ORIGINAL ARTICLE

Higher tibial quantitative ultrasound in young female swimmers

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Background: It has been found that swimming, a non-impact sport, generally has no effect on bone mineral density.
Objectives: To examine bone properties, as measured by quantitative ultrasound, among female swimmers in comparison with control girls and women.
Methods: Subjects included 61 swimmers and 71 controls aged 8.5 to 26.5 years. None of the swimmers was at the elite level and none had included resistance training in her schedule. Bone speed of sound (SOS) was measured bilaterally at the distal radius and the mid-tibia.
Results: No differences were observed between swimmers and controls in body mass (mean (SD): 49.7 (12.3) *v* 50.7 (12.4) kg, respectively), although swimmers were taller (159 (12) *v* 155 (12) cm) and had lower body fat (18.3 (4.2)% *v* 22.3 (5.4)%). No difference was found in time since menarche (5.2 (4.0) and 4.5 (2.9) years in swimmers and controls, respectively; 21 swimmers and 25 control were premenarcheal). Radial speed of sound (SOS) increased with age but did not differ between swimmers and controls (non-dominant: 3904 (172) and 3889 (165) m/s for swimmers and controls, respectively). Tibial SOS also increased with age and was significantly higher in swimmers than in controls (non-dominant: 3774 (155) *v* 3712 (171) m/s). No differences were found between dominant and non-dominant sides.
Conclusions: Swimming appears to be associated with higher bone SOS in the lower but not in the upper extremities. Further studies are needed to assess whether this difference reflects higher habitual activity among the swimmers or swimming specific mechanisms.

Physical exercise has been shown to have a positive effect on bone mineral density (BMD) among children, adolescents, and adults. The effect of exercise is seen mainly following impact or weight bearing activity, and not in response to an active load which does not involve weight bearing, such as swimming.[1] Thus numerous studies report similar BMD in swimmers or athletes in the aquatic sports and in non-athletic control groups or athletes involved in non-impact or weight bearing sports. This has been reported among adult,[1 2] adolescent,[3 4] and prepubertal[5] subjects, both male and female.

In contrast to these cross sectional studies in humans, there are several intervention studies in animals which clearly show an increase in BMD following swimming training in young growing,[6] adult,[7] and aged animals.[8] Furthermore, in young rats, swimming exercise has been shown to result in an increased cortical cross sectional area, mainly because of periosteal apposition, increased longitudinal growth, and increased moment of inertia and compressive force (increased strength).[6] Finally, Hoshi *et al* reported an increase in bone elasticity in female adult mice following six weeks of swimming training.[7] These intervention studies show that, although swimming is not a weight bearing sport and involves no impact, it may indeed affect bone properties, and this may not necessarily be detected by bone mineral content measurements or BMD calculations.

The human studies examining BMD in swimmers, as mentioned above, used dual energy *x* ray absorptiometry (DXA) to assess the possible effect of exercise on bone mineral content and density. While BMD as determined by DXA may be highly correlated with bone strength, the latter is also dependent on other bone properties, such as elasticity and internal architecture and geometry,[9] which are not reflected in DXA measurements. Additionally, BMD as measured by DXA is a two dimensional measure and is highly influenced by body size.[10] BMD, as measured by quantitative computed tomography (QCT), is volumetric density (bone organ density, including the mineral content and the spaces within the bone). Block *et al* used QCT to assess hip and spinal BMD in adult male water polo players and weight training athletes.[11] These investigators reported no difference in BMD between the two groups of athletes, both of whom had higher BMD than the control, non-athletic group. The discrepancy in the QCT results compared with DXA raises the question of whether swimming exercise in humans—children and adults—may indeed affect bone mass, bone density, and bone geometry.

