The BPAQ: a bone-specific physical activity assessment instrument

Author

Weeks, BK, Beck, BR

Published

2008

Journal Title

Osteoporosis International

DOI

https://doi.org/10.1007/s00198-008-0606-2

Title:

The BPAQ: A bone-specific physical activity assessment instrument

Running title:

Bone-specific physical activity questionnaire

Authors and institutions:

Benjamin K. Weeks[1], and Belinda R. Beck[1]

1. School of Physiotherapy and Exercise Science
   Griffith University, Gold Coast campus
   Australia
   b.weeks@griffith.edu.au, b.beck@griffith.edu.au

Corresponding author details:

Belinda R. Beck, Ph.D.
School of Physiotherapy and Exercise Science
Gold Coast campus
GRIFFITH UNIVERSITY QLD 4222
AUSTRALIA
Ph: +61-7-5552 8793
Fax: +61-7-5552 8674
Email: b.beck@griffith.edu.au

Words: 4,888 (32,137 characters)

Figures/Tables: 6

Conflict of interest: No disclosures

A newly-developed bone-specific physical activity questionnaire (BPAQ) was compared with other common measures of physical activity for its ability to predict parameters of bone strength in healthy, young adults. The BPAQ predicted indices of bone strength at clinically relevant sites in both men and women, while other measures did not.

Introduction and Hypothesis: Only certain types of physical activity (PA) are notably osteogenic. Most methods to quantify levels of PA fail to account for bone relevant loading. Our aim was to examine the ability of several methods of PA assessment and a new bone-specific measure to predict parameters of bone strength in healthy adults.

Methods: We recruited 40 men and women (mean age 24.5). Subjects completed the modifiable activity questionnaire, Bouchard 3-day activity record, a recently published bone loading history questionnaire (BLHQ), and wore a pedometer for 14 days. We also administered our bone-specific physical activity questionnaire (BPAQ). Calcaneal broadband ultrasound attenuation (BUA) (QUS-2, Quidel) and densitometric measures (XR-36, Norland) were examined. Multiple regression and correlation analyses were performed on the data.

Results: The current activity component of BPAQ was a significant predictor of variance in femoral neck bone mineral density (BMD), lumbar spine BMD, and whole body BMD (R^2 = 0.36-0.68, $p < 0.01$) for men, while the past activity component of BPAQ predicted calcaneal BUA (R^2 = 0.48, $p = 0.001$) for women.

Conclusions: The BPAQ predicted indices of bone strength at skeletal sites at risk of osteoporotic fracture while other PA measurement tools did not.

Key words: bone mass; exercise; ground reaction force; pedometer.

INTRODUCTION

It is well known that certain forms of exercise have positive effects on the bone strength parameters of mass and geometry. The bone response to mechanical stimuli is particularly dependent on the nature of those stimuli. Activities that subject the skeleton to large magnitude forces [1, 2] at rapid loading rates [3, 4] confer the greatest benefit. Furthermore, the age at which the skeleton is loaded appears to influence the degree of effect, youth being the most mechano-responsive period [5].

Human bone strain during running and walking has been directly measured *in vivo* from a small number of superficial bony sites [6-11]. The skeletal strains associated with the vast majority of other physical activities and bony sites, however, are largely unknown, primarily due to the highly invasive nature of the measurement procedure. Measurement of bone strains from the very deep clinically relevant sites such as the femoral neck and spine is effectively unachievable in the *in vivo* research setting. Ground reaction forces (GRF) are a non-invasive surrogate measure of bone strain during weight bearing activity. Of the myriad conceivable physical activities, the associated peak forces and rates of force application of only relatively few have been determined [12-14].

A physical activity assessment tool that accounts for bone-relevant loading has been conspicuously absent from the bone research field. Traditional physical activity measurement instruments (e.g. pedometers, questionnaires, and diaries) fail to record the critical elements of force and loading rate associated with physical activities. One recent exception [15], a bone-loading history questionnaire (BLHQ) for premenopausal women, that estimates loads on the hip and spine experienced during particular stages of life (e.g. high school, young adult, adult, etc.) is yet to be examined against other common measures of physical activity.

The BLHQ is a relatively time-consuming instrument, and load factors for physical activities were not derived from direct measures.

We have developed a brief bone-specific physical activity questionnaire (BPAQ) to record both current and historical activity, and have applied GRF-derived loading values. An algorithm was developed to weight the factors of load intensity, years of participation, and frequency of historical and current activity (based on the principles of the evidence-based *osteogenic index* described by Turner and Robling [16]) in order to convert the raw BPAQ data into a score that reflects total bone-relevant physical activity history.

The aim of the current study was to evaluate the ability of the BPAQ analysis to predict indices of skeletal strength compared with the predictive ability of traditional measures of physical activity (i.e. physical activity questionnaires, physical activity record, and pedometer) and the recently developed BLHQ. We hypothesised that (1) BPAQ scores would significantly predict variance in bone strength variables at clinically relevant sites, (2) traditional physical activity measures would not predict variance in bone strength at those sites, (3) there would be no significant relationship between BPAQ scores and scores from traditional measures of physical activity, and (4) there would be a significant positive relationship between scores from the BPAQ and the BLHQ.

