ORIGINAL ARTICLE

Effects of weight bearing and non-weight bearing exercises on bone properties using calcaneal quantitative ultrasound

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Objective: This study was designed to investigate bone properties using heel quantitative ultrasound (QUS) in young adults participating in various sports.
Methods: A cross sectional study was performed on Chinese male students (n = 55), aged 18–22 years. Subjects with previous fractures or suffering from any diseases known to affect bone metabolism or taking any medication with such an effect, were not included. The subjects were categorised according to their main sporting activities, including soccer (n = 15) (a high impact, weight bearing exercise), dancing (n = 10) (a low impact, weight bearing exercise), and swimming (n = 15) (non-weight bearing exercise). A sedentary group acted as controls (n = 15). A reproducibility study of the velocity of sound (VOS) and the broadband ultrasound attenuation (BUA) measurement was performed and analysed using the intraclass correlation coefficient (ICC).
Results: There was good intra-investigator and inter-investigator agreement (ICC$\geqslant$0.8; p$<$0.05) in the measurement of BUA and VOS. No significant differences in BUA and VOS (p$>$0.05) were found between the dominant and non-dominant heel. Soccer players (137$\pm$4.3 dB/MHz; 1575$\pm$56 m/s; 544.1$\pm$48.4) and dancers (134.6$\pm$3.7 dB/MHz; 1538$\pm$46 m/s; 503.0$\pm$37.0) had significantly higher BUA, VOS, and stiffness index (SI) scores (p$<$0.05), respectively, than swimmers (124.1$\pm$5.1 dB/MHz; 1495$\pm$42 m/s; 423.3$\pm$46.9) and the sedentary control group (119.9$\pm$6.1 dB/MHz; 1452$\pm$41 m/s; 369.9$\pm$46.4). A trend of a significant linear increase with the weight bearing and high impact exercise was revealed in all QUS parameters (p$<$0.05).
Conclusion: This cross sectional study indicated that regular participation in weight bearing exercise in young people might be beneficial for accruing peak bone mass and optimising bone structure.

Bone strength is determined by both bone mass and bone structure, while "osteoporosis is characterised by low bone mass and structural deterioration of bone tissue, leading to bone fragility and an increase in susceptibility to fractures, especially for hip, spine and wrist".[1] The current understanding is that maximising peak bone mass is key to preventing osteoporosis and osteoporotic fractures.[2–6]

Although genetic factors appear to have the greatest impact, exercise, hormonal status, and nutrition can modify the modelling and remodelling of the bone to optimise and maintain peak bone mass.[7 8] The desired outcome of all treatment regimens is to improve bone strength. Physical exercise, especially weight bearing activity, has been reported to have beneficial effects on the skeleton in both adolescents[8–10] and the elderly.[11–12]

Many studies have shown that weight bearing exercise can increase bone mineral density (BMD), particularly at a young age. It has been widely accepted that engaging in weight bearing activity can elicit significant positive bone mass adaptation. Groups that engaged in such exercise were compared with a non-weight bearing exercise group and a sedentary control group using dual energy *x* ray absorptiometry (DXA) for BMD measurements,[3–6 13–15] which indicate the site specific effects of osteogenesis induced by mechanical stimuli.[15]

DXA used for the above studies is a common technique for diagnosing osteoporosis. However, DXA only measures bone status in terms of BMD, not bone structure.[16 17] Techniques such as bone histomorphometry and microCT are used for quantitative studies of bone structure, but they are invasive. In recent years, non-radiation quantitative ultrasound (QUS) has been introduced for assessing skeletal status related to bone structure and mechanical properties in osteoporosis.[18 19] The calcaneus is the most common measurement site due to its accessibility, suitable shape, and high trabecular content.[18 19] A recent study has shown that physical activity is associated with QUS measurements on the heel independently of BMD.[11]

The aim of the present study was to use heel QUS to elaborate potential differences in the beneficial effects of weight bearing and non-weight bearing exercises in college athletes.

