)	19 (5.45)	<0.001	27.4 (7.03)	0.001	–0.68 (0.24)	0.036	0.82 (0.28)	0.027			0.31
60 % radius	Total BMC (mg mm^{-1})	−73.6 (26.4)	10.6 (1.98)	<0.001	27.3 (2.82)	<0.001			0.33 (0.11)	0.024	85.6 (17.1)	<0.001	0.76
	Total CSA (mm^2)	−153 (33.4)	9.81 (2.22)	<0.001	22.2 (3.13)	<0.001	0.71 (0.1)	<0.001			134 (18.5)	<0.001	0.70
	Cortical CSA (mm^2)	−54.5 (21.7)	8.98 (1.63)	<0.001	23.1 (2.32)	<0.001			0.29 (0.09)	0.013	65.8 (14.1)	<0.001	0.76
	Cortical BMD (mg mm^{-3})	1,239 (14)			20 (5.11)	0.001	−1.54 (0.22)	<0.001					0.26
	Periosteal circumference (mm)	−2.23 (5.00)	1.46 (0.33)	<0.001	3.39 (0.47)	<0.001	0.11 (0.02)	<0.001			20.2 (2.76)	<0.001	0.70
	Endocortical circumference (mm)	−3.17 (5.96)					0.14 (0.02)	<0.001			10.1 (3.21)	0.014	0.19
	Polar moment of resistance (mm^4)	−532 (130)	26.2 (8.63)	<0.001	92.8 (12.7)	<0.001	1.95 (0.4)	<0.001	1.38 (0.48)	0.032	351 (78)	<0.001	0.70
60 % ulna	Total BMC (mg mm^{-1})	63.6 (8.76)	10.6 (2.63)	<0.001	39.6 (3.36)	<0.001			0.81 (0.13)	<0.001			0.73
	Total CSA (mm^2)	33.6 (12.8)	9.8 (2.59)	0.005	33.7 (3.69)	<0.001	0.57 (0.13)	<0.001	0.89 (0.15)	<0.001			0.68
	Cortical CSA (mm^2)	50.8 (7.13)	8.56 (2.14)	0.001	32.6 (2.74)	<0.001			0.67 (0.11)	<0.001			0.73
	Cortical BMD (mg mm^{-3})	1,244 (12.8)					−1.07 (0.20)	<0.001					0.14
	Periosteal circumference (mm)	26.8 (1.78)	1.39 (0.4)	0.004	4.84 (0.51)	<0.001	0.08 (0.02)	<0.001	0.13 (0.02)	<0.001			0.69
	Endocortical circumference (mm)	−11.8 (5.29)					0.14 (0.02)	<0.001			13.8 (2.84)	<0.001	0.26
	Polar moment of resistance (mm^4)	−65.4 (56.4)	49.6 (12.6)	0.001	141 (16.3)	<0.001	2.11 (0.56)	0.001	3.91 (0.69)	<0.001			0.66
35 % humerus	Total BMC (mg mm^{-1})	−183 (68.8)	56.8 (5.23)	<0.001	67.4 (7.69)	<0.001			1.30 (0.29)	<0.001	172 (45.0)	0.001	0.80
	Total CSA (mm^2)	−233 (77.3)	47 (5.12)	<0.001	46.6 (7.79)	<0.001	0.99 (0.24)	<0.001	1.03 (0.28)	0.002	209 (46.0)	<0.001	0.74
	Cortical CSA (mm^2)	−137 (57.9)	47.4 (4.34)	<0.001	57.8 (6.38)	<0.001			1.13 (0.24)	<0.001	127 (37.3)	0.006	0.80
	Cortical BMD (mg mm^{-3})	1,247 (12.2)					−0.97 (0.19)	<0.001					0.14
	Periosteal circumference (mm)	7.02 (7.61)	4.64 (0.50)	<0.001	4.59 (0.77)	<0.001	0.10 (0.02)	<0.001	0.10 (0.03)	0.002	21.3 (4.52)	<0.001	0.75
	Endocortical circumference (mm)	21.8 (2.13)					0.19 (0.03)	<0.001					0.16
	Polar moment of resistance (mm^4)	184 (114)	324 (34.3)	<0.001	460 (44.5)	<0.001			9.19 (1.74)	<0.001			0.74
Forearm MuscA (mm^2)		888 (206)	546 (61.6)	<0.001	1,020 (78.9)	<0.001			30.0 (3.13)	<0.001			0.82
Upper arm MuscA (mm^2)		964 (265)	264 (57.3)	<0.001	991 (74.8)	<0.001	−7.95 (2.55)	0.016	26.8 (2.97)	<0.001			0.83
Hand grip force (N)		260 (44.9)	49.8 (10.1)	<0.001	121 (13.2)	<0.001	−1.88 (0.44)	<0.001	1.80 (5,170)	0.004			0.62