MATERIALS AND METHODS

Subjects and subject selection

A total of 40 healthy, moderately physically active, young adults (20 men and 20 women) between the ages of 18 and 30 years (mean age 24.5 ± 2.9 years) volunteered to participate in the trial. The 18-30 year age-range was chosen as the age by which peak bone mass is largely achieved, but prior to the age that musculoskeletal pathology may be increased. Subjects were excluded if they had a recent or current musculoskeletal injury, a history of rheumatological or endocrine disease, previous lower extremity orthopaedic surgery (e.g. knee reconstruction), lower limb osteoarthritis, any condition of impaired balance or coordination, took medications known to influence bone (e.g. corticosteroids, bisphosphonates, or hormones), or suffered any other medical condition that is incompatible with performing several repetitions of weight-bearing activities. Women were also screened for menstrual dysfunction.

The study was approved by the Griffith University Human Research Ethics Committee and written informed consent was obtained from each subject.

Anthropometrics

Subject height was measured to the nearest mm using the stretch stature method with a portable stadiometer (HART Sport & Leisure, Australia). Weight was measured to the nearest 0.1 kg using digital scales (Soehnle Co., Switzerland). Body mass index (BMI) was determined from measurements of height and weight per the accepted method (BMI = weight/height^2, kg$\cdot$m^{-2}).

Ground reaction force (GRF) measurements

A randomized subsample of our cohort (n = 20; 10 males/10 females), took part in GRF testing. After a brief warm-up, GRFs were recorded for 19 different activities selected to represent components of most sporting and daily physical activities (see Table 1). An investigator (BW) demonstrated each activity prior to subject performance. Subjects practiced each activity until comfortable with the movement, but not fatigued, before three consecutive attempts on a 900 x 600 mm, Type 9287A, multicomponent force platform

(Kistler, Winterthur, Switzerland) were recorded through a Type 9865C, 8-channel charge amplifier (Kistler, Winterthur, Switzerland) with Vicon supported software (Vicon Peak, Colorado, USA). Peak vertical GRF (N), and rate of force application ($N \cdot s^{-1}$) were recorded for each activity. All force data were averaged across the three attempts. Subjects were instructed to perform each activity with normal footwear worn during physical activity to maintain safety and to simulate the typical sporting situation. Activities were randomly ordered for each subject to avoid the potential for fatigue biasing performance during later activities.

TABLE 1

Bone-specific Physical Activity Questionnaire (BPAQ)

The BPAQ is designed to be self-administered and to quickly and simply obtain a comprehensive account of lifetime physical activity (Appendix A). Respondents record type, frequency and years of physical activity involvement. Independent sections for past (from one year of age) and current (previous 12 months) regular activity facilitate examination of the temporal and age-specific effects of mechanical loading on the skeleton.

BPAQ analysis algorithms

Algorithms were developed to apply weightings to the exercise parameters recorded on the questionnaire (i.e. load intensity, frequency and years of participation). Those weightings were based on the observed response of bone to a variety of experimental load protocols recently described by Turner and Robling [17] (see Appendix B). The measured GRFs were used to determine the effective load ratings (R) assigned to activities and utilized in the algorithms. Each sport and physical activity was ranked according to its effective load rating based on the predominant type of loading encountered during the activity. Forces were ascribed to each sport by, in most cases, direct GRF measurement of the highest intensity action fundamental to each sport (Table 1 and Appendix C, "Peak GRF"). For the small number of activities for which fundamental actions could not be directly measured on the force plate (e.g. ice-skating) the force of the most similar manoeuvre measured was assigned (e.g. take-off II). It is well-recognized that gymnastics involves some of the highest GRFs of all activities, and that gymnasts typically exhibit very high bone mass as a consequence [18]. Thus, effective load ratings were normalised relative to gymnastics, which was assigned an arbitrary effective load rating of 100.

Although the algorithms themselves are quite simple (and available in Appendix B), combining scores for numerous different current and past activities for one individual creates a somewhat complex computation. To simplify the procedure, a custom-designed LabVIEW program (National Instruments, Texas, USA) was developed to compute total BPAQ score from the products of the current activity and past activity algorithms. A free-access web-based program is under construction for BPAQ users.

Other physical activity measurements

Subjects also completed the Modifiable Activity Questionnaire (MAQ) [19], the Bouchard 3-day Physical Activity Record (3DR) [20] (two weekdays and one weekend day), and the Bone Loading History Questionnaire (BLHQ) [15]. Only total bone loading exposure was calculated from the BLHQ. Each subject wore a digital pedometer (HART Sport & Leisure, Australia) for a period of 14 consecutive days to record number of foot contacts.

Bone parameters

Broadband ultrasound attenuation (BUA) of the dominant calcaneus was measured using the QUS-2 ultrasound densitometer (Quidel Corporation, CA, USA). The same investigator (BW) performed all ultrasound assessments. Calibration quality control was accomplished via an automated verification process that involved the scanning of a phantom model of known BUA each testing day. Short term BUA measurement precision with repositioning was 2.8%.

Bone mineral content (BMC), bone mineral density (BMD), and bone area (BA) of the dominant femoral neck (FN), lumbar spine (LS), and whole body (WB) were examined with an XR-36 Quickscan densitometer (Norland Medical Systems, Inc., USA) using host software, version 2.5.3a. The same investigator (BW) performed all dual-energy xray absorptiometer (DXA) scans. Short-term measurement precision for repeated measures with repositioning for FN, LS, and WB was 1.3%, 1.1%, and 1.4% respectively. Lean tissue mass and body fat parameters were generated from DXA WB scans using host software. We calculated bone mineral apparent density (BMAD) [21] as a means of size-adjusting our FN and LS results. Parameters of bone strength including index of bone structural strength (IBS), and cross-sectional moment of inertia (CSMI) were calculated from the DXA measures using formulae described by Sievanen and colleagues [21].