DXA provides an accurate and precise measurement of BMC. However, it is expensive and time consuming, and involves the use of some radiation.[12] In recent years, a quantitative ultrasound method (QUS) has been developed for bone assessment. The QUS method is portable, relatively inexpensive, and does not involve any radiation. The QUS parameters are related to bone density and structure,[13] but not to cortical thickness.[14] Previous studies have shown that in elderly subjects, QUS parameters can predict fracture risk independently of BMD.[15] In relation to swimming training, Taaffe *et al* reported higher calcaneal BMD in jumpers than in aquatic athletes, but similar calcaneal bone ultrasound attenuation (BUA), measured by quantitative ultrasound, in the two groups of adult male athletes.[16] These results suggest that possible effects of swimming exercise in humans on bone of the lower extremities may not be reflected similarly by DXA or other techniques.

Abbreviations: BMD, bone mineral density; DXA, dual energy *x* ray absorptiometry; QUS, quantitative ultrasound; SOS, (bone) speed of sound

To date, few studies have used QUS to investigate the effect of exercise on bone properties of young athletes. Several studies have shown a favourable relation between various high impact sports and bone ultrasound indices.[17–19] Our aim in this study was to compare bone speed of sound, as measured by QUS, between swimmers, athletes engaged in a non-impact sport, and non-athletic subjects.

METHODS

Participants in the study were all female, and included 71 non-athletic girls and 61 swimmers who were recruited from regional sports clubs. Only teams which trained and competed year round were approached. Training experience was at least 1.5 years (varying between 1.5 years for the 8.5 year old girls to 15 years for the 26.5 year old adults), and all trained between two and six times a week. None of the swimmers undertook resistance training as part of their regular training. Four swimmers reported participating in water polo activities one to two times a week. The control group included 71 girls who volunteered to participate in the study in response to an advertisement that was posted in local social clubs and health clubs. Control subjects did not participate in regular physical activity more than twice a week (as determined by a questionnaire). All subjects were white. Pubertal stage was determined by self assessment according to breast characteristics.[20]

Candidates known to have any chronic disease or who had been taking any drug treatment regularly that could affect bone metabolism (for example, steroids, thyroid replacement therapy) for the previous six months were not included in the study. None of the subjects had an eating disorder, according to the eating attitude test-26 questionnaire.[21]

Each subject who volunteered for the study received an explanation of the purpose of the study, the methods involved, the benefits, and the potential risks or discomforts. The older subjects, or a parent or legal guardian of the younger subjects, signed a form of informed consent for participation in the study, in accordance with the Helsinki declaration.

Each subject filled out a questionnaire regarding her medical history, training history, and other physical activities, as well as nutritional habits. For the younger subjects, one of the parents filled out the questionnaire for their daughter. The completed questionnaire was checked by one of the investigators to verify that the information was correct. Each subject was also interviewed about the previous day's dietary intake in order to estimate daily energy and calcium intakes. The completed forms were analysed using a local nutrition analysis program which contains local products.

Anthropometric measures—including body weight, height, and skinfold thickness values—were determined using standard methods. Skinfold thickness was determined at four sites (biceps, triceps, suprailiac, and subscapular) in triplicate, and the mean of the three measurements was recorded. The sum of two (triceps, subscapular), or four (biceps, triceps, suprailiac, and subscapular) skinfold measurements was used to calculate the percentage of body fat in children and adults, respectively.[22 23] All anthropometric measurements were undertaken by the same investigator.

Bone SOS measurement was done with the Sunlight Omnisense^{TM} device (Sunlight Medical, Tel Aviv, Israel). This consists of a main unit and hand held probes designed to measure SOS at specific skeletal sites. For a detailed description of the device and technique, see Njeh *et al*.[14] Briefly, the probe contains a set of two transmitters and two receivers. The SOS measurement reflects the shortest time that elapses between pulse transmission and the first reception of a signal. The exact path of the signal is determined by Snell's law[24]: as it enters the bone from the soft tissue, the signal is refracted through a critical angle, which is a function of the ratio of the speed of sound in soft tissue and bone. After it propagates along the bone, the sound wave emerges at the same critical angle. The time taken for the signal to travel between the transmitting and receiving transducers is used to infer the SOS in bone.[25]