Table 4 Prediction of side asymmetries (as percentage in favour of the racquet arm) in pQCT muscle and bone parameters and hand grip force by multiple regression. Positive regression coefficients relate to greater side asymmetries in males, older people and young starters, respectively. R^2, coefficient of variation explained by model including all significant factors; β, regression coefficient for relevant parameters; SE(β), standard error of the regression coefficient. *P* values relate to model including all significant factors. Parameters for which side asymmetries could not be significantly predicted by age, gender or starting age are not included within the table

Site	Variable	Prediction of relevant parameter by multiple regression								
		Intercept	Sex		Age		Starting Age		R^2	*P*
		β (SE(β))	β (SE(β))	*P*	β (SE(β))	*P*	β (SE(β))	*P*		
4 % radius	Total CSA (mm^2)	0.4 (1.6)					6.4 (2.0)	0.015	0.10	0.015
60 % radius	Total CSA (mm^2)	2.6 (1.4)					7.5 (1.8)	<0.001	0.16	<0.001
	Cortical BMD (mg mm^{-3})	1.4 (0.3)					−1.6 (0.4)	<0.001	0.16	<0.001
	Periosteal circumference (mm)	3.6 (0.9)					3.6 (0.9)	<0.001	0.17	<0.001
	Endocortical circumference (mm)	−2.9 (1.6)					6.6 (1.9)	0.007	0.11	0.007
	Polar moment of resistance (mm^4)	27.3 (7.1)			−0.3 (0.11)	0.023			0.07	0.023
60 % ulna	Total BMC (mg mm^{-1})	2.7 (1.1)					7.2 (1.4)	<0.001	0.23	<0.001
	Total CSA (mm^2)	1.8 (1.1)					7.4 (1.4)	<0.001	0.25	<0.001
	Cortical CSA (mm^2)	2.2 (1.2)					8 (1.5)	<0.001	0.26	<0.001
	Cortical BMD (mg mm^{-3})	0.8 (0.2)	−1.0 (0.3)	0.007					0.11	0.007
	Periosteal circumference (mm)	0.8 (0.5)					3.6 (0.7)	<0.001	0.26	<0.001
	Polar moment of resistance (mm^4)	5.9 (2.2)					10.1 (2.7)	0.003	0.13	0.003
35 % humerus	Total BMC (mg mm^{-1})	35.1 (7.1)	7.4 (2.4)	0.017	−0.31 (0.10)	0.024	5.3 (2.5)	0.040	0.24	<0.001
	Total CSA (mm^2)	22.4 (5.3)	7.3 (1.8)	0.001	−0.23 (0.08)	0.026	6.5 (1.9)	0.006	0.35	<0.001
	Cortical CSA (mm^2)	44.8 (7)	8.8 (2.5)	0.005	−0.41 (0.11)	0.002			0.22	<0.001
	Periosteal circumference (mm)	10.5 (2.4)	3.3 (0.8)	0.001	−0.1 (0.04)	0.029	3.0 (0.9)	0.006	0.35	<0.001
	Polar moment of resistance (mm^4)	43.3 (10.2)	11.5 (3.4)	0.007	−0.43 (0.15)	0.031	10.7 (3.6)	0.030	0.29	<0.001
Forearm muscle CSA (mm^2)		12 (1.6)					6.0 (2.0)	0.025	0.09	0.004
Hand grip force (N)		35.5 (6.5)			−0.32 (0.10)	0.013			0.10	0.002