Statistical analyses

All statistical analyses were performed using SPSS version 14.0 for Windows (SPSS, Chicago, IL, USA). Independent sample t-tests were used to generate descriptive statistics and examine gender differences in subject characteristics, physical activity scores, and bone measures. Stepwise multiple regression analyses were performed to determine the ability of all physical activity measures to predict variance in each bone strength variable. Data was ranked according to BPAQ score and a second regression analysis was run on subjects falling in the upper and lower quartiles of loading intensity to determine if the ability of BPAQ to predict variance in bone strength parameters improved at the extremes of the loading spectrum. Correlation analyses were performed to test the relationship between each of the physical activity measures. Statistical significance was set at $p < 0.05$.

RESULTS

Table 2 displays all subject characteristics and bone parameters for men and women. Men were taller, heavier, had greater lean tissue mass and a lower body fat percentage than women ($p < 0.05$). There were no statistically significant differences in age or BMI between the sexes. Not unexpectedly, men exhibited greater bone size (FN area, FN CSMI, LS area, and LS IBS) and had significantly greater calcaneal BUA than women, however, no other parameters were significantly different between the sexes.

[TABLE 2]

Peak vGRFs, rates of force application, and the consequent effective load ratings for each activity measured on the force plate are represented in Table 3. The activity with the highest force magnitude was the drop jump at 5.5 times bodyweight, while the foot stomp recorded the highest rate of force application at 473.6 bodyweights per second.

[TABLE 3]

No statistically significant sex differences were found between men and women for any physical activity scores except for the Bouchard 3-Day Physical Activity Record (3DR). Men recorded higher energy expenditure than women on the 3DR (14062 ± 2660 kJ vs 12086 ± 3336 kJ, p = 0.05). As weight features strongly in the calculation of energy expenditure, it is likely that the difference is accounted for by the greater bodyweight of men compared to women in the study cohort.

For men, the current component of BPAQ was the only physical activity measure to predict variance in bone strength variables, predicting 68% (p = 0.001), 65% (p = 0.001), 36% (p = 0.007), 38% (p = 0.005), and 45% (p = 0.002) of variance in FN BMD, FN BMAD, LS BMD, LS IBS, and WB BMD respectively (Figure 1a-c). For women, the past component of BPAQ predicted 48% (p = 0.001) of the variance in calcaneal BUA only (Figure 1d). None of the other measures of physical activity, the BLHQ, MAQ, pedometer steps, or 3DR, predicted variance in any bone strength variable for either men or women. Analysis of subjects in the upper and lower quartiles of loading intensity improved the ability of past BPAQ to predict variance in female BUA (R^2 = 0.95; p = 0.001), but did not improve either current or past components for any other variable.

[FIGURE 1]

Table 4 presents the relationships between all physical activity scores from the total study cohort. While there was a moderate positive relationship (r = 0.33, p = 0.04) between scores from the current and past components of BPAQ, neither related to scores from the BLHQ or any other measure of physical activity. Scores from the two components of the BLHQ displayed a strong positive relationship to each other (r = 0.94, p = 0.001), but not with any other physical activity measure. Scores from the pedometer and the 3DR showed moderate positive relationships (r = 0.39, p = 0.024, and r = 0.45, p = 0.003 respectively) with scores from the MAQ.

[TABLE 4]

DISCUSSION

Our goal was to examine the ability of a purpose-designed bone-specific physical activity questionnaire to detect a relationship between physical activity and parameters of bone strength in comparison with the abilities of other physical activity measures to do so. We found that past and current BPAQ scores significantly predicted variance in indices of bone strength at clinically relevant sites in young adult males and females. By contrast, neither traditional physical activity measures, nor a recently published bone loading questionnaire (BLHQ) were predictive of bone strength parameters.

Animal studies have been instrumental in determining the characteristics of mechanical loads that invoke the greatest response from the skeleton; namely loads inducing high bone strain or those applied at high rates. In lieu of the direct measurement of human bone strain (an inherently invasive technique), skeletal strain during mechanical loading can be inferred from ground reaction force (GRF) data. Indeed, strong relationships between actual bone strain magnitudes and simultaneous ground reaction forces have been observed in cadaveric studies [22]. Ground reaction forces are thus a valid surrogate measure of bone strain and frequently employed to report exercise intensity [23], as in the current investigation.

Until recently, the bone research community has relied on generic tools of physical activity measurement to account for the effects of previous physical activity on the skeleton.

Unfortunately, such measures fail to account for loading characteristics of relevance to bone, such as load magnitude and rate of application. Independently from our BPAQ project, Dolan and colleagues [15] recently developed the bone loading history questionnaire (BLHQ). Load ratings ascribed to activities in that study were not based on direct measures. We developed a simple bone-specific physical activity measure that would account for the magnitude and rate of force application of past (whole of life) and current physical activities (previous 12 months) based on empirical (GRF) measures.