METHODS

Subjects

Fifty five healthy Chinese male students aged 18–22 were recruited from a local university. They were categorised by the main sporting activities in which they engaged, from high to low impact weight bearing and non-weight bearing exercises: soccer (n = 15), dancing (n = 10), swimming (n = 15), and no exercise (the sedentary control group; n = 15). The criteria for those that exercised were that they had to have had at least 2 years of training in the above-mentioned supervised exercises, not less than twice a week, for 2 h at a time. The study protocol was approved by Departmental Research Committee, Department of Optometry and Radiography, The Hong Kong Polytechnic University. The written informed consent of all the participants was obtained before the study was carried out.

Abbreviations: BMD, bone mineral density; BMI, body mass index; BUA, broadband ultrasound attenuation; DXA, dual energy *x* ray absorptiometry; GRF, ground reaction forces; ICC, intraclass correlation coefficient; MLD, maximum longitudinal diameter; MTD, maximum transverse diameter; QUS, quantitative ultrasound; SD, standard deviation; SI, stiffness index; VOS, velocity of sound

Questionnaire
Health and food frequency questionnaires were administered to collect information for each individual on calcium intake, age, history of lower limb fractures, family history of osteoporosis, diseases, medications, and treatments known to affect bone metabolism. The individual's usual calcium intake in milligrams per day was obtained using a food list on which the individual was asked to indicate his food intake for the previous 7 days. Compiled from the Dietetic Information Center of the Hong Kong Hospital Authority, 33 food items commonly consumed in Hong Kong were listed.[20] For each food item, the participants were asked to indicate their usual consumption in terms of frequency. Their calcium intake was calculated using the method published by the Hong Kong Hospital Authority.

Anthropometry
Body weight and body height of the participants were recorded and body mass index (BMI) was calculated. The maximum transverse and longitudinal diameters (MTD and MLD) of their feet were also recorded.

Ultrasound measurement
The bilateral calcanei of each subject were measured using a heel ultrasound densitometer (Paris, Norland Medical System, Fort Atkinson, WI, USA). Quality assurance was performed using a dedicated phantom (supplied by the manufacturer) before the first measurement of the day. The dominant foot was determined by the foot used to kick a ball.[21] Ultrasound gel was applied as a coupling medium to ensure good contact. The velocity of sound (VOS) and broadband ultrasound attenuation (BUA) were measured. A stiffness index (SI) was then derived from both the VOS and BUA, where, as defined by the manufacturer, $SI = (0.8471 \times VOS) + (4.1034 \times BUA) - 1352.2$. Each subject had three measurements without repositioning to calculate mean value.

Reproducibility of QUS measurement
The dominant heel of 15 control group subjects was used to evaluate the intra-investigator and inter-investigator reliability of the QUS measurement. The measurement was repeated three times with repositioning.

Statistical analysis
One way ANOVA was used to test if there was a difference among the groups in terms of anthropometric parameters, calcium intake, and QUS parameters. A Tukey post hoc test was employed to determine the pairwise difference if the one way ANOVA was significant. A paired *t* test was used to examine the significance of the differences in the QUS parameters between the dominant and non-dominant heels. The level of significance was set at $p<0.05$. In the intraclass correlation coefficient (ICC) measurement, a two way ANOVA mixed test model with 95% confidence intervals (CI) and absolute agreement was employed, with a test value of 0.8, to calculate the intra-investigator and inter-investigator variability. All the statistical analyses were performed using SPSS 10.0 for Windows. The results are expressed as mean $\pm$ standard deviation (SD), unless stated otherwise.

RESULTS
Subject characteristics
There was no significant difference ($p>0.05$) in age, body weight, body height, BMI, calcium intake, MTD, and MLD among all the groups (table 1).