Bone SOS was determined bilaterally (dominant and non-dominant) at the distal one third of the radius and the mid-shaft of the tibia. The dominant limb was determined by asking the subject which hand she preferred for writing and which leg she preferred for kicking. All measurements were performed according to a specific methodology, as follows:

Distal radius—A line was marked midway between the olecranon process of the elbow and the extended third phalanx. The probe was placed parallel to the radius on its medial surface and a wide scan from side to side was carried out.

Tibia—A line was marked midway between the apex of the top of the knee and the sole, while the subject was in a sitting position. The probe was placed parallel to the bone surface and a wide scan from side to side was carried out.

At the start of each day of testing, probe and system were checked by undertaking a system quality verification procedure against a standard acrylic phantom. The phantom SOS changes with any change in room temperature. Thus the system quality verification is temperature dependent and the correction is made by using a temperature conversion table. The in vivo precision of tibial and radial measurements, done with repositioning in 10 adults, was 0.90% and 0.45%, respectively. Two measurements were made for each adult and all measurements were undertaken by the same technician.

Statistical analysis

Differences in physical characteristics between groups (for example, height or body mass index) were examined using an independent *t* test (two tailed). A correlation analysis (using the Pearson product moment correlation procedure) was done between bone SOS and the various independent variables to determine possible influencing factors. The strongest independent correlate was age. A curve fitting procedure showed that the best fit function between age and bone SOS was a quadratic function. Thus a stepwise regression was done using age and $[age]^2$, as well as other variables (for example, sports group, maturation, anthropometric variables, and nutritional intake) as independent variables, and bone SOS as the dependent variable. Differences between groups were significant when the sports group variable (0 = control, 1 = swimmers) entered the regression model. A partial correlation analysis (controlling for age) was done between bone SOS and other independent variables (for example, training volume). Data were analysed using SPSS statistical programs, and level of significance was set at $p<0.05$ (two tailed). Data are reported as mean (SD).

RESULTS

The subjects' age and physical characteristics appear in table 1. Swimmers were significantly older than the control group ($p = 0.001$), although this age difference was less than one year. No difference was observed between groups in body mass, but swimmers were taller ($p = 0.001$) and had a lower percentage of body fat ($p<0.001$) and BMI ($p = 0.002$). Additionally, swimmers had a higher fat-free mass ($p<0.001$). No differences were observed in the years since menarche between the two groups, and a similar number of girls were premenarcheal in both groups (21 swimmers and 25 controls). No differences were observed in the pubertal stage between groups.

Table 1 Physical characteristics of female swimmers and control girls

Variable	Swimming	Control
n	61	71
Age (years)*	15.9 (4.9) (8.6 to 26.5)	15.0 (4.0) (8.5 to 24.4)
Mass (kg)	49.68 (12.27) (26.60 to 69.45)	50.71 (12.44) (23.10 to 76.10)
Height (cm)*	159.1 (12.1) (129.5 to 182.0)	155.2 (11.9) (125.0 to 176.0)
BMI (kg/m^2)	19.3 (2.8) (13.7 to 25.8)	20.7 (3.1) (14.8 to 27.1)
BMI (centile)*	40.7 (2.8) (4.7 to 85.8)	57.4 (25.1) (4.8 to 98.7)
Body fat (%)*	18.3 (4.2) (12.0 to 31.3)	22.3 (5.4) (13.3 to 49.6)
Fat-free mass (kg)*	40.3 (9.0) (22.7 to 56.5)	34.5 (7.8) (18.4 to 52.5)
Years since menarche	5.2 (4.0)	4.5 (2.9)
Tanner stage 1, n	17	12
Tanner stage 2, n	4	13
Tanner stage 3, n	14	10
Tanner stage 4, n	10	17
Tanner stage 5, n	16	19

Values are mean (SD) with range, or n.
*Significant difference between swimmers and controls ($p<0.05$).