We devised algorithms to analyse the raw data from the BPAQ based on known principles of effective bone loading. Weighting factors (see Appendix B) were utilised to moderate the influences of load intensity, frequency and years of participation on BPAQ scores. Load magnitude has long been known to exert a strong osteogenic influence on bone [2, 24]. Later, strain rate (or rate of load application) was recognised to be a potent bone stimulus [3, 4]. Thus, load intensity (effective load stimulus) was derived from force magnitude (peak vGRF) and rate of force application (time to peak vGRF), and weighted preferentially in the algorithms. All activities were normalised to be relative to gymnastics, an activity of renowned high load stimulus [18]. As bone is known to lose mechanosensitivity in the short term [25], cycle number was deemphasised in the algorithms. Frequency of activity participation (bouts per week) was given moderate weighting considering that bone mechanosensitivity is likely regained after a 24-hour rest period [26]. As short bouts of loading appear to be just as effective bone stimuli as longer bouts [27, 28], duration of activity was not considered in the BPAQ. Finally, age-weightings were incorporated to recognise the greater osteogenic effects of exercise during growth [5] as opposed to exercise after skeletal maturity.

Our ground reaction force data represent a diverse range of activities that can be used to estimate mechanical loads on the skeleton across a broad number of sports and physical activities. Although the ground reaction forces for a number of sports have been reported, most have done so in isolation and with elite athlete cohorts [12-14, 29-31]. Thus, to the best of our knowledge, an accurate and relatively comprehensive representation of physical actions fundamental to most weight bearing sports has not previously been published.

While the calculations used to derive BPAQ scores for each activity are quite simple, as illustrated in the Appendices, the integration of scores for all sports and activities recorded for each individual, including age-relevant adjustment is more challenging. With the use of a custom-designed LabVIEW program, however, the calculations can be executed very simply and can be performed on any capable software platform. A free-access, web-based version of the analysis software is under construction.

The sensitivity of the BPAQ to differences in loading history can be demonstrated using a hypothetical case (Table 5). An example of past BPAQ scores for a 28 year old male participating in low, moderate and/or high effective loading activities for varying numbers of years clearly exhibits the effect of the algorithm factor weightings. Participation in a high intensity load activity such as gymnastics substantially magnifies the BPAQ score, whereas even a considerable history of regular swimming has only a very small effect on overall score. As swimming is known to be a poor bone stimulus [32] and gymnastics a potent bone stimulus [18], the algorithm appears to appropriately assign bone-relevant scores that reflect the current evidence base.

Our bone findings suggest that the BPAQ is indeed sensitive to bone-relevant recent historical loading. While the total BPAQ score (the product of combining past and current BPAQ scores) was unable to predict bone strength parameters in either sex, analysis of the individual BPAQ components (past and current scores) yielded illuminating results. Interestingly, we observed only a weak relationship between the current and past scores from the BPAQ, suggesting that patterns of bone-relevant physical activity in young adulthood do not necessarily reflect behaviour in youth. Furthermore, we observed age-specific relationships between physical activity and bone strength parameters according to sex. Our observations appear to reflect the previously reported sex difference in the nature and timing of the relationship of physical activity to bone mass [33, 34]. That is, a sex difference in sensitivity of bone to loading between youth and young adulthood appears to exist. As such, the typical earlier maturation of the female skeleton versus the male may account for the ability of the past component of BPAQ to predict calcaneal BUA in women, but not men in our cohort. A trial of the BPAQ with prepubertal children would further test the ability of the instrument to reflect bone loading history in females, and expound any influence of timing of loading on the effect of physical activity on the skeleton.. That the current component of BPAQ predicted DXA-derived bone strength parameters in men but not women may reflect the same sex-specific maturational influence. The relationship of past BPAQ to calcaneal BUA in women corresponded to greater female past participation in gymnastics than male (30% vs 10%, respectively). Recording and controlling for gynecological age may have provided additional information with respect to factors influencing parameters of female bone strength.

When relationships between the physical activity measures were examined, several interesting findings were identified. Notably, BPAQ scores were not related to scores from the recently published bone loading history questionnaire (BLHQ) [15]. Given the critical influence of strain magnitude on the bone response to mechanical loading, the lack of relationship is likely to reflect dissimilarity of algorithms between the two studies. Specifically, load ratings for the BPAQ were obtained from measured GRFs, while BLHQ ratings were not. Furthermore, weighting factors in our equations were used to apply appropriate emphases on different strain elements.

Not surprisingly, pedometer counts and the 3DR scores were related positively to MAQ values, reflecting the common emphasis of duration and metabolic load on the computation of those scores. Reflecting their different focus, scores from neither bone-relevant assessment instrument (the BPAQ and the BLHQ) related to scores from any of the generic physical activity measures. The observed strong positive relationship of the two components of the BLHQ was not unexpected as the same responses (and therefore activities participated in) are included in each component (i.e. hip and spine) and loading factors utilised are the same for each activity.

Limitations

Further studies including subjects from youth to very old age are required to determine if the predictive observations of the BPAQ can be generalised from our cohort to others. Additionally, in the absence of more direct measures of bone geometry such as MRI or QCT, we calculated DXA-derived geometric indices of bone strength based on previously published procedures [21]. We recognise those calculations are unlikely to be as accurate as real measures.

Conclusions

Our results highlight the importance of using a bone-specific instrument to evaluate the influence of historical physical activity on skeletal health. We found that the current component of BPAQ predicts indices of bone strength at the hip, spine and whole body in healthy young adult men, while traditional measures of physical activity and the recently developed BLHQ did not. The past component of BPAQ predicted an index of bone strength at the heel for healthy young adult women while traditional measures of physical activity and the recently developed BLHQ did not. We conclude that the BPAQ was a simple, quick method to determine the influence of previous mechanical loading on site and sex specific elements of the skeleton and is superior in this respect to existing instruments of physical activity assessment.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the assistance of Dr Rod Barrett and Dr Justin Kavanagh in the data collection phase of the project. There were no external funding sources for this project.

