J Musculoskelet Neuronal Interact 2011; 11(1):21-26

Original Article

Hylonome

Inter-limb musculoskeletal differences in competitive ten-pin bowlers: A preliminary analysis

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Abstract

Objectives: To compare musculoskeletal characteristics of the loaded and non-loaded forearm and upper leg of competitive ten-pin bowlers. **Methods:** 10 competitive bowlers (30.6±6.8 yrs) had their areal bone mineral density (aBMD) and body composition measured with Dual Energy X-ray Absorptiometry (DXA). Volumetric bone mineral density (vBMD) and bone characteristics were assessed at 4% and 66% of the limb length of each radius and 50% of the limb length of each femur using a pQCT. Bone and muscle characteristics of the loaded and non-loaded limbs were compared and analyzed using paired t-tests. **Results:** The loaded arm of competitive bowlers had significantly ($p<0.05$) greater bone free lean body mass (BFLBM) (5%) and ultra distal radius site (UD radius) aBMD (6.3%) compared to the non-loaded side. Cortical and trabecular vBMD was significantly ($p<0.05$) greater (1.3%, 4.8%) at the radius 66% and 4% sites in the loaded forearm, respectively. aBMD of the femoral neck, trochanter, and total hip were significantly greater (12.2-15.6%) in the slide leg. Total (5.2%) and cortical (9.2%) bone areas, total (8.2%) and cortical (8.7%) bone mineral content (BMC), and cortical wall thickness (9%) were significantly greater at the 50% femur site in the slide leg compared to the contralateral side. **Conclusion:** The femoral shaft of bowlers adapts by increasing bone area and cortical thickness without a change in vBMD, while the loaded radius adapts by increasing vBMD.

Keywords: pQCT, DXA, Bone Mineral Density, Loading, Bone Free Lean Body Mass

Introduction

According to the mechanostat theory, bone has a regulatory mechanism that is responsible for monitoring mechanical loading or strain imposed upon the skeleton[1]. Bone adaptation to physical activity in humans has been studied comparing athletic populations to their recreationally active or sedentary age-matched counterparts. However, bone adaptation is a multifactoral process including metabolic, nutritional, hormonal, and genetic influences[2]. In this regard, studies comparing side to side limb differences in athletes participating in sports of unilateral nature can control for these influences. Several investigations have reported substantial aBMD and BMC differences in the loaded limb compared to the non-loaded limb. For example, the playing arm of squash and tennis athletes[3-5] as well as the take-off lower-limb of gymnasts[6] have been reported to have higher bone mass. More recently, it has been established that bone adaptation to loading also occurs by changes in geometry and size, if the loading is initiated at a young age[7]. Studies employing the use of peripheral quantitative computed tomography (pQCT) and magnetic resonance imaging (MRI) have reported greater bone cross-sectional area and cortical thickness in the loaded limbs of primarily unilateral athletes when compared to the non-loaded limbs[7-11]. Importantly, bones that adapt by increasing in size and increased bone mineral accrual will result in a strong, more competent bone and may decrease bone loss later in life[7,12].

Ten-pin bowling is a popular recreational activity in many countries. It is also a competitive sport among amateurs and professionals. Bowling provides a unique unilateral model to study bone adaptation in both an upper and lower limb, as the throwing arm and slide leg are under considerable mechanical load compared to the non-throwing arm and non-slide leg. In a traditional 4 or 5-step approach, the bowler creates momentum driving off and sliding to an abrupt stop before ball release to generate power which is critical in developing a high rate of

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The authors have no conflict of interest.

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Edited by: F. Rauch
Accepted 6 February 2011

ROI	Cont Mode	Peel Mode	Trabecular Threshold 1	Trabecular Threshold 2	Cort Mode	Cortical Threshold 1	Cortical Threshold 2
Radius 4%	3	4	169	650	2	480	0
Radius 66%	1	2	710	710	2	710	0
Femur 50%	1	2	710	710	2	710	0
Rad 66% MCSA (1)	1	2	-100	40	4	710	40
Rad 66% MCSA (2)	1	2	710	40	4	-100	2000
Fem 50% MCSA (1)	1	2	-100	40	1	710	0
Fem 50% MCSA (2)	1	2	710	40	4	-100	2000

MCSA: Muscle Cross-sectional Area; Rad: Radius; Fem: Femur; (1): Ananlysis 1; (2): Analysis 2.

Table 1. pQCT analysis settings for individual ROI's.

revolution on the 6.81-7.27 kg bowling ball[13]. In addition, the throw arm of the bowler is responsible for stabilization of the ball during backswing. During the front swing phase, the bowler quickly pronates the wrist to develop the spin or "revolution rate" on the 6.81-7.27 kg bowling ball. To the best of our knowledge, bone and muscle adaptation in competitive bowlers has never been investigated. The purpose of this study was to compare bone and muscle characteristics of the loaded and non-loaded forearm and upper leg of competitive bowlers utilizing pQCT and dual energy x-ray analysis (DXA). It was hypothesized that the bone and muscle measures of interest would be greater in the loaded limbs than the non-loaded limbs.

Materials and methods

Subjects

Ten (4 female, 6 male) competitive bowlers (30.6±6.8 years) volunteered and gave written informed consent to participate in the study. All athletes were actively bowling and competing at the time of the study and had been for at least the past five years. Subjects were excluded if they were outside the age range of 20-40 years, had been training for less than five years, and were currently taking any medications or had any conditions known to affect bone density. Subjects completed several questionnaires including health history, bowling specific training, estimated calcium intake, and bone-loading history questionnaire (BLHQ)[14]. The BLHQ was also used to assess bowling history throughout their lifespan, as well as to rule out participation in any other sports that may have been unilateral in nature. Based on the power analyses using previous studies that examined many of the same variables in tennis players[7] and gymnasts[6], sample sizes in the range of 9-45 are required for 80% statistical power. The study was approved by the University of Oklahoma Institutional Review Board.