SOS increased with age in both groups (fig 1). The mean SOS results in the radii and tibiae are described in figs 2 and 3. There were no differences between the dominant and non-dominant sides, neither were differences observed between groups in SOS of the radius (dominant: 3901 (171) and 3916 (170) m/s for control and swimmers, respectively; non-dominant: 3889 (165) and 3904 (172) m/s, respectively)—that is, the regression analysis showed that only age and [age]^2 were significant predictors of both the dominant and the non-dominant radial SOS ($p<0.01$). Tibial SOS in the swimmers was higher than in the control group (dominant: 3715 (176) and 3791 (165) m/s for control and swimmers, respectively; non-dominant: 3712 (171) and 3774 (155) m/s, respectively). The regression analysis showed that age, [age]^2, and BMI were predictors of both dominant and non-dominant tibial SOS ($p \leqslant 0.02$), while the group factor was significant for the dominant tibial SOS ($p = 0.02$) and tended towards significance for the non-dominant tibial SOS ($p = 0.08$).

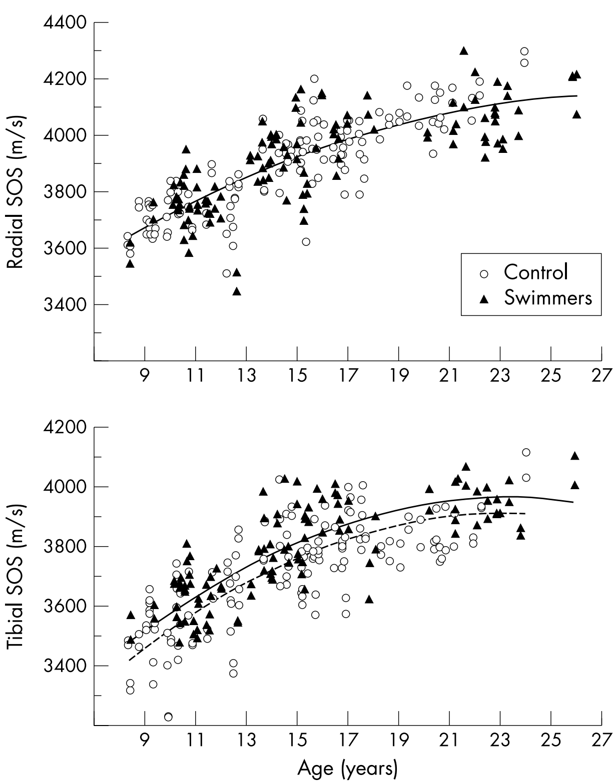

Figure 1 The increase in radial (top) and tibial (bottom) speed of sound (SOS) measurement with increasing age in swimmers and control girls. Data are individual values. See text for calculation of regression line. No differences were found between groups in radial SOS. Tibial SOS was higher in swimmers than in control girls ($p = 0.02$).

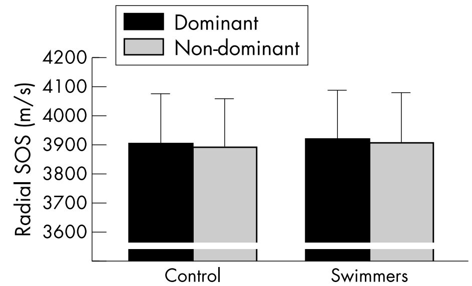

Figure 2 Radial speed of sound (SOS) in the dominant and non-dominant side among swimmers and non-athletic girls. Data are means, error bars = SD.

No differences were observed between groups in calcium intake (swimmers, 568 (330) mg/d; control, 604 (304) mg/d). It is noteworthy that almost all subjects consumed far below the recommended daily intake of calcium (1000 to 1300 mg/d). No differences were observed between groups in total energy intake (swimmers, 2076 (834) kcal/d; control, 1971 (634) kcal/d), or the intake of other minerals.