REFERENCES

1. Rubin, CT (1984) Skeletal strain and the functional significance of bone architecture. Calcif Tissue Int 36 Suppl 1:S11-8

2. Rubin, CT and Lanyon, LE (1985) Regulation of bone mass by mechanical strain magnitude. Calcif Tissue Int 37:411-7

3. O'Connor, JA, Lanyon, LE and MacFie, H (1982) The influence of strain rate on adaptive bone remodelling. J Biomech 15:767-81

4. Turner, CH, Owan, I and Takano, Y (1995) Mechanotransduction in bone: role of strain rate. Am J Physiol 269:E438-42

5. Kannus, P, Haapasalo, H, Sankelo, M, et al. (1995) Effect of starting age of physical activity on bone mass in the dominant arm of tennis and squash players. Ann Intern Med 123:27-31

6. Burr, DB, Milgrom, C, Fyhrie, D, et al. (1996) In vivo measurement of human tibial strains during vigorous activity. Bone 18:405-10

7. Ekenman, I, Halvorsen, K, Westblad, P, et al. (1998) Local bone deformation at two predominant sites for stress fractures of the tibia: an in vivo study. Foot Ankle Int 19:479-84

8. Lanyon, LE, Hampson, WG, Goodship, AE, et al. (1975) Bone deformation recorded in vivo from strain gauges attached to the human tibial shaft. Acta Orthop Scand 46:256-68

9. Milgrom, C, Miligram, M, Simkin, A, et al. (2001) A home exercise program for tibial bone strengthening based on in vivo strain measurements. Am J Phys Med Rehabil 80:433-8

10. Milgrom, C, Radeva-Petrova, DR, Finestone, A, et al. (2007) The effect of muscle fatigue on in vivo tibial strains. J Biomech 40:845-50

11. Milgrom, C, Finestone, A, Levi, Y, et al. (2000) Do high impact exercises produce higher tibial strains than running? Br J Sports Med 34:195-9

12. Hurrion, PD, Dyson, R and Hale, T (2000) Simultaneous measurement of back and front foot ground reaction forces during the same delivery stride of the fast-medium bowler. J Sports Sci 18:993-7

13. Perttunen, JO, Kyrolainen, H, Komi, PV, et al. (2000) Biomechanical loading in the triple jump. J Sports Sci 18:363-70

14. Salci, Y, Kentel, BB, Heycan, C, et al. (2004) Comparison of landing maneuvers between male and female college volleyball players. Clin Biomech 19:622-8

15. Dolan, SH, Williams, DP, Ainsworth, BE, et al. (2006) Development and reproducibility of the bone loading history questionnaire. Med Sci Sports Exerc 38:1121-31

16. Turner, CH and Robling, AG (2003) Designing exercise regimens to increase bone strength. Exerc Sport Sci Rev 31:45-50

17. Turner, CH and Robling, AG (2005) Exercises for improving bone strength. Br J Sports Med 39:188-9

18. Snow, CM, Williams, DP, LaRiviere, J, et al. (2001) Bone gains and losses follow seasonal training and detraining in gymnasts. Calcif Tissue Int 69:7-12

19. Kriska, AM and Bennett, PH (1992) An epidemiological perspective of the relationship between physical activity and NIDDM: from activity assessment to intervention. Diabetes Metab Rev 8:355-72

20. Bouchard, C, Tremblay, A, Leblanc, C, et al. (1983) A method to assess energy expenditure in children and adults. Am J Clin Nutr 37:461-7

21. Sievanen, H, Kannus, P, Nieminen, V, et al. (1996) Estimation of various mechanical characteristics of human bones using dual energy x-ray absorptiometry: Methodology and precision. Bone 18:17S-27S

22. Peterman, MM, Hamel, AJ, Cavanagh, PR, et al. (2001) In vitro modeling of human tibial strains during exercise in micro-gravity. J Biomech 34:693-8

23. McKay, H, Tsang, G, Heinonen, A, et al. (2005) Ground reaction forces associated with an effective elementary school based jumping intervention. Br J Sports Med 39:10-14

24. Hert, J, Liskova, M and Landa, J (1971) Reaction of bone to mechanical stimuli. Part 1. Continuous and intermittent loading of tibia in rabbit. Folia Morphol 19:290-300

25. Umemura, Y, Ishiko, T, Yamauchi, T, et al. (1997) Five jumps per day increase bone mass and breaking force in rats. J Bone Miner Res 12:1480-5

26. Robling, AG, Burr, DB and Turner, CH (2001) Recovery periods restore mechanosensitivity to dynamically loaded bone. J Exp Biol 204:3389-99

27. Robling, AG, Hinant, FM, Burr, DB, et al. (2002) Shorter, more frequent mechanical loading sessions enhance bone mass. Med Sci Sports Exerc 34:196-202

28. Robling, AG, Hinant, FM, Burr, DB, et al. (2002) Improved bone structure and strength after long-term mechanical loading is greatest if loading is separated into short bouts. J Bone Miner Res 17:1545-54