Reproducibility of QUS measurement
Agreement between the investigators who measured the same QUS parameters on three occasions in 15 subjects with repositioning, was assessed by ICC. Intra-investigator ICC values were 0.949 (95% CI: 0.921–0.968), 0.866 (95% CI: 0.795–0.916), and 0.954 (95% CI: 0.930–0.971) for VOS, BUA, and SI, respectively. Inter-investigator ICC values were 0.944 (95% CI: 0.878–0.979), 0.953 (95% CI: 0.858–0.975), and 0.949 (95% CI: 0.889–0.981) for VOS, BUA and SI, respectively. All ICC values were compared with the test value, 0.8 ($p<0.05$).

Site specificity of exercise effect: dominant and non-dominant foot
No significant differences were found in VOS, BUA, and SI in the QUS measurements of the dominant and non-dominant sides in each study group ($p>0.05$) (table 2).

Comparison of QUS parameters among exercising and non-exercising control groups
One way ANOVA showed that there were significant differences ($p<0.001$) in VOS, BUA, and SI among the four groups in both feet (table 2). The BUA of both the dominant and non-dominant sites are shown in fig 1. The mean BUA value at the dominant site of the soccer group was 14.3% ($p<0.001$) and 5.3% ($p<0.001$) higher than the value for the control and swimming groups, respectively. The mean BUA of the dancing group was 12.2% ($p<0.001$) and 8.5% ($p<0.001$) higher than that of the control and swimming groups, respectively. The mean BUA value obtained from the non-dominant site of the soccer group was 16.6% ($p<0.001$) and 10.4% ($p<0.001$) higher than that of the control and swimming groups, respectively. The mean BUA obtained from the non-dominant site of the dancing group was 14.4% ($p<0.001$) and 8.3% ($p<0.001$) higher than for the control and swimming groups, respectively. The mean BUA of the swimming group was 5.7% ($p<0.01$) higher than that of the

Table 1 Subject characteristics (mean $\pm$ SD)

Parameter	Control (n = 15)	Swimming (n = 15)	Dancing (n = 10)	Soccer (n = 15)
Age (years)	21.3±1.2	20.9±1.3	20.6±0.7	21.2±1.7
Body height (cm)	174.4±5.4	175.6±6.1	172.3±5.2	175.3±7.6
Body weight (kg)	64.8±8.3	67.5±7.8	65.1±10.7	67.8±5.9
BMI (kg/m^2)	21.3±2.3	21.8±1.3	21.9±3.2	22.0±1.1
Calcium intake (mg/day)	274.3±190.7	376.2±290	302.9±169.5	225.7±148.1
Frequency (times/week)	–	3.5±3.1	3.9±1.2	2.4±1.0
Duration (h/time)	–	1.7±0.5	3.6±0.5	2.5±0.8
MTD (dominant, cm)	9.4±0.6	9.7±6.0	9.4±0.6	9.6±0.6
MTD (non-dominant, cm)	9.2±0.5	9.4±0.5	9.3±0.6	9.5±0.5
MLD (dominant, cm)	25.3±1.2	25.2.±1.2	24.9±1.3	25.2±1.6
MLD (non-dominant, cm)	25.1±1.4	25.4±1.1	24.8.±1.4	24.9±1.5

BMI, body mass index; MLD, maximum longitudinal diameter; MTD, maximum transverse diameter. There were no statistically significant differences among the four groups, so no adjustments were made for body weight and height, etc.

Table 2 Result of QUS measurements

	Control	Swimming	Dancing	Soccer
VOS (m/s)				
Dominant	1452±41‡§	1495±42§	1538±46*	1575±56*†
Non-dominant	1454±46†‡§	1503±27*§	1521±52*§	1579±60*†‡
BUA (dB/MHz)				
Dominant	119.9±6.1‡§	124.1±5.1‡§	134.6±3.7*†	137.0±4.3*†
Non-dominant	118.1±6.2†‡§	124.8±4.1*‡§	135.1±5.1*†	137.8±5.3*†
SI				
Dominant	369.9±46.4†‡§	423.3±46.9*‡§	503.0±37.0*†	544.1±48.4*†
Non-dominant	364.2±54.2†‡§	433.5±23.8*‡§	490.7±55.3*†§	551.3±63.4*†‡

BUA, broadband ultrasound attenuation; SI, stiffness index; VOS, velocity of sound.
*Significantly different from the control group; †significantly different from the swimming group; ‡significantly different from the dancing group; §significantly different from the soccer group.

control group. In general, there was a significant ascending trend in the BUA of both sites in the following order of groups: control, swimming, dancing, and soccer ($p<0.001$).