Side asymmetry—age effects

Only in proximal radius R_p were any age effects on magnitude of side asymmetry in radius or ulna found - being greater in younger players (P=0.04). Most pronounced were age effects in the humerus, where side asymmetries in BMC, total and cortical area, periosteal circumference and R_p were 41–48 % smaller at age 80 than age 40 (all P<0.05). Side asymmetries in MuscA were not affected by age, but grip force asymmetry was less in older players (P=0.01).

Side asymmetry—starting age effects

Young starters had greater side asymmetries in total bone CSA, periosteal circumference and R_p at each site (P<0.05; Fig. 1) with the exception of proximal radius R_p (not significant). Asymmetry in humerus (P=0.04) and ulna total BMC and proximal radius endocortical circumference (both P<0.01) were also more pronounced in young starters. Conversely, at the proximal radius, old starter BMD differences were more pronounced (P<0.001).

Side-to-side differences—other effects

There were no significant effects of body mass, height or weekly training volume on magnitude of side asymmetry.

Muscle-bone relationships

Muscle CSA and cortical bone CSA were correlated at all diaphyseal locations (all P<0.001, R^2=0.66–0.79, Fig. 2). These relationships remained significant at P<0.001, with reduced coefficients of determination (R^2=0.49–0.78), when limb length was taken into account via partial correlation. Muscle/bone relationships (assessed as ratio of muscle CSA to bone CSA) were similar in both forearms (dominant radius ratio 41.3±5.5, non-dominant 39.4±5.3, dominant ulna 33.1±3.6, non-dominant 30.8±3.6), but muscle/bone relationships were lower for the dominant (12.3±3.5) than for the non-dominant (13.9±4.0) upper arm (P<0.001). Muscle/bone ratio was higher in men than women in the non-racquet arm ulna (P<0.05) and humerus (P<0.01). There was a significant age-related decline in muscle/bone ratio in both ulnae and non-racquet arm humerus (all P<0.01).

