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Original Article

Hylonome

Age-dependency in bone mass and geometry: a pQCT study on male and female master sprinters, middle and long distance runners, race-walkers and sedentary people

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Abstract

Objective: To investigate whether athletic participation allows master athletes to preserve their good bone health into old age. **Methods:** Bone strength indicators of the tibia and the radius were obtained of master runners and race-walkers (n=300) competing at World and European Master Championships and of 75 sedentary controls, all aged 33-94yrs. **Results:** In the tibia, diaphyseal cortical area (Ar.Ct), polar moment of resistance (RPol) and trabecular bone mineral density (vBMD) were generally greater in athletes than controls at all ages. In the athletes, but not the controls, Ar.Ct, RPol (females) and trabecular vBMD were negatively correlated with age ($p<0.01$). Radius measures were comparable between athlete and control groups at all ages. The amalgamated data revealed negative correlations of age with Ar.Ct, RPol (females), cortical vBMD and trabecular vBMD (males; $p<0.005$) and positive correlations with endocortical circumference ($p<0.001$). **Conclusion:** This cross-sectional study found age-related differences in tibial bone strength indicators of master athletes, but not sedentary controls, thus, groups becoming more similar with advancing age. Age-related differences were noticeable in the radius too, without any obvious group difference. Results are compatible with the notion that bones adapt to exercise-specific forces throughout the human lifespan.

Keywords: Track and Field Runners, Ageing, Bone Strength, Volumetric Bone Mineral Density (vBMD), Exercise

Introduction

It is well established that bone mass decreases with age[1,2]. It is also broadly accepted that the young skeleton responds to mechanical loading by increasing its bone mineral mass, altering its geometrical structure and thus adapting in bone strength[3-7]. In line with this, there is increasing evidence that master athletes, who train for and compete in sports into older age (often into their eighties or even nineties), have enhanced bone strength at mechanically loaded skeletal sites. For instance, cross-sectional studies have reported increased bone strength surrogates or stiffness indices at the loaded skeletal sites of both male master cyclists and female master track and field athletes compared to control data: these differences range between ~10 and 20%[8,9]. Comparable to that, in a study involving 300 master runners and race-walkers[10] we found that male and female sprinters had approximately 15% and 25% greater indicators of bone strength in the tibia diaphysis than the control group; in the tibia epiphysis this group difference amounted to approximately +8% in male and +13% in female sprinters. Middle distance runners, long distance runners and race-walkers had also enhanced indicators of bone strength, but the difference from the controls' tibias became smaller as exercise-specific speed decreases. No systematic differences between athletes and control participants were observed in the radius.

The authors have no conflict of interest.

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			Age (yrs)	Height (m)	Tibia length (cm)	Body mass (kg)
Men[a,b]	Controls	**Mean**	**54**	**1.77**	**38.9**	**81**
	n=32	SD	13	0.07	2.7	14
	Race-walk	**Mean**	**57**	**1.73**	**37.8**	**70****
	n=21	SD	11	0.05	1.8	7
	Long Dist.	**Mean**	**62***	**1.73**	**38.1**[a]	**66***[b]
	n=58	SD	12	0.07	1.9	6
	Middle Dist.	**Mean**	**58**	**1.75**	**38.3**	**71****
	n=27	SD	13	0.09	2.7	12
	Sprint	**Mean**	**59**	**1.74**	**37.6**[a]	**74***
	n=51	SD	15	0.05	2.1	8
Women[a]	Controls	**Mean**	**59**	**1.60**	**34.1**	**67**
	n=43	SD	13	0.06	2.0	13
	Race-walk	**Mean**	**54**	**1.62**	**35.3**	**59****
	n=28	SD	9	0.07	2.0	7
	Long Dist.	**Mean**	**59**	**1.64**	**35.4**	**56*****
	n=35	SD	11	0.06	2.2	6
	Middle Dist.	**Mean**	**55**	**1.62**	**35.2**	**56*****
	n=25	SD	12	0.07	2.0	6
	Sprint	**Mean**	**59**	**1.63**	**35.0**[a]	**59*****
	n=55	SD	14	0.07	2.4	7

Table 1. Age and anthropometric characteristics of study participants. Statistically significant differences from the control group are indicated as follows: ***p<0.001, **p<0.01, *p<0.05. Superscripts indicate negative correlations of age and tibia length[a] or body mass[b]. Ulna length was not correlated with age in any group.

Although the evidence for enhanced bone strength at loaded skeletal sites of master athletes is convincing, it is not clear as to whether participating in strenuous and regular physical activity allows them to preserve their good bone health into old age. Current literature provides few studies that investigated age effects upon bone in master athletes. The existing ones generally assessed areal bone mineral density (aBMD) by dual x-ray absorptiometry (DXA)[11-13]. There seems to be a consensus in these studies that aBMD is not affected by age in the exercised bones of male master athletes, however, disadvantages of the DXA technology need to be borne in mind[14]. The peripheral Quantitative Computed Tomography (pQCT) technology offers a more sophisticated approach to bone as it assesses true volumetric bone mineral density, and it can distinguish cortical and trabecular bone compartments. Moreover, the cross sectional images yield geometrical bone measures indicative of bone strength and stiffness[15,16].