The result of the VOS measurements of both the dominant and non-dominant sites is shown in fig 2. The mean VOS value at the dominant site of the soccer group was 8.5% ($p<0.001$) and 5.4% ($p<0.001$) higher than the value of the control and swimming groups, respectively. The mean VOS of the dancing group was 5.9% ($p<0.001$) higher than that of the control group. The mean VOS value obtained from the non-dominant site of the soccer group was 8.6% ($p<0.001$), 5.1% ($p<0.001$), and 3.8% ($p>0.05$) higher than that of the control group, swimming group, and dancing group, respectively. The value of the dancing group was 4.6% ($p<0.05$) higher than that of the control group; and that of the swimming group was 3.4% ($p<0.05$) higher than that of the control group. In general, there was a significant ascending trend in the VOS of both sites in the following order of groups: control, swimming, dancing, and soccer ($p<0.001$).

The SI values of both the dominant and non-dominant sites are shown in fig 3. For the dominant site, the mean SI value of the soccer group was 47% ($p<0.001$) and 28.5% ($p<0.001$) higher than that of the control and swimming groups, respectively. The mean SI of the dancing group was 36.0% ($p<0.001$) and 18.8% ($p<0.001$) higher than that of the control and swimming groups, respectively. The mean SI of the swimming group was 14.4% ($p<0.05$) higher than that of the control group. For the non-dominant site, the mean SI value of the soccer group was 51.4% ($p<0.001$), 27.2% ($p<0.001$), and 14.8% ($p<0.05$) higher than that of the control, swimming, and dancing groups, respectively. The mean SI of the dancing group was 34.7% ($p<0.001$) and 13.2% ($p<0.05$) higher than that of the control and swimming groups, respectively. The mean SI of the swimming group was 5.7% ($p<0.05$) higher than that of the control group. In general, there was a significant ascending trend of SI in both sites in the follow order of groups: control, swimming, dancing, and soccer ($p<0.001$).

DISCUSSION

The main purpose of this study is to demonstrate the osteogenic effect of different exercise modes using calcaneal QUS. In the present study, all the exercise groups have significantly higher QUS parameters for bilateral calcanei than the control group. Moreover, significantly higher QUS parameters were measured in exercises with a greater weight bearing loading on the calcaneus. This demonstrates that exercise has a positive effect on bone status and that such a positive effect was increased by the higher impact of weight bearing loading.

Many previous studies have demonstrated an osteogenic effect of high impact and weight bearing exercise on BMD using DXA.[3 6 13–15] However, the latter densitometric measurement did not provide information on bone structure and mechanical properties. A previous study using DXA and QUS measurement by Lehtonen-Veromaa *et al* demonstrated that both femoral neck BMD and heel QUS parameters increased in the following order: control, runners, and gymnasts.[22] These results concur with the present study in that the athletes generally had better bone ultrasonic properties than