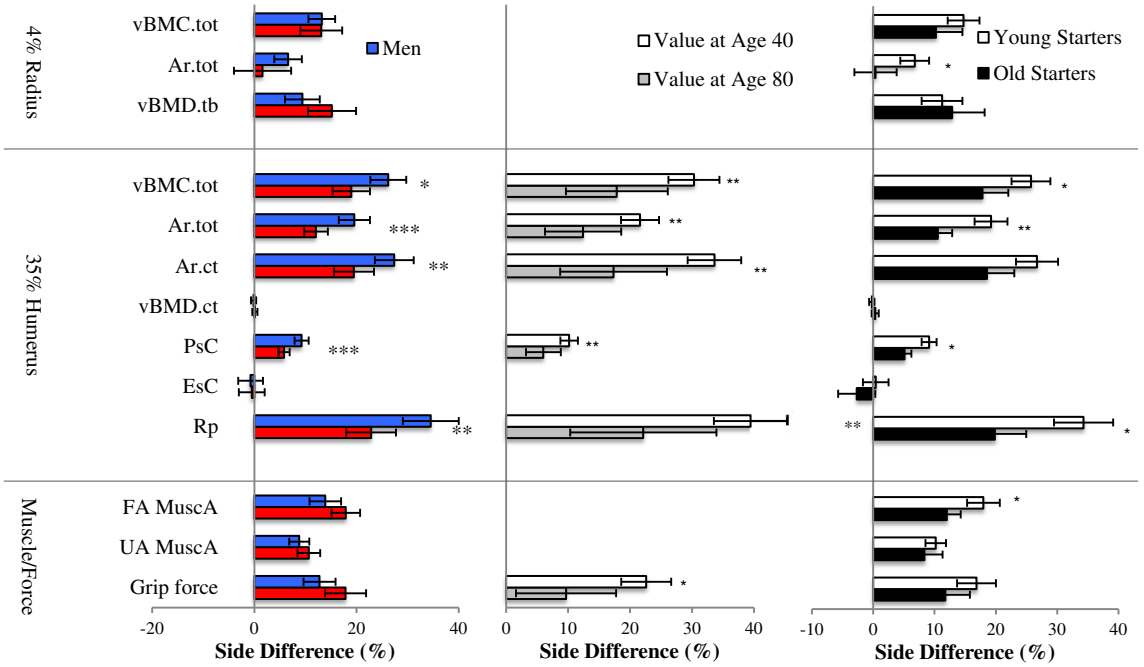

Fig. 1 Effects of sex, age and starting age (as mean±95 % confidence interval) on side asymmetries in humerus and distal radius bone parameters, muscle size and grip force. *Asterisks* indicate significant differences between groups: *$P<0.05$, **$P<0.01$, *$P<0.001$. *vBMC.tot* total BMC (mg mm^{-1}), *Ar.tot* total bone area (mm^2), *Ar.ct* cortical bone area (mm^2), *vBMD.tb* trabecular BMD (mg mm^{-3}), *vBMD.ct* cortical BMD (mg mm^{-3}), *PsC* periocortical circumference (mm), *EcC* endosteal circumference (mm), R_p polar moment of resistance (mm^4), *FA MuscA* forearm muscle cross-sectional area (mm^2), *UA MuscA* upper arm muscle cross-sectional area (mm^2), *Grip force* hand grip force (N). Values for males/females and old/young starters were obtained from cohort data; values at age 40 and age 80 were obtained from regression coefficients