In this study we investigate the relationship between age and bone measures in athletes and control participants of the aforementioned study cohort[10]. In our previous paper, we proposed that exercise-specific forces are responsible for the apparent enhancement of bone strength in master runners and race-walkers[10]. Since running speed decreases with age in master athletes[17], and the musculoskeletal forces associated with running must also be expected to decline with age in these people, we hypothesized that old age would be associated with lower bone strength indicators in the tibia of master runners and race-walkers (primary hypothesis). Moreover, ageing is associated with a loss in muscle mass and strength of both proximal and distal muscles in healthy people with habitual loading[18], leading to lower musculoskeletal forces at older age. Based on this assumption, we expected old age to be associated with lower bone strength indicators in the radius of both control participants and athletes (secondary hypothesis) and also in the tibia of control people (third hypothesis). We anticipated that it might be challenging to find control people, who are healthy mentally active but physically inactive.

Materials and methods

Participants

A total of 157 male and 143 female Master athletes of a previously described cohort study were recruited and tested at World, European and British Master Athletics Competitions between 2004 and 2006[10]. Athletes were eligible for the study if they competed in one of the respective championships and considered their best discipline to be running or race-walking. To allow a more detailed analysis, athletes were classified into four different event categories, depending on their self-rated best discipline: race-walkers (5 km, 10 km, 20 km), long distance runners (5 km, 10 km, Marathon), middle distance runners (800 m, 1500 m) and sprinters (100 m, 200 m, 400 m; Table 1).

The control participants consisted of 32 males and 43 females, who were members of the local University of the Third Age or employees of Manchester Metropolitan University, UK. Control participants were mentally active, but participated in little or no physical activity; that is less than two hours per week of endurance exercise and no exhaustive or resistive ex-

		Diaphysis (60%)					Epiphysis (4%)		
		Ar.Ct [mm²]	RPol [mm³]	PsC [mm]	EsC [mm]	vBMD.ct [mg/cm³]	vBMD.tb [mg/cm³]	vBMC.tb [mg/mm]	Ar.tot [mm²]
All Men	R^2	0.03*	0.00	0.02*	0.08***	0.09***	0.07***	0.02*	0.03*
	$\%\Delta_{40\_80}$	-6.8	-1.7	2.5	16.7	-2.2	-13.7	-8.1	7.2
All Women	R^2	0.17***	0.05**	0.00	0.17***	0.21***	0.01	0.00	0.00
	$\%\Delta_{40\_80}$	-20.1	-14.8	0.0	28.8	-4.1	-5.2	-3.0	2.9

Table 2. Overview of the results of regression analysis for the radius measures. The goodness of fit of the model (R^2) and differences between values at age 40 and at age 80 ($\%\Delta_{40\_80}$), as assessed from these correlations and expressed as percent value in relation to the value at age 40. Significant correlations are shown in black and non-significant ones in grey. Since virtually no significant group differences were found for the radius, values are given for the entire study cohort. Asterisks indicate a significant change with age as follows: ***p<0.001, **p<0.01, *p<0.05. See "Materials and methods" for abbreviations.

ercise (either job or leisure time related). Further details on the study cohort and also the selection and inclusion criteria are explained in our previous publication[10].

The study participants' age ranged between 33 and 94 years. They were all free of any diagnosed musculoskeletal condition and did not take any medication for the purpose of treating bone conditions. Participants had given written informed consent before inclusion into the study. The study had been approved by the ethical committee of Manchester Metropolitan University and by the local ethical committees in the respective countries where competitions were held.

Measurements

Participants' height and body mass were measured and both a health and a sport's history questionnaire were completed. Athletes were also questioned about their competition level.

Tomographic scans of the right lower leg and the right forearm were obtained with two XCT2000 scanners (STRATEC Medizintechnik GmbH, Pforzheim, Germany) and image analyses were performed with the integrated software version 5.40 D of one of the scanners. Both scanners were initially calibrated by the manufacturer, and their compliance was better than 2% (personal communication J. Willnecker, Stratec). During the study, they underwent daily quality assessment.

Epiphyseal and diaphyseal scans were taken at 4% and 60% of the ulna length and at 4% and 38% of the tibia length, with a voxel size of 0.5 mm in the transverse direction and 2.4 mm in the longitudinal direction. Normally, the right limbs were scanned, however, the left limb was scanned when a fracture had occurred within the last 24 months.

Image analysis

Segmentation thresholds to separate bone from surrounding soft tissue were set to 180 mg/cm³ for the epiphyses and to 650 mg/cm³ for the diaphyses[10]. From the radius and tibia diaphyses, we assessed vBMC.tot, cortical area (Ar.Ct)[a], the density weighted polar moment of resistance (RPol) as well as endocortical and periosteal circumferences (EsC and PsC, respectively). In addition, the cortical BMD (vBMD.ct) was analysed, which was corrected for partial volume error as described by Rittweger et al.[19]. From the epiphyses, bone mineral content (vBMC.tb), trabecular bone mineral density (vBMD.tb) and total area (Ar.tot) were assessed. The *in vivo* precisions of pQCT measurements of the laboratory are described elsewhere[20,21]. They range between 0.2-0.5% for tibial Ar.tot, Ar.Ct and vBMC.tot and 1.3-1.7% for RPol.

It should be mentioned here, that bone scans were also obtained at the 14% metaphyseal site of the tibia. However, results from this site were very similar to the results from the 38% diaphyseal site, and they are therefore not reported here.