Correlations

High correlation coefficients were found between bone SOS and age in both groups ($r = 0.67$–0.86, $p<0.001$ for all correlations). High correlation coefficients were also observed between the dominant and non-dominant sides of the tibias ($r = 0.92$, 0.87 for controls and swimmers, respectively, $p<0.001$ for both), and radii ($r = 0.89$, 0.90 for controls and swimmers, respectively, $p<0.001$ for both). Moderate correlations were observed between the tibia and radius of the respective sides ($r = 0.69$–0.74, $p<0.001$ for all correlations). A correlation (controlled for age) between bone SOS and fat-free mass was observed among swimmers ($r = 0.33$–0.47, $p<0.01$ for all correlations), but not among controls. Among swimmers, a significant correlation (controlled for age) was observed between training hours per week and tibial SOS ($r = 0.47$ and $r = 0.39$ for dominant and non-dominant tibia,

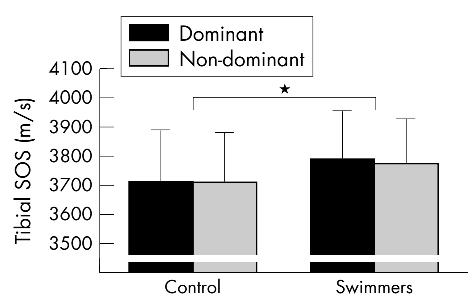

Figure 3 Tibial speed of sound (SOS) in the dominant and non-dominant side among swimmers and non-athletic girls. Data are means, error bars = SD. *Significant difference between groups ($p = 0.02$).

respectively; p<0.01 for both correlations), but there was no correlation with radial SOS.

DISCUSSION

In this study we investigated bone SOS among female swimmers and control girls over a wide age range (8.5 to 26.5 years). Consistent with published reports on healthy children, bone SOS increased with age (fig 1). The main finding of our study was that, while radial SOS measures did not differ between swimmers and non-athletic controls, tibial SOS values were significantly higher in the swimmers.

Over a decade ago, Bourrin *et al* demonstrated bone loss in a histomorphometric study of young rats who swim-trained six hours a day, five days a week, for five weeks.[26] They suggested that water immersion for such an extended period induced a lack of ground reaction forces and contributed to the observed bone loss. In the present study, most swimmers trained only two hours a day (three swimmers reported training three hours a day). Therefore, swim training was not expected to have a deleterious effect on bone.

No differences were observed between groups in radial SOS. To our knowledge, there has been no study evaluating bone properties among swimmers using any QUS parameters. Nevertheless, the similar results obtained at the radius in the two groups is consistent with the BMD literature on children and adults, in which similar BMD values were observed in aquatic athletes and control groups in the spine[1–4] and the upper extremities.[1–3] As suggested by previous studies, the lack of a difference between swimmers and controls may be explained by the fact that swimming, although a highly active sport, does not apply any impact to the bones of the upper extremities.

However, the higher tibial SOS values observed in the swimmers in the present study contrast with published BMD findings.[1–4] It should be stressed that none of the swimmers engaged in any resistance training. Therefore, this could not have been a contributing factor to the observed difference. Also, daily calcium intake was similar among the groups and no differences were observed in body mass. Finally, no difference was found in the years since menarche, and a similar number of girls in both groups were premenarcheal. Therefore neither nutritional intake, body mass, nor possible differences in maturity—all of which have been shown to affect BMD—can explain the higher tibial SOS observed in the swimmers.

A possible explanation for the observed differences in tibial SOS in the swimmers may be that swimming does indeed exert mechanical loads on the lower extremities which affect bone properties other than density (for example, elasticity, microstructure). These effects may be detectable by the QUS method but not necessarily by the DXA method, which measures only mineral content. Indeed, several intervention studies among animals have clearly demonstrated a positive effect on bone properties, such as elasticity[7] and structural strength, [6 8] as well as on BMD, as measured by the Compton scattering technique. Additionally, Forwood and Parker[27] showed that in growing rats, running and swimming exercise can also modify bone vascular morphology. The investigators suggested that these changes could have an important function in determining the fatigue resistance of bone.