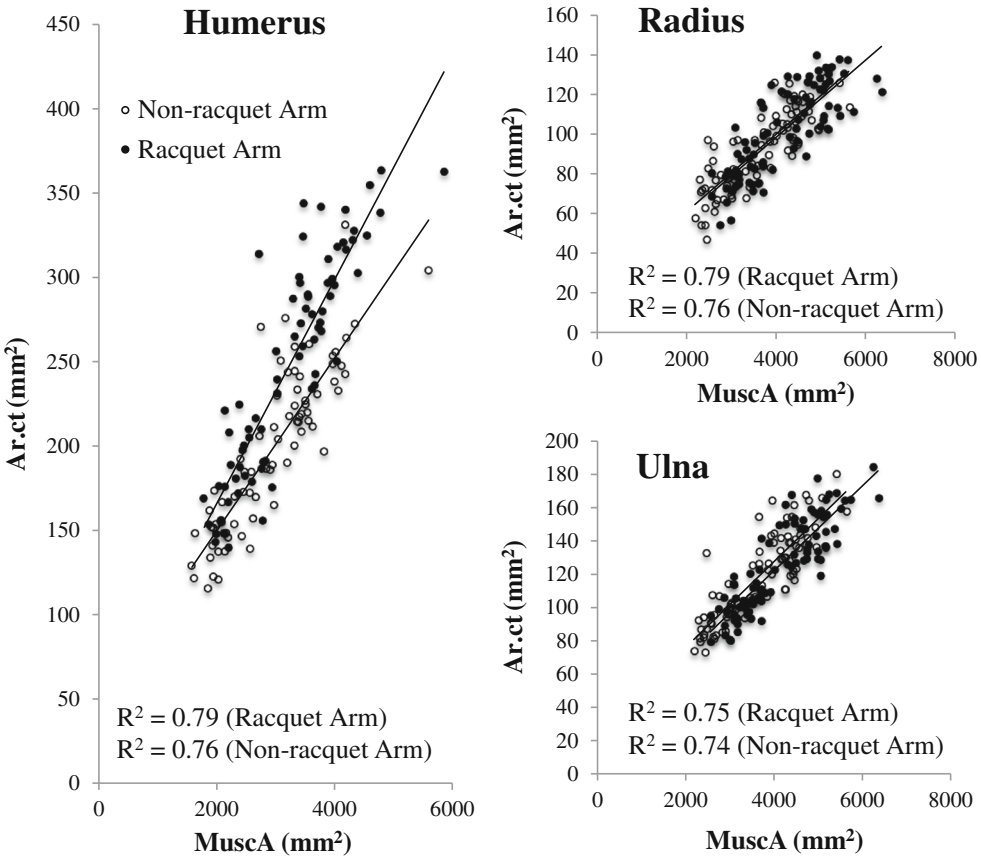

Fig. 2 Linear regressions showing relationship between muscle CSA (*MuscA*) and cortical bone CSA (*Ar.ct*) at mid-shaft radius, ulna and humerus sites in racquet and non-racquet arm. For all correlations, $P<0.001$

Discussion

The main purpose of this study was to investigate the impact of regular exercise on bone strength by measuring side asymmetries in pQCT-based bone strength indicators in the upper limbs of tennis players. In tennis players, the non-racquet arm serves as an internal control, circumventing self-selection bias evident in comparisons of athletes and sedentary counterparts. We chose veteran tennis players to ascertain whether the impact of tennis was still evident in older players and to what extent the impact was affected by starting to play before or after adulthood.

Muscle and bone size and strength were all much larger in the racquet arm, most markedly the 22–23 % side asymmetries in humerus bone size and BMC. Side asymmetries in distal radius BMC were due to greater trabecular BMD and bone size, whilst diaphyseal bone asymmetries were due to greater racquet arm bone CSA but not BMD. Periosteal but not endosteal circumferences were larger in the racquet arm (Table 3); therefore, cortical thickness was also greater than in the non-dominant limb. Conversely, cortical BMD was lower in the racquet arm, possibly reflecting greater bone turnover and hence number of resorption cavities. These results are similar qualitatively but smaller in magnitude than those in previous studies of younger players [6, 7, 11].

The lack of age-related differences in training volume suggests a similar training effort in participants across the age range. Side asymmetries in grip force were much smaller in older players; racquet arm advantage at age 80 was predicted to be only 43 % that at age 40. According to the mechanostat theory, bones adapt in response to the strains they experience [17]. As internal muscle forces are a greater stressor to bone than external reaction forces, reduced side asymmetry in maximal force in older age will lead to a reduced differential in bone strength between the two arms. Accordingly, side asymmetries in a number of bone strength indicators—particularly in the humerus—were less pronounced in older players. Humeral BMC and polar moment of resistance side asymmetries were less pronounced in older players as racquet arm advantages in periosteal circumference and total area were smaller. Similar patterns were found at the other diaphyseal sites, although the majority of these associations were not significant once Bonferroni correction had been applied. In contrast, BMC side asymmetry at the epiphyseal distal radius site was not affected by age (P=0.863); as this is a common fracture site [5], this is an exciting finding for the potential of exercise in reducing fracture risk.

Another contributing factor to the lower side asymmetries in older players may be the reduced osteogenic response of older bone to mechanical stimuli [13, 29, 30]. However, assuming both arms will be exposed to this diminished mechanical sensitivity, this should not affect relative magnitude of side asymmetry, which will depend on maximal force asymmetry. This is supported by similar age-related declines in humeral bone strength parameters (41–48 %) and hand grip force (57 %) side asymmetry predicted between 40 and 80 years of age within this study. Side asymmetry studies are more stringent than cross-sectional designs; that the exercise-induced advantage in the racquet arm decreases with age suggests that bone strength would decrease with age in normally active people even if physical activity levels were maintained. Whilst the exercise advantage in bone strength is lower in older tennis players, it is still considerable; at age 80, humerus strength in bending and compression was still predicted to be 18–22 % greater in the racquet arm. This is comparable to the age-associated decrease in upper limb BMC between the ages of 20 and 90 [1]. The only previous study to examine bone strength in athletes and controls across adult life found that older athletes had smaller bone strength advantages over controls than young athletes [14]; however, whether this was a result of BMC, size or geometrical differences could not be established. Self-selection bias between athletes and controls is also a possible confounder in that study, whereas this study employed a within-subject control. This allowed the identification of reduced periosteal circumference advantage as the cause of age-associated decline in humerus side asymmetries in BMC and moment of resistance. Also, epiphyseal side asymmetries in BMC were not affected by age.