29. Frederick, EC, Determan, JJ, Whittlesey, SN, et al. (2006) Biomechanics of skateboarding: kinetics of the Ollie. J Appl Biomech 22:33-40

30. Kellis, E, Katis, A and Vrabas, IS (2006) Effects of an intermittent exercise fatigue protocol on biomechanics of soccer kick performance. Scand J Med Sci Sports 16:334-44

31. Otago, L (2004) Kinetic analysis of landings in netball: is a footwork rule change required to decrease ACL injuries? J Sci Med Sport 7:85-95

32. Taaffe, DR, Snow Harter, C, Connolly, DA, et al. (1995) Differential effects of swimming versus weight-bearing activity on bone mineral status of eumenorrheic athletes. J Bone Miner Res 10:586-93

33. Bass, S, Delmas, PD, Pearce, G, et al. (1999) The differing tempo of growth in bone size, mass, and density in girls is region-specific. J Clin Invest 104:795-804

34. Bradney, M, Karlsson, MK, Duan, Y, et al. (2000) Heterogeneity in the growth of the axial and appendicular skeleton in boys: Implications for the pathogenesis of bone fragility in men. J Bone Miner Res 15:1871-8

List of Appendices

Table 1: Descriptions of activities for which ground reaction forces were measured

Activity	Description
Dance step	Basic dance step known as 'the vine' whereby the subject walks in a sideways fashion by alternately crossing one foot in front of the other for three steps before performing a hop to change directions
Depth jump	Jumping forward from a 0.3m high box onto the platform and immediately jumping forward in a plyometric fashion onto a 0.2m high box
Drop jump	Two-footed landings on the force platform from a 0.3m high box
Foot stomp	Lifting one foot off the ground before forcibly returning it to the ground flat-footed, i.e. 'stomping'
Heel drop	Standing on toes and passively dropping onto heels
Hop	Hopping on a single leg on the force platform
Jump	Standing with feet shoulder-width apart, then bending the knees and hips before performing a maximal jump for height and landing on the force platform (i.e. to mimic a standing basketball/netball rebound and standing jumps in other sports)
Jump squat	Similar to a jump, but landing in the 'squat' position with both knees and hips flexed
Lunge	Stepping forward with one leg onto the force platform such that the knee and hip of the front leg are flexed to approximately 90 degrees
Run	Running at preferred speed
Side lunge	Stepping laterally onto the force plate such that the knee of the stepping leg will flex to approximately 90 degrees

Side-step	Side-step at 45 degrees while running at preferred speed (to imitate cutting actions common in tennis, football and other sports)
Star jump	Jumps whereby hips and shoulders are abducted slightly on alternate landings
Stop-and-turn	Running at preferred speed, plant foot to stop, turn and run back to the starting place
Stride jump	Jumps whereby landings are performed with one foot in front of the other
Take off I	Single-leg take-off at preferred speed with the emphasis on distance (to imitate the take off action of activities such as long jump and triple jump)
Take off II	Single-leg take-off at preferred speed with the emphasis on height (to imitate the take off action of a high jump or basketball rebound)
Tuck jump	Double-leg take-off, elevating the knees toward the chest during flight and landing on the force platform with two feet
Walk	Walking at preferred speed

Table 2: Subject characteristics and bone parameters for young healthy adult males and females in the BPAQ study (n = 40)

Characteristic	Males (n = 20)	Females (n = 20)	p value
Age (years)	24.0 ± 2.9	25.1 ± 2.8	NS
Height (m)	1.80 ± 0.08	1.68 ± 0.05	0.001
Weight (kg)	76.2 ± 10.3	63.5 ± 9.3	0.001
BMI ($kg{\cdot}m^{-2}$)	23.5 ± 2.9	22.4 ± 2.6	NS
Lean tissue mass (g)	57451 ± 6483	39663 ± 4635	0.001
Percent body fat (%)	14.3 ± 5.8	24.0 ± 6.6	0.001
BUA ($dB{\cdot}MHz^{-1}$)	102.6 ± 13.9	93.0 ± 9.1	0.01
FN Area (cm^2)	5.6 ± 0.5	4.8 ± 0.3	0.001
FN BMD ($g{\cdot}cm^{-2}$)	1.10 ± 0.15	1.05 ± 0.19	NS
FN BMAD ($g{\cdot}cm^{-3}$)	0.38 ± 0.06	0.42 ± 0.08	NS
FN CSMI (cm^4)	5.63 ± 1.44	3.31 ± 0.82	0.001
TR BMD ($g{\cdot}cm^{-2}$)	0.93 ± 0.16	0.86 ± 0.12	NS
LS Area (cm^2)	52.1 ± 4.9	45.9 ± 4.4	0.001
LS BMD ($g{\cdot}cm^{-2}$)	1.23 ± 0.15	1.16 ± 0.08	NS
LS BMAD ($g{\cdot}cm^{-3}$)	0.16 ± 0.02	0.17 ±0.02	NS
LS IBS ($g^2{\cdot}cm^{-4}$)	1.95 ± 0.46	1.72 ± 0.23	0.05
WB BMD ($g{\cdot}cm^{-2}$)	1.11 ± 0.12	1.07 ± 0.07	NS

BMAD = bone mineral apparent density, BMD = bone mineral density, BMI = Body mass index, BUA = broadband ultrasound attenuation, CSMI = cross-sectional moment of inertia, FN = femoral neck, IBS = index of bone structural strength, LS = lumbar spine, WB = whole body.