It is of interest that tibial SOS was measured at a point where there is no muscle attachment. Therefore, it cannot be argued that it is the muscle contraction which specifically affected the bone site measurement. Indeed, Hart *et al* used histochemical methods and DXA to demonstrate enhanced bone structure and formation, as well as enhanced BMD at the mid-diaphyseal shaft of the femur, among swimming trained adult rats.[8] Thus factors other than gravitational pull and direct muscle pull affected the bone in the latter and the present studies.

It is intriguing that differences in bone SOS between groups were observed in the lower but not the upper extremities. One possibility for the difference in bone properties, particularly at the tibia, may be that during training, swimmers repeatedly push against the wall at each turn. While such a stimulus may appear negligible, repeated stimuli may have an effect; thus in a typical two hour practice, swimmers may have over 200 turns, each time pushing and pressing against the wall. In support of this explanation is the correlation observed between training volume and tibial but not radial SOS among the swimmers.

Another possible explanation is that the swimmers were generally more active in everyday life, above and beyond the swimming training. Numerous studies have shown that weight bearing physical activity is a contributing factor to BMD of the lower extremities among both children and adults.[28 29] Higher habitual and spontaneous activity in daily living is more likely to affect the lower than the upper extremities. Habitual and spontaneous physical activity (other than training) was not measured in this study. Nevertheless, we speculate that swimmers are habitually more spontaneously active and this would partly explain their higher tibial SOS values. It may also explain the difference in tibial SOS between groups which was already apparent at an early age—that is, it is possible that the higher tibial SOS in the swimmers partly reflects some selection bias.

Although the tibial SOS in the swimmers was only 1.75% higher than in the control group, it is worth noting that previous studies have all found *lower* BMD (or no difference) in swimmers compared with control subjects. Indeed, as can be seen from the 95% confidence interval of the tibial SOS for the two groups (3701 to 3756 *v* 3746 to 3805 m/s for the controls and swimmers, respectively, corrected for age and BMI), the difference between the two groups is small. However, the clinical significance of our finding is in the *direction* of the difference and not necessarily in its size. Additionally, it should be noted that for some individuals, even such a small difference may be important in terms of osteoporosis and its implications (below or above the osteoporotic fracture threshold).

Finally, relatively high correlations were observed between the dominant and non-dominant side in both limbs, with no significant differences between sides. This is to be expected in both groups, as swimming is a symmetrical sport. Previous studies of healthy children and adolescents showed high correlations in QUS parameters of left and right heels ($r = 0.80$ to 0.89), and no significant differences between sides.[2 30] This was also the case among peripubertal gymnasts,

Take home message

- Physical exercise, especially high impact exercise, has been shown to enhance bone mass in children, adolescents, and young adults. This does not usually include swimming, in which there is no impact and the body weight is supported by the water. Only in animals have studies shown a beneficial effect of swimming on bone.
- This is the first study suggesting that swimming activity may be beneficial to bone properties in humans. More specifically, the results suggest that swimming may be beneficial from an early age. The enhanced bone properties were detected using ultrasound technology.

runners, and non-athletic girls.[18] Among adults, Lee *et al* found similar BMD in the right and left arms of female swimmers.[2]

Conclusions

In this study, we found similar radial SOS but enhanced tibial SOS values in young and mature female swimmers compared with non-athletic controls. While these results should be viewed with caution owing to the cross sectional nature of the study, we propose that, contrary to previous findings using the DXA technology, swimming training may indeed affect bone properties, reflecting increased strength. Future studies need to focus on the mechanism responsible for the enhanced bone properties and the critical age during which these effects occur.

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