Statistical analysis

Descriptive summary statistics were calculated using means and standard deviations (SD). Correlation and regression analysis of reported variables were performed to obtain Pearson's correlation coefficient (R) and the regression equation (Table 2 & 3). Due to our primary hypothesis, one-tailed tests were used for bone measures. There was no consistent evidence that tibia length and body mass were correlated with age (Table 1). Therefore, unadjusted analyses and analyses adjusted for either tibia length or body mass were conducted. If not stated otherwise, p-values from the unadjusted analysis are reported in the text. Ulna length was not correlated with age and results were not different if adjusted for either ulna length or body mass, thus the unadjusted analysis is presented. For the regression, linear models were chosen since no non-linear model increased the adjusted R^2 value by more than 0.03[22]. Other models tried were logarithmic, inverse and polynomial. From the resulting regression equations we then computed the difference between values at age 40 and at age 80, which is given in percent as Δ_{40_80}. In order to summarise the original data for display purposes, means and standard deviations were computed for the 4th to the 8th decade of life for each group (Figures 1-3). To test differences between athletes and control participants, analysis of variance (ANOVA) was carried out. Significance was

[a] Diaphyseal vBMC.tot and Ar.Ct yielded very similar age-related effects, and we therefore report on Ar.Ct.

			Diaphysis (38%)					Epiphysis (4%)		
			Ar.Ct [mm²]	RPol [mm³]	PsC [mm]	EsC [mm]	vBMD.ct [mg/cm³]	vBMD.tb [mg/cm³]	vBMC.tb [mg/mm]	Ar.tot [mm²]
Men	Control	R^2	0.03	0.00	0.00	0.07	0.17*	0.06	0.01	0.14*
		$\%\Delta_{40\_80}$	-5.6	-2.1	0.7	11.8	-2.8	-9.7	5.4	18.1
	Race-walk	R^2	0.04	0.04	0.01	0.01	0.13[i]	0.00	0.00	0.02
		$\%\Delta_{40\_80}$	-6.9	-9.6	-1.9	3.7	-2.1	0.6	-3.4	-4.1
	Long Dist.	R^2	0.03	0.01	0.01	0.00	0.02	0.10**[e]	0.03	0.03[e]
		$\%\Delta_{40\_80}$	-5.2	-3.5	-1.3	2.9	1.1	-15.0	-8.2	7.5
	Middle Dist.	R^2	0.18*	0.08	0.10	0.00	0.02	0.00	0.00	0.01
		$\%\Delta_{40\_80}$	-10.6	-10.8	-4.7	-0.4	1.1	-1.3	1.0	2.7
	Sprint	R^2	0.13***[b,e]	0.06*[a,d]	0.04	0.03[b]	0.01	0.05	0.00	0.04[b,e]
		$\%\Delta_{40\_80}$	-10.4	-9.5	-2.8	8.2	1.0	-7.7	-2.3	5.8
	All Athletes	R^2	0.09***[b,e]	0.04**[a,d]	0.03*[a,d]	0.01[c,e]	0.00	0.04**[c,e]	0.01	0.02*[c,f]
		$\%\Delta_{40\_80}$	-9.0	-8.3	-2.5	5.6	0.4	-8.8	-4.6	4.7
Women	Control	R^2	0.01	0.01	0.02	0.01	0.19**	0.02	0.01	0.00
		$\%\Delta_{40\_80}$	3.4	4.3	2.4	4.3	-3.9	7.7	7.9	0.7
	Race-walk	R^2	0.09	0.09	0.00	0.13*[b]	0.30**[f]	0.16*	0.08	0.00
		$\%\Delta_{40\_80}$	-15.1	-18.3	0.3	25.6	-7.7	-21.3	-20.1	1.5
	Long Dist.	R^2	0.19**[c,f]	0.10*[e]	0.02	0.04	0.14**	0.12*	0.04[b,e]	0.01
		$\%\Delta_{40\_80}$	-18.2	-19.4	-3.5	15.5	-5.0	-20.5	-14.7	6.1
	Middle Dist.	R^2	0.38**	0.14**[a,d]	0.18*[a]	0.10	0.02	0.26**	0.18*	0.01
		$\%\Delta_{40\_80}$	-22.8	-16.2	-6.0	16.7	-1.2	-20.5	-17.8	3.8
	Sprint	R^2	0.26***	0.10*[a]	0.05*[a,d]	0.14**[c]	0.05*	0.18**	0.09*[d]	0.01
		$\%\Delta_{40\_80}$	-18.0	-14.8	-3.6	20.2	-2.2	-17.3	-14.9	2.3
	All Athletes	R^2	0.18***	0.08***[b,e]	0.03*[a,d]	0.09***	0.08***	0.10***[b,e]	0.06**[b,e]	0.01
		$\%\Delta_{40\_80}$	-17.2	-14.8	-3.1	17.6	-3.1	-16.7	-14.0	2.9

Table 3. Overview of the results of regression analysis for the tibia measures, presented in analogy to Table 2. See "Materials and methods" for abbreviations, and Table 2 for technical details. Superscripts indicate that the statistical significance of the adjusted and the unadjusted models differ: [a]p>0.05, [b]p<0.05 & ≥0.001, [c]p<0.001 if adjusted for tibia length; [d]p>0.05, [e]p<0.05 & ≥0.001, [f]p<0.001 if adjusted for body mass.

assumed if $p<0.05$. Statistical analyses were performed using SPSS 11 software for Mac OS X (SPSS Inc®, Chicago, IL, USA).

Results

Participant data

In total, 106 sprinters, 52 middle distance runners, 93 long distance runners, 49 race-walkers and 75 control participants were included in this study. The mean age graded performance of athlete groups, i.e. the performance relative to the age- and sex-specific world record, was between 74% and 89%. Reported weekly training hours were 9.7 (SD 4.7) and 9.1 (SD 4.9) hours in male and female athletes aged 60 years or younger and 7.4 (SD 3.7) and 8.0 (SD 3.2) hours in male and female athletes older than 60 years (p>0.05; adjusted for discipline). No difference was found in the mean age and height of athletes of both genders compared to the controls, except for male long distance runners, who were older than the controls ($p<0.05$; Table 1). About 60% of the females were postmenopausal; 18 women reported to currently use hormone replacement therapy.