Table 3: Peak vertical ground reaction forces, rates of force application and effective load ratings for measured activities for young healthy adult males and females (n = 20).

Activity	Peak vGRF (BW)	Rate of force application ($BW \cdot s^{-1}$)	Effective load rating (vGRF x Rate)
Lunge	1.1	7.1	7.8
Walk	1.2	8.4	10.1
Side lunge	1.2	8.4	10.1
Stop and turn	1.8	41.7	75.1
Stride jump	2.1	56.2	118.0
Run	2.6	46.9	121.9
Dance step	2.7	49.3	133.1
Side-step	2.9	117.4	340.5
Hop	3.4	46.3	157.4
Take off I	3.5	136.4	477.4
Take off II	3.5	122.6	429.1
Heel drop	3.6	36.6	131.8
Jump squat	3.8	57.0	216.6
Star jump	4.3	52.0	223.4
Foot stomp	4.6	473.6	2178.6
Jump	4.7	67.3	316.3
Tuck jump	4.8	78.5	376.8
Depth jump	5.2	85.4	444.1
Drop jump	5.5	142.6	784.3

BW = bodyweights, vGRF = vertical ground reaction force.

Table 4: Correlation matrix of scores from all physical activity measures from young healthy males and females (n = 40)

	Ped	cBPAQ	pBPAQ	3DR	MAQ	BLHQ (Hip)	BLHQ (Spine)
Ped	1	0.25 (NS)	0.02 (NS)	0.26 (NS)	0.39 (p = 0.02)	0.08 (NS)	0.13 (NS)
cBPAQ		1	0.33 (p = 0.04)	-0.29 (NS)	-0.26 (NS)	0.01 (NS)	-0.01 (NS)
pBPAQ			1	-0.16 (NS)	0.14 (NS)	0.06 (NS)	0.05 (NS)
3DR				1	0.45 (p = 0.003)	-0.05 (NS)	-0.01 (NS)
MAQ					1	0.18 (NS)	0.26 (NS)
BLHQ (Hip)						1	0.94 (p = 0.001)
BLHQ (Spine)							1

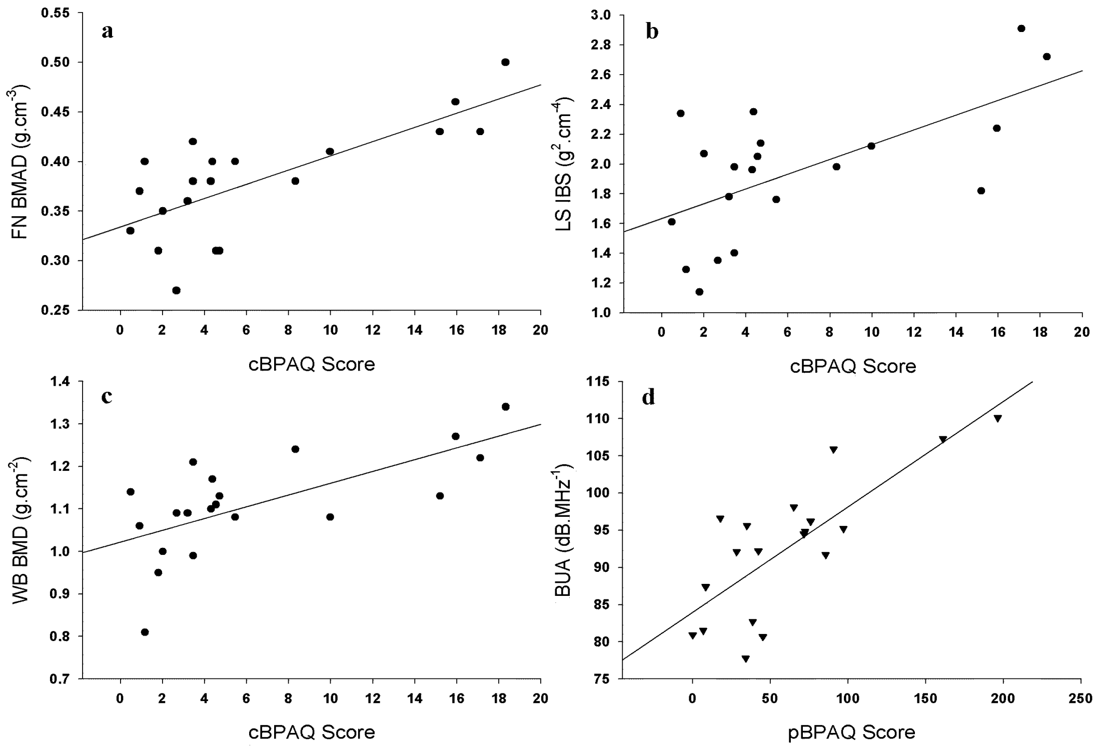
cBPAQ = current Bone-specific Physical Activity Questionnaire, BLHQ = Bone Loading History Questionnaire, MAQ = Modifiable Activity Questionnaire, pBPAQ = past Bone-specific Physical Activity Questionnaire, Ped = Pedometer.

Table 5: Hypothetical illustration of the effect of varying years of participation in low, moderate and high intensity activities on past BPAQ score for a 28 year-old male

Example	**Swimming** (years) *low intensity*	**Soccer** (years) *moderate intensity*	**Gymnastics** (years) *high intensity*	**Past BPAQ score**
1	3	3	3	34.11
2	0	3	3	34.09
3	3	3	0	4.11
4	3	0	3	30.02
5	9	0	0	0.06
6	0	9	0	12.26
7	0	0	9	90.00

BPAQ = Bone-specific Physical Activity Questionnaire.