In line with previous observations [19], bone and muscle size and strength were larger in men than women even when body size was controlled. Despite no sex effects on muscle or force asymmetry, bone strength side asymmetries were more pronounced in men. This was particularly evident in the humerus where all measured bone asymmetries were 22–37 % smaller in women. The only exceptions to this were humeral BMD and endocortical circumference asymmetries which were similar in both sexes. Both sexes had a similar training volume, and although women had a higher ranking, there are four times as many men registered in the rankings, suggesting that ranking differences may not have reflected lower ability in male players.

The majority of women were post-menopausal. The rise of oestrogen following menarche and fall following menopause are associated with increase and decrease in BMC, respectively [31, 32]. The changing levels of circulating oestrogen have been suggested to have an effect on bone mechanosensitivity [33]. This could explain why smaller asymmetries in bone were found in women in this study, without concurrent smaller asymmetries in muscle size/force. This is supported by similar findings in a youth tennis player cohort where 50 % of female participants were pre-menarcheal [11], whereas in adult players, side asymmetries were similar in both sexes [20]. That no effect of menopause on bone parameters was found when age was included as a covariate in analysis may seem surprising, but this study was not aimed at detecting such effects. Only nine women were of typical menopausal age

(45–55 years of age), making detection of significant menopausal effects difficult. A previous study has shown exercise benefits from the same intervention to be smaller in post- than pre-menopausal women [34], although pre-menopausal women were 20 years younger and age was not controlled. Similarly, the study was not powered to investigate the effects of HRT; however, a previous study found no effect of HRT on exercise benefits in the bone [34]. Amenorrhea is known to attenuate exercise gains in the bone in younger women [35], but incidence was not recorded in the current cohort—a limitation of the study. A study investigating exercise benefits in age-matched pre- and post-menopausal women examining effects of HRT, amenorrhea, etc. on bone strength would be a valuable progression of that study.

The national ranking of young and older starters was similar. Whilst young starters had played tennis longer, this factor did not affect side asymmetry; young starters were also younger and had a smaller training volume, factors accounted for by inclusion of age and training volume as covariates in analysis. Side asymmetries in forearm muscle and bone strength were more pronounced in young starters, supporting existing findings [15, 18]. In diaphyseal bone, this was most evident in total bone area and periosteal circumference, where side asymmetries in young starters were 1.8–4.3 times greater resulting in more pronounced BMC and moment of resistance side asymmetry than in adult starters. However, racquet arm advantages in density and endocortical circumference were more pronounced in older starters. In epiphyseal bone, the impact of starting early was more stark; whilst racquet arm bone area was 7 % greater in young starters, an average of 30 year tennis playing in old starters did not result in any side asymmetry in bone size. This finding supports the conjecture that joint size is adapted to peak loads at the end of puberty (although modest periosteal apposition continues throughout life) [16, 17]. Whilst this is an important finding for bone health, a greater joint size would—*ceteris paribus*—result in reduced joint stress. Hence, it may also have implications for soft tissue health and conditions such as osteoarthritis.

The only previous study to compare exercise benefits in the bone in young and old starters contained only women. The groups differed in age by ~20 years, and age was not included as a factor in analysis [18]. This is important as we have shown that side asymmetries are smaller in old than young age, independent of being an early or late starter. After epiphyseal closure, it is suggested that maximal force is limited in an attempt to prevent soft tissue damage—a proposal supported by the finding of smaller muscle size and strength side differences in adult starters. Whilst increases in bone size during adulthood slow down in mid- and late teens in females and males, respectively [24–26], it is unclear when the 'hard stop' for bone cross-sectional growth occurs. Epiphyseal closure would seem to be the most likely point although this is currently unexplored. As this could be an important factor, the analysis was also completed using typical ages of upper limb physeal closure in males and females [36] as a threshold for defining young and old starters. This had no significant effect on the results, likely because only a handful of participants were affected by this re-analysis. Exercise begun in older age still appears to increase bone strength (although less effectively than that begun in childhood) through increases in BMD and endocortical apposition/retention, although the ability of exercise to stimulate periosteal apposition is diminished, particularly in epiphyseal sites. This would also explain why little exercise benefit in bone strength was found in the only previous pQCT study on side asymmetries in bones of veteran tennis players [37]; participants were female and only started playing in their fourth decade, factors shown in this study to be associated with reduced or absent side asymmetries.

Hand grip force and muscle size were negatively associated with age in both arms, similar to results from a previous study in master throwers [38]. Older player's bones were much bigger, whilst negative age effects on BMD were less pronounced; hence, there were no significant age effects on BMC at any site. Larger diaphyseal periosteal and endocortical circumferences resulted in greater bone torsional strength in older people.

The lack of an age association with lower BMC is in contrast to a previous study [1]. However, the previous study's cohort were taken from the general population; therefore, it is likely that the older participants were less physically active [39]. Results in that study could reflect both age-related physiological and behavioural changes, whereas this study more effectively isolates the effects of physiological ageing. That bone strength indicators in older players were maintained or greater despite lower maximal force appears to contradict the Mechanostat Theory [17], whereby bone strength is purported to be regulated by peak bone strains. Negative age effects on osteogenic response to mechanical loading [13, 29, 30] were expected to cause more pronounced age-related declines in bone than muscle strength. However, material properties of bone change with age [40] such that despite lower muscular forces acting upon the bone in the elderly, strain engendered within the material may be similar, hence preserving the mechanostat's principle tenet. The finding of a strong relationship between bone measures and body size supports existing findings in the newborn [41, 42] and elderly [43].

Close muscle-bone relationships found at all sites—even when limb length was taken into account—support the idea of a strong influence of muscular action on bone strength. These relationships differed between the humeri, as found in a previous study [11], suggesting that muscle size alone does not fully describe variance in muscular influence on bone. As postulated previously [11], tennis probably requires the muscles to act in a different way to habitual usage, or perhaps the influence of individual muscles within a cross section varies. In addition, whilst the direct influence of muscular action on the bone is becoming widely appreciated, common endocrine

signalling pathways may also link adaptation of the two [44, 45]. Women are known to have a lower muscle/bone ratio [46, 47], and muscle/bone ratio decreases with age [48]—both trends supported by results in this study.

This is a cross-sectional study; hence, statistical effects of age may be influenced by secular changes or self-selection. Therefore, the main focus of this study is on side asymmetries. That such side asymmetries are greater in tennis players than those in sedentary controls is well established [6, 18] and was not the aim of this study; hence, a control group was not examined. Given that participants were all highly active tennis players and did not engage to great extent in other sports, it is most likely that the observed side differences are indeed the result of differential loading of the arms.

In summary, regular participation in tennis is associated with large side asymmetries in muscle size and strength and bone strength in the racquet arm in veteran players. The relative effectiveness of exercise in maintaining muscle and in particular bone size and strength diminished with age in diaphyseal but not epiphyseal bone, and exercise benefits are more pronounced in men than women. The exercise benefits in the racquet arm are greater when exercise is begun in childhood, reinforcing the importance of ensuring regular physical activity during childhood and in particular adolescence.

Conflicts of interest None.

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