Muscle and bone characteristics

Volumetric BMD (vBMD) and bone characteristics (BMC, area, and cortical thickness (CTh)) of the loaded and non-loaded radius and femur were assessed using a pQCT scanner XCT 3000 with software version 6.00 (Stratec Medizintechnik GmbH, Pforzheim, Germany) by a trained technician. Measurement sites included 4% and 66% of the limb length proximal to the bony endplate of each radius and 50% of the limb length proximal to the bony endplate of each femur. Muscle cross-sectional area (MCSA) of the forearm was determined from the 66% site and thigh MCSA was determined from the 50% femoral site. Scans were acquired employing a voxel size of 0.4 mm, a slice thickness of 2.2 mm, and a scan speed of 30 mm/sec (radius) and 20 mm/sec (femur). Bone parameters were determined by drawing a region of interest (ROI) around the obtained bone slice and analyzed using the manufacturer's threshold driven software. Specific pQCT analyses threshold settings are presented in Table 1. MCSA of the thigh and forearm was determined by subtracting the total fat area from the whole limb cross-sectional area to give 'muscle+bone area'. The second analysis subtracts the total bone area from the muscle+bone area. Specifically, MCSA is derived as: Subcortical area (Analysis 1) – Subcortical area (Analysis 2) – Cortical area (Analysis 1). Smoothing filters F03F05 and F01F06UO1 were used for the forearm and thigh MCSA measurements, respectively. Coefficients of variation (%CV) for the duplicate measures assessed 24 hours apart on 15 subjects ranged from 1.28-5.9% for the radius 4% site variables, 0.5-2.1% for radius 66% site variables, and 0.3-0.9% for femur 50% site variables.

Bilateral DXA was used to assess aBMD and BMC of proximal femur (femoral neck, trochanter, total hip) and left and right forearm (ultra-distal and 33%) (GE Medical Systems, Lunar Prodigy encore software version 10.50.086, Madison, WI). A total body scan was performed in order to obtain appendicular bone free lean body mass (ABFLBM). All scans were performed by a single trained technician with day to day technician precision ranging from 0.38-2.4% for the bone variables and 0.56-0.78% for the body composition variables of interest.

Statistical analysis

Analyses were performed using SPSS for Windows version 16.0 (Chicago, IL). Data are presented as mean ± standard deviation. Side to side limb comparisons of muscle and bone characteristics were determined using paired t-tests. Pearson's correlation coefficient was used to assess the relationship between muscle and bone characteristics. Significance was set at $p<0.05$.

Characteristic	Bowlers (N=10)	Male (N=6)	Female (N=4)
Age (yrs)	30.6±6.8	27.7±6.9	35.0±3.8
Height (m)	1.72±0.13	1.79±0.08	1.62±0.11
Weight (kg)	83.4±14.3	83.1±16.0	83.8±13.6
BMI (kg/m^2)	28.1±4.5	25.6±3.1	32.1±3.4
Years Competitive	13.2±9.2	9.5±7.8	19.2±8.7
Training Sessions/week	3.5±1.5	4.1±1.6	2.4±0.6
Pin Average	200.5±24.6	208.8±21.6	188.1±26.3
Calcium Intake (mg)	775.7±312.3		
BLHQ Hip Score	496.8±182.5		
BLHQ Spine Score	546.5±228.3		

BLHQ: Bone Loading History Questionnaire.

Table 2. Subject characteristics.

Variable	Loaded limb	Non-Loaded Limb	% Diff	*p* value
Arm BFLBM (g)	3209.3±1093.5	3081.6±1141.4	5.3±7.7	0.048
Leg BFLBM (g)	8450.1±1840.5	8620.2±1736.4	2.3±4.1	0.141
UD Radius aBMD (g/cm^2)	0.552±0.08	0.522±0.09	6.3±6.3	0.010
Radius 33% aBMD (g/cm^2)	0.964±0.11	0.963±0.12	0.05±7.1	0.985
Femoral Neck aBMD (g/cm^2)	1.213±0.11	1.089±0.14	12.2±11.2	0.005
Trochanter aBMD (g/cm^2)	1.024±0.11	0.889±0.09	15.6±11.8	0.002
Total Hip aBMD (g/cm^2)	1.236±0.10	1.101±0.11	12.8±9.6	0.002

*BFLBM: Bone-Free Lean Body Mass; UD: Ultra Distal; aBMD: Areal Bone Mineral Density % Diff: (loaded - Non-loaded)/ Non-loaded * 100*

Table 3. DXA-derived limb differences.

Results

Subject characteristics are presented in Table 2. Competitive bowlers in this study had been playing competitively in their respective sport for 13±9.2 years and bowling 3.5±1.5 days per week. Average estimated daily calcium intake was 775.7±312.3 mg and the bone loading scores from the bone loading history questionnaire were 496.8±182.5 and 546.5±228.3 for the total hip and total spine, respectively.

DXA-derived aBMD and ABFLBM measures are presented in Table 3. Significant ($p<0.01$) differences between the loaded and non-loaded limbs existed at the UD radius, femoral neck, trochanter, and total hip sites, with no difference at the radius 33% site. Appendicular arm lean mass was significantly ($p<0.05$) greater in the loaded arm with no difference in lean mass between lower limbs.

Side to side limb comparisons of pQCT derived bone and muscle characteristics are presented in Table 4. Total and trabecular bone