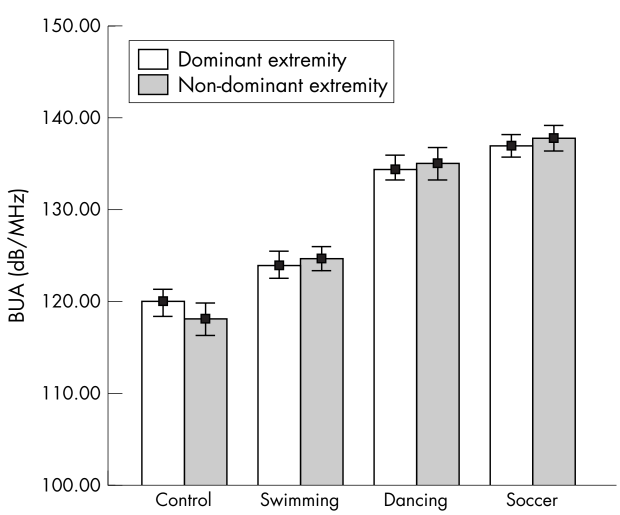

Figure 1 BUA (dB/MHz) (mean±SE) of the dominant and non-dominant extremities of the subject groups.

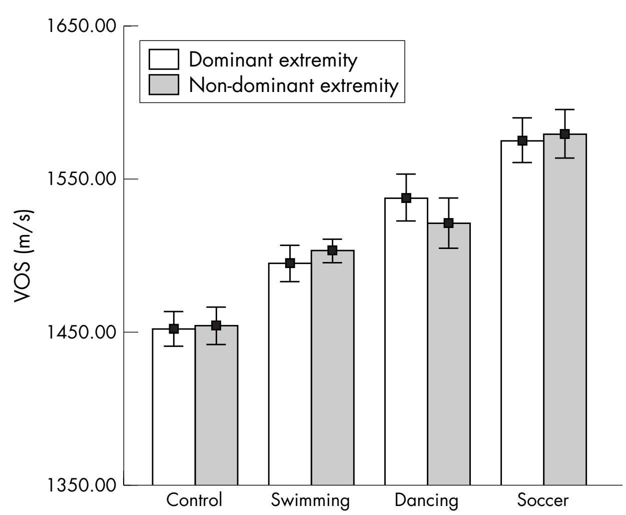

Figure 2 VOS (m/s) (mean±SE) of the dominant and non-dominant extremities of the subject groups.

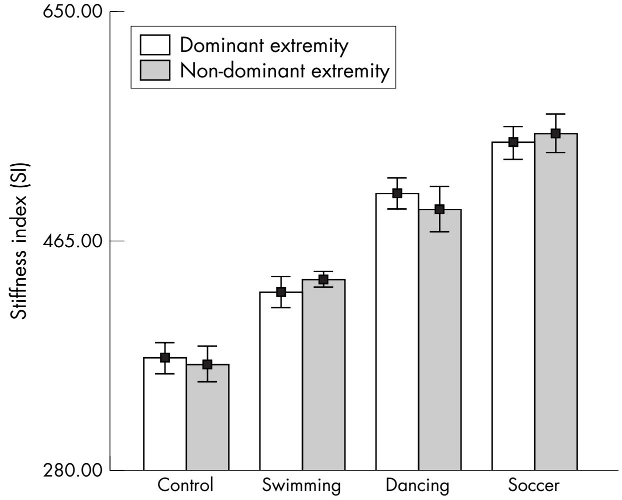

Figure 3 Stiffness index (SI) (mean ± SE) of the dominant and non-dominant extremities of the subject groups.

did the age and gender matched sedentary controls and, in particular, that higher impact loading exercises are more beneficial to bones.

In humans, the main stresses applied at the level of the calcaneus are ground reaction forces (GRF) as the heel strikes during locomotion.[23] Based on the GRF, swimming (GRF$<$1×body weight), dancing (GRF between 1 and 4×body weight), and soccer (GRF$>$4×body weight) can be classified as low, moderate, and high impact exercise, respectively.[24] The level of impact has been identified, in both animal and human studies, as an important determinant of the skeleton's adaptive response to mechanical loading. More osteogenesis was found when bones were subjected to progressively greater magnitudes of strain through artificial loading in animal experiments.[25] An in vivo human study also showed a significantly high correlation between level of activity and QUS parameters.[26] The relationship between loading magnitude and bone can be explained by the bone mechanostat theory proposed by Frost,[27] who stated that exercise has a combined effect on bone modelling and remodelling, in that bone mass is increased by modelling and the added bone is retained by remodelling. Mechanical loading is also beneficial to bone structure. If a load is imposed, the bone will accommodate and undergo an alteration in mass, external geometry, and internal micro-architecture.[28]