Fig. 1 Relationships between a sample of significant predictors and bone strength parameters for healthy young adult males and females. (a) cBPAQ score versus FN BMAD for healthy young adult males (R2=0.65, p=0.001). (b) cBPAQ score versus LS IBS for healthy young adult males (R2=0.38, p=0.005). (c) cBPAQ score versusWB BMD for healthy young adult males (R2=0.45, p=0.002). (d) pBPAQ score versus calcaneal BUA for healthy young adult females (R2=0.48, p=0.001). Closed circles represent male data. Closed inverted triangles represent female data. BMAD=bone mineral apparent density; BMD=bone mineral density; BPAQ=bone specific physical activity questionnaire; BUA=Broadband ultrasound attenuation; cBPAQ=Current BPAQ; FN=Femoral neck; IBS=index of bone strength; LS=lumbar spine; pBPAQ=past BPAQ; WB=whole body



Bone-Specific Physical Activity Questionnaire (BPAQ)

SUBJECT ID:	DATE:

1. **Please list <u>any</u> sports or other physical activities you have participated in regularly. Please <u>tick</u> the boxes to indicate how old you were for each sport/activity and how many years you participated for.**

Age: Activities	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30

Age: Activities	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60

Age: Activities	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90

Developed by B.K. Weeks and B.R. Beck
Griffith University, QLD, Australia

Bone-Specific Physical Activity Questionnaire (BPAQ)

SUBJECT ID:	DATE:

2. **Please list the sports or other physical activities (be as specific as possible) you participated in regularly during the <u>last 12 months</u> and indicate the average frequency (sessions per week)?**

Activity: ______________________________ Frequency (per week): __________

Activity: ______________________________ Frequency (per week): __________

Activity: ______________________________ Frequency (per week): __________

Activity: ______________________________ Frequency (per week): __________

Activity: ______________________________ Frequency (per week): __________

Activity: ______________________________ Frequency (per week): __________

Activity: ______________________________ Frequency (per week): __________

Activity: ______________________________ Frequency (per week): __________

APPENDIX B

Current BPAQ (cBPAQ) algorithm:

cBPAQ = [R + 0.2R(n-1)] x a

R = effective load stimulus (derived from GRF testing)
n = frequency of participation (per week)
a = age weighting factor
(age weightings: <10 yrs = 1.2; 10-15 yrs = 1.5; 15-35 yrs = 1.1; >35 yrs = 1.0)

Past BPAQ (pBPAQ) algorithm:

pBPAQ = R x y x a

R = effective load stimulus (derived from GRF testing)
y = years of participation
a = age weighting factor
(age weightings: <15 yrs = 0.25; >15 yrs 0.10)

APPENDIX C

Effective load ratings assigned to common sports and activities from GRF measures of fundamental actions observed in each sport/activity.

Sport/Activity	Peak GRF	Rate	Effective Load Stimulus
Swimming*	0.7	2.5	0.07
Rowing*	1.0	3.0	0.12
Cycling*	0.8	5.0	0.16
Diving (platform)	1.0	7.0	0.28
Scuba*	1.0	7.1	0.28
Stairmaster	1.1	7.1	0.31
Windsurfing*	1.1	7.1	0.31
Golf	1.2	8.4	0.40
Walking/Hiking	1.2	8.4	0.40
Shot put	1.2	8.4	0.40
Resistance training (lower limb)*	1.8	7.1	0.51
Skiing	1.2	15.0	0.72
Waterskiing	1.2	15.0	0.72
Rollerblading*	1.2	20.0	0.96
Skateboarding	1.2	20.0	0.96
Ice hockey*	1.2	35.0	1.68
Horse-riding*	1.5	50.0	3.00
Judo	2.1	56.2	4.72
Cricket	2.6	46.9	4.88
Running/Jogging	2.6	46.9	4.88
Track	2.6	46.9	4.88
Triathlon	2.6	46.9	4.88
Ultimate	2.6	46.9	4.88

Dance	2.7	49.3	5.32
Cross-country	2.9	56.2	6.52
Netball	2.9	56.2	6.52
Tennis	4.7	41.7	7.84
Lacrosse	3.5	67.3	9.42
Racquet ball	2.6	117.4	12.21
Squash	2.6	117.4	12.21
Kung Fu*	4.7	67.3	12.65
Basketball	4.7	67.3	12.65
Jump Rope	4.7	67.3	12.65
T-ball	2.9	117.4	13.62
Baseball	2.9	117.4	13.62
Softball	2.9	117.4	13.62
Flag football	2.9	117.4	13.62
Rugby League/Union	2.9	117.4	13.62
Soccer	2.9	117.4	13.62
Touch Football	2.9	117.4	13.62
Badminton	4.7	117.4	22.07
Australian Rules	4.7	122.6	23.05
Ballet	4.7	136.4	25.64
Ice skating (figure/dance)*	4.8	136.4	26.19
Volleyball	5.5	142.6	31.37
Aerobics	5.5	250.0	55.00
Cheerleading	5.5	250.0	55.00
Gymnastics*	10.0	250.0	100.00

***** Indicates sports for which the fundamental loading movements could not be measured directly from the force plate.   In those cases, the force of the most similar manoeuvre measured was assigned.