Values for R^2 and Δ_{40_80} that were obtained from the regression analysis of radius data and age are given in Table 2, and those for the tibia are given in Table 3. For the tibia we analysed both, all athletes combined and groups separately. As there were generally no significant differences among athletes and control participant's radius measures at any age decade, values in Table 2 refer to all participants of this study.

Cortical area

Radius Ar.Ct showed no systematic athlete vs. control group effect at any presented age decade. The Δ_{40_80} value amalgamated for all study participants was -6.8% in men ($p=0.013$) and -20.1% in women ($p<0.001$; Figure 1a; Table 2). In the tibia, Ar.Ct was systematically greater in the athlete groups than in control participants for the age decades (Figure 1b). Tibial Ar.Ct was negatively correlated with age in all female athlete groups ($p<0.01$, except for race-walkers where $p>0.05$), and also in male sprinters and middle distance runners ($p<0.05$). Regression lines were very similar among the different athletic groups for each gender, and amalgamating them yielded a Δ_{40_80} of -9.0% in the male athletes, and -17.2% in the female athletes ($p<0.001$ in both cases, see Table 3 and Figure 1b). By contrast, the control participants who had much lower tibial Ar.Ct in their fifth decade of life than the athletes did not show any significant age effect. Consequently the athletes and the control participants tended to be more alike with advancing age (Figure 1b).

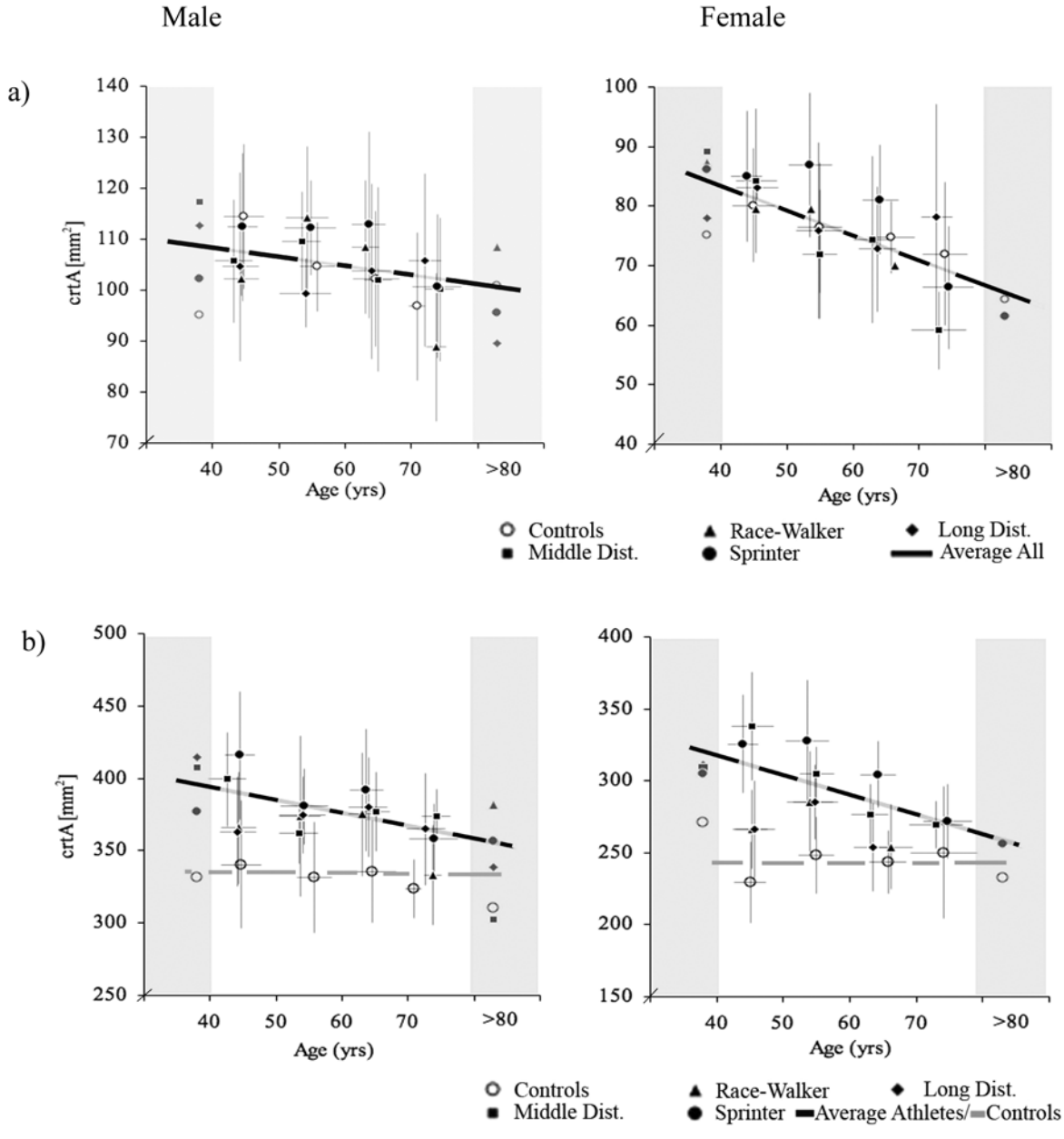

Figure 1. Cortical area of a) the radius and b) the tibia diaphysis in relation to age. Data points displayed here are means; SDs are shown for the 5th to the 8th age decades where at least 5 participants were in each group. Shaded areas indicate that the sample size was often <5 people. The displayed curves are either regression lines (where significant) or group mean values (where no significant correlation with age was observed). In the radius, there were no differences between the athlete and the control groups. The combined regression of the female and the male groups shows a significant effect of age in both genders (p<0.05). For the tibia, regression analysis suggests a decline in the amalgamated male and the female athlete groups (p<0.001). In the control groups, however, no significant effect of age was observed for the tibia, and the mean value is therefore displayed as dashed horizontal line. See also Tables 2 & 3 for the strength of correlations (R^2) and the difference between predicted values at age 40 and 80.

Polar moment of inertia

Results for RPol paralleled in principle the findings for Ar.Ct, although statistical significance was weaker particularly in males. Values of the radius diaphysis showed no systematic athlete vs. control group effect among the various age decades. The Δ_{40_80} value for the amalgamated women group was -14.8% (p<0.01), but no significant correlation with age was found for RPol in the radius of the amalgamated male group (Table 2). In the tibia, RPol values were generally larger in athletes than in control people throughout the age decades. When all athlete groups were amalgamated, Δ_{40_80} for RPol was found to be -14.8% in female athletes (p<0.001) and -8.3% in the male athletes

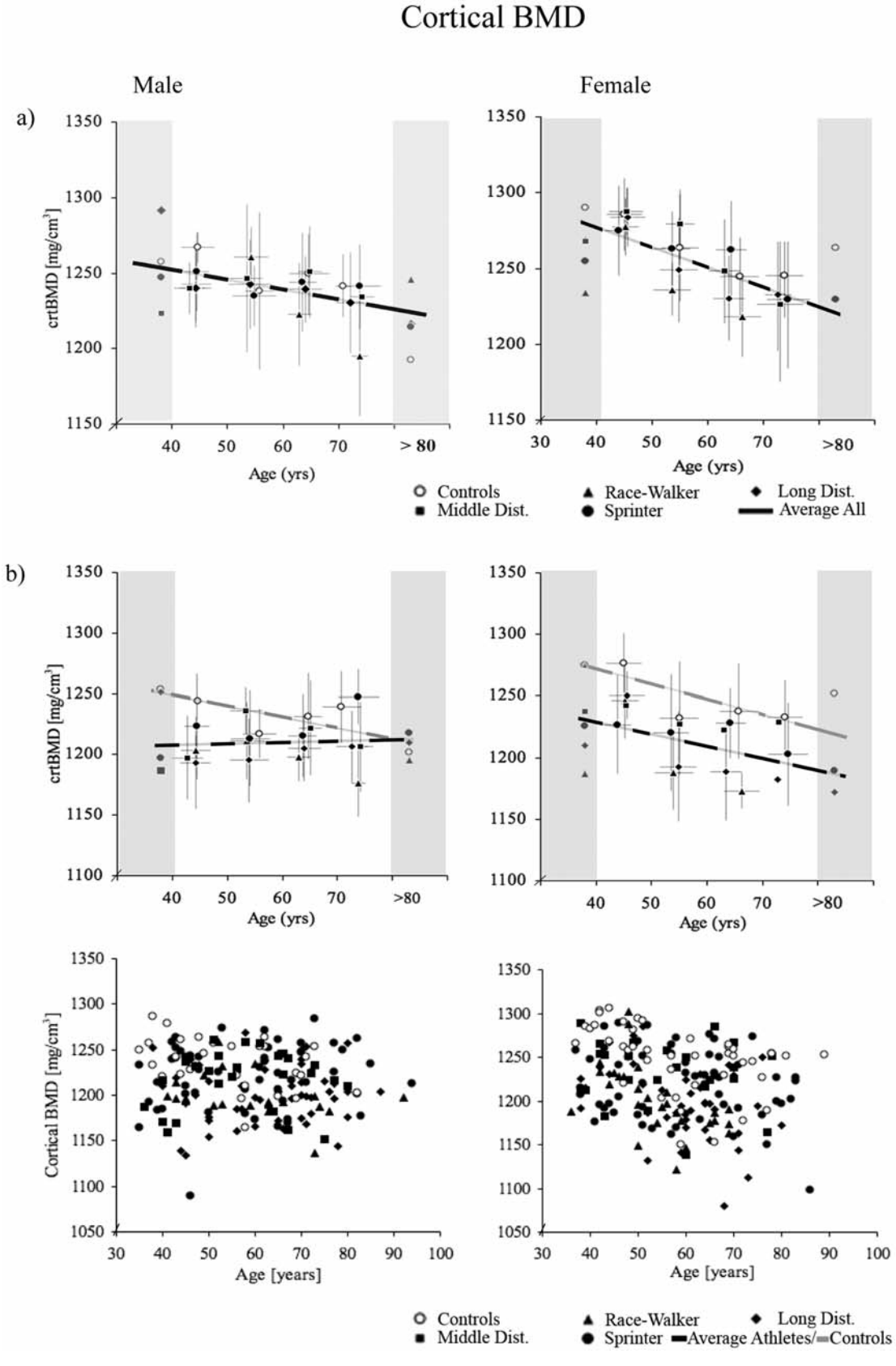

Figure 2. Cortical bone mineral density of the radius (a) and the tibia (b) diaphysis in relation to age. Data are displayed in a way analogous to Figure 1. In addition, scatter plots present the individual data points. No significant age effect was observed in the tibia of female control participants and of male athletes.

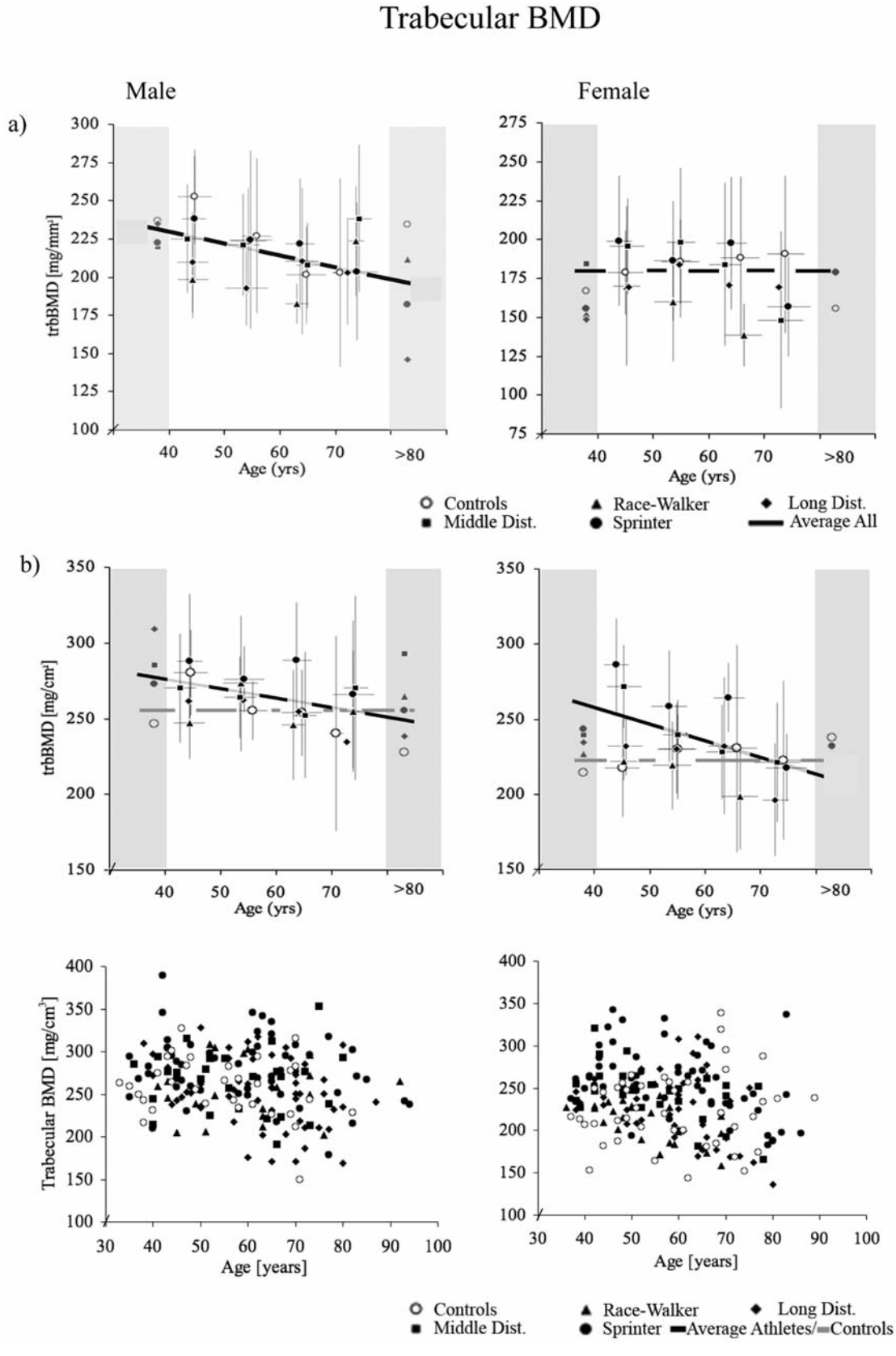

Figure 3. Trabecular bone mineral density of the radius (a) and the tibia (b) epiphysis in relation to age. Data are displayed in a way analogous to Figures 2 and 3. No significant age effect was observed in the amalgamated women's radius and in the tibia of male and female control participants.

(p<0.01; Table 3). After adjusting the data for either tibia length or body mass, this negative correlation was no longer statistically significant in the male group.

Periosteal circumference

Again, no athlete vs. control group differences were found in PsC for the radius diaphysis throughout the different age decades. For the amalgamated men's group, a small positive Δ_{40_80} of +2.5% was observed (p<0.05), which was mainly contributed to by the sprinters and control participants. No significant effect of age, however, was observed in the amalgamated group of women (p=0.49; Table 2).

For the tibia, PsC values were generally larger in athletes than in control people throughout the age decades. Significant correlations were found between age and PsC of the tibia of both the amalgamated male and female athlete groups; however, the difference between age 40 and 80 yrs was less than 4% (p<0.05; Table 3). After adjusting for either tibia length or body mass, those correlations were no longer statistically significant. There was no association between PsC and age in the control groups, suggesting that total bone shaft size was not or very slightly affected by age in both athletes and controls.

Endocortical circumference

Positive values of Δ_{40_80} were obtained for EsC of the radius in all groups separately, suggesting that older people have a larger marrow cavity. No athlete vs. control group differences were found throughout the various age decades. In quantitative terms, the Δ_{40_80} value for the amalgamated groups amounted to +28.8% in women and to +16.7% in men (p<0.001 in both cases; Table 2).

In the tibia, age-related differences in EsC were less systematic and generally smaller than in the radius (Table 3). The EsC values of the athlete groups were similar for the various age decades, and Δ_{40_80} values for the amalgamated athlete groups were +17.6% in female athletes (p<0.001) and +5.6% in male athletes (unadjusted p-value=0.068; adjusted p-values <0.05). In the control group, positive Δ_{40_80} values for tibia EsC were also encountered (Table 3). However, these were not statistically significant (p=0.052 for males and p=0.28 for females).

Cortical bone mineral density

In the radius, vBMD.ct values were comparable among the athlete and control groups, and Δ_{40_80} was -4.1% in women and -2.2% in men (p<0.001 in both cases; Table 2 and Figure 2a). In the tibia, the controls had generally greater vBMD.ct values than the athletes. In the tibia, vBMD.ct was also negatively correlated with age in all groups, except for the male athletes and the female middle distance runners (p=0.3 and 0.269, respectively, see Table 3 and Figure 2b).

Epiphyseal measures

Trabecular BMD of the radius did not reveal any systematic athlete vs. control group effect in the various age decades in both males and females (Figure 3a). A significant age effect was found for the amalgamated men's group (p<0.001), with Δ_{40_80} yielding -13.7%. For the amalgamated women's group, however, no significant effect of age was observed (p=0.17; Table 2 and Figure 3a).

In the tibia, vBMD.tb was negatively associated with age in all female athlete groups regarded separately, and Δ_{40_80} tended to be very similar among the groups (Figure 3b). Combining the data for all female groups, Δ_{40_80} was -16.7% (p<0.001). When the male athletes were analysed per single group, only long distance runners showed a significant correlation of vBMD.tb with age (p<0.01). However, amalgamating all male athletes yielded a Δ_{40_80} of -8.8% (p=0.004; Figure 3b).

Results for epiphyseal vBMC.tb of both the radius and the tibia generally paralleled results for vBMD.tb, although the effects were generally smaller and less often found to be significant (Table 2 & 3). Finally, total epiphyseal bone area (Ar.tot) tended to yield positive values in both the radius and the tibia (Table 2 & 3), which were statistically significant for both skeletal sites in the amalgamated men's group, and also for the tibia in the male control group, indicating that older people tended to have somewhat larger joints than younger study participants.

Discussion

The purpose of this analysis was to assess the age-related differences measurable by pQCT in the radius and in the tibia of master runners, race-walkers and physically inactive control participants. In support of our primary hypothesis, bone strength indicators of the tibia were negatively associated with age in master athletes, as shown by our results for cortical area and polar moment of resistance in the tibia diaphysis, and of trabecular BMD in the tibia epiphysis in both male and female athletes. In support of our second hypothesis, it was found that older age is associated with lower bone strength indicators in the radius of master athletes and control people alike, as evidenced by results for cortical area (men and women) and polar moment of resistance (women only) in the radius diaphysis, and by trabecular BMD values in the radius epiphysis (men only). The results, however, contradict the third hypothesis that sedentary people would experience age-related reductions in bone strength in the tibia, since no significant correlation was observed between age and diaphyseal cortical area, polar moment of resistance or trabecular BMD.

Study sample

As previously reported[10], master athletes included into this study had typically started to practice their athletic discipline in the third decade of life. They are therefore not former elite athletes in a strict sense. On the other hand, typically they had maintained their current training regime for more than a decade, and they accomplished comparatively large volumes of training at a high level. It is therefore fair to describe them as a group of highly motivated people. This gives us an idea in how far exercising at a high level can prevent age-related declines of musculoskeletal function[23]. Comparable to the master athletes, control participants in this study were mentally active as evidenced by occupation or educational participation.

They had however refrained from any sports and exercise for the most part of their lives[10] and can therefore be described as a model group of healthy 'sedentarians', who were carrying out the habitual activities of daily living only.

Age-related differences in the tibia

Despite of all their efforts, master athletes experience a marked decline in running speed[24-26] and power across all running events[17]. Slower locomotion speeds at different running disciplines, and also reduced running speeds with age have been associated with lower peak vertical ground reaction forces[27-29]. Reduced ground reaction forces, *ceterus paribus*, will translate into smaller peak strains, as evidenced by strain measurements in the human tibia[30-32]. According to the mechanostat theory[33] this will lead to bone loss, which may be a major explanation for the age-related differences in the tibia of our athletes. Due to the cross-sectional design of this study we cannot, however, exclude self-selection and secular effects within the population studied.

The female athlete data are in general agreement with Wiswell et al., who demonstrate a Δ_{40_80} value of -23% for areal BMD of the hip[34]. However, our work is in contrast with a study by Hawkins et al.[13] that reports no age-related bone loss in female runners, and also with three other studies that did not find any age-related differences in male runners[11,12,24]. It is likely that the different technological approach accounts for most of this discrepancy (areal BMD by DXA vs. volumetric BMD by pQCT). Moreover, the above-cited previous studies were smaller, and it may be that statistical power considerations also play a role.

Quite strikingly, the tibial bone strength indicators in our control participants, which were lower than in our athletes at all age decades, demonstrated no significant age dependency. This was an unexpected finding, i.e. our initial third hypothesis had to be rejected. For men, but not for women, this finding is supported by previous epidemiological pQCT studies[35,36]. However, great care is necessary before concluding that there is generally no age-related reduction in bone strength in the tibia of sedentary people. Firstly, our sample of control people was considerably smaller than our combined sample of athletes. Hence, the lack of significant age-related effects could be due to an under-sampling problem. In fact, a closer look at Table 3 reveals that there was a negative Δ_{40_80} value of -5.6% for cortical area in the male control participants, and sample size estimation (http://www.danielsoper.com/ statcalc/calc01.aspx) suggests that a sample of 258 control participants would have been required to yield a significant result (with R^2=0.03, α=0.05 and β=0.2), but only 32 participants were actually included. Secondly, older people in this study generally had somewhat larger epiphyseal bone area, and thus joint size. Assuming that joint size is an important determinant of peak joint forces and thus bone strength[37], it might well be that older people in this study had 'constitutionally' stronger bones, and that this effect mitigated any truly existing age effect. Hence, even if our data suggest that age-related bone losses, at least in the tibia, are smaller than often assumed[38], it is clear that longitudinal studies are required in order to elucidate this issue.

Age-related differences in the radius

Although not specifically assessed for this study, athletes and control participants probably used their forearms in a very similar way. It is therefore in line with our expectation that bones adapt to peak musculoskeletal forces that no systematic differences among athletic or control groups were found in the radius.

Of all the variables assessed in the radius, diaphyseal endocortical circumference depicted the clearest age-related differences, with Δ_{40_80} values of almost +30% in women and +17% men (Table 2 and Figure 1). On the contrary, there was virtually no age-related difference in periosteal circumference. Accordingly, diaphyseal cortical area was reduced in older women (Δ_{40_80}=-20%) and older men (Δ_{40_80}=-7%). Our findings are therefore compatible with the view of an age-related expansion of the marrow cavity[39]. Interestingly, age-related differences were less pronounced for the polar moment of resistance, where Δ_{40_80} was -15% in women and not even significant in men (Table 2 and Figure 2), suggesting that compressive strength of the radius may be more affected by age than torsional and bending strength.

Taken by themselves, these data might just reflect the apparent age-related bone loss in the general population that has been reported repeatedly[40-42]. However, this interpretation would completely ignore the strikingly small age-related differences in the tibia of our control participants. On the other hand, age-related losses of muscle mass and strength in the upper extremities have been reported previously[43], and these must be expected to lead to reduced musculoskeletal forces in the arm muscles of older people. Therefore, the adaptation to musculoskeletal forces, again, seems a likely explanation to account for the age-related differences observed in the radius. Future studies, however, e.g. on the arm bones of master throwers, will be required to provide evidence in favour or against this interpretation.

Cortical Bone Mineral Density

Mechanical loading is associated with enhanced microdamage and increased intracortical remodelling[44-46]. Increased remodelling is associated with a decrease in the mean degree of mineralisation, resulting in reduced vBMD for the same amount of bone tissue[47]. Finally, evidence suggests that estrogen has a protective effect on bone[46,48,49].

These considerations provide a theoretical framework to explain the eight main observations we made for vBMD.ct: 1) Generally, vBMD.ct values are greater for the radius than for the tibia (with the exception of the control males). However, 2) in the radius itself of either males or females, vBMD.ct values are comparable amongst the discipline groups (Figure 2a). 3) Females have larger vBMD.ct values at all age decades than males, both in the radius of the amalgamated groups and in the tibia of the control participants (Figure 2). 4) In the tibia of younger people, vBMD.ct values are larger in control participants than in athletes. Furthermore, 5) vBMD.ct is negatively correlated with age both in the radius of all amalgamated groups and in the tibia of male control participants. 6) Male athletes show no age dependency in the tibial vBMD.ct, and thus male control participants become more similar to the athletes with advancing age. 7) In female control participants, a higher

tibial vBMD.ct can be observed at ages younger than 50 as opposed to older age. 8) Finally, in the female athletes, tibial vBMD.ct is negatively correlated with age (Figure 2, Table 3).

As much as mechanical loading promotes intracortical remodelling, lower vBMD.ct values should be expected in the exercised tibia as compared to the radius (observation 1), and also when comparing the tibia of athletes and of control people (observation 4). However, as groups probably did not differ in the way they loaded their arms, radius vBMD.ct values would be expected to be similar across groups. This was indeed the case (observation 2). On the other hand, in line with epidemiological studies[35,36,50] vBMD.ct seemed to have been independently affected by age (observation 5 & 7). Another factor was that vBMD.ct appears to be elevated during the fertile period in females (observations 3 & 7), which is in agreement with the proposition of oestrogen having a protective effect on bone[47-49].

As to observation 6, i.e. a constant tibial vBMD.ct throughout life in male athletes, we would argue that the age-related decline in running speeds and the associated reduction of musculoskeletal forces are related to a reduction of the remodelling activity, and that this effect has mitigated the age-related decrease in tibial vBMD.ct to some extent. In female athletes, however, such a balancing effect was not observed (observation 8), indicating that intracortical remodelling is comparatively prevalent in this group at all ages.

Limitations

The analysis strongly suggests that maximal voluntary mechanical loading up to old age might not fully prevent an age-related loss in bone strength. However, the age-related differences observed are, by the very nature of the cross-sectional design, inter-individual, and therefore only highlight what may happen within an individual's lifespan. A longitudinal study would be beneficial to add to our understanding.

Conclusion

In summary, this cross-sectional study found age-related differences in bone strength indicators of the mechanically loaded tibia in master runners and race-walkers. No such age-related differences were found in the sedentary controls. It seems that the greater mechanical competence that is observed in the tibia of young athletes is not preserved beyond the age of 80 years. In the non-weight bearing radius, conversely, age-related differences are noticeable in and comparable among athletes and control participants. Results are compatible with the notion that bones adapt to exercise-specific forces throughout the human lifespan.

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