Previous studies indicated the existence of a site specificity effect in volleyball players and squash players.[29 30] However, site specificity between the dominant and non-dominant foot is not shown in this study. As regards biomechanics, the physical activities entailed in swimming and dancing may exert similar strains on both legs.[31] For soccer players, the supporting leg on the ground during kicking withstands high strains that have comparable loading to the kicking leg.[15]

Most previous studies using DXA found that swimming does not affect the acquisition of bone minerals.[29 32] However, the present study is inconsistent with those previous studies. We found that the group of swimmers had higher VOS (3.0–3.4%) and BUA (3.5–5.6%) in their bilateral calcanei than the sedentary controls. Similar to the present study, Falk *et al*[31] also found a higher tibial VOS in a group of swimmers than in a control group. They suggested that swimming may affect bone properties other than density, such as elasticity and microstructure, due to the effect of the straining of muscles during swimming, which are only detectable in QUS but not in DXA. They showed that although weight bearing may generate strain on the bone, muscle contractions may also have osteogenic effects.[33 34] A study on rats also found that swimming had favourable effects on bone structure, turnover, and strength.[35] However, this view is not widely supported by the other previous studies as the difference may be due to the bias of a cross sectional study.

Apart from physical exercise, bone status has been shown to be significantly associated with age, BMI, calcium intake, foot dimensions, and site specificity. These confounding variables on QUS measurement, however, were matched among the groups in the present study. There are many random variations that may affect the reliability of calcaneal QUS measurement, including equipment drift, heel core temperature, heel positioning in the ultrasonic beam, and the properties of the surrounding soft tissue and its thickness.[36] A recent study by our group on the short term coefficient of variation for the QUS densitometer was 2.88% for BUA and 1.70% for VOS.[37] In order to measure the reproducibility of QUS in the present study, ICC was used to investigate intra-investigator and inter-investigator agreement.[38] The results of our QUS measurement were reliable, as we validated the intra-investigator and inter-investigator variability of the QUS parameters, with ICC significantly greater than 0.8 for the three QUS measurement parameters. A reliability coefficient of 0.8 is an acceptable level, indicating good intra-investigator and inter-investigator agreement.[38] Thus, the comparative study of QUS parameters among the study groups as regards exercise effect could be well controlled. Evaluation of bone status using QUS has added value compared to DXA. The BUA parameter is related to the bone structure, whereas the VOS and SI values are correlated to bone density and its elasticity. Therefore, QUS allows examination not only of bone density, but also the biomechanical properties of bone, such as the size and structural changes of the bone in response to exercise. The major limitation of this cross sectional design is the potential bias of self selection in sampling. Prospective studies are desirable to elaborate how radiation-free QUS is useful in monitoring the beneficial effects of various modes of exercises on the properties of bone.

In conclusion, all QUS parameters were higher in exercise groups compared with the control group. There was a trend towards better QUS parameters in high impact exercise. These findings support the importance of high impact, weight

What is already known on this topic

Previous exercise intervention studies using the preferred technique, dual energy *x* ray absorptiometry (DXA), have demonstrated an osteogenic effect. However, DXA only measures bone status in terms of bone mineral density. There has been growing interest in using non-ionising quantitative ultrasound to demonstrate both bone density and structural changes.

What this study adds

The findings of this study support the importance of high impact weight bearing exercises in accruing peak bone mass. Swimming, a non-weight bearing exercise, which is believed to have an insignificant effect on bone density increase, may have favourable effects on bone properties, such as elasticity and microstructure, which are detectable in QUS but not in DXA.

bearing exercise at a young age in maximising peak bone mass with better mechanical strength. Our findings suggest that such exercises should be promoted among children to maximise and optimise their bone mass and quality and, hence, prevent osteoporosis in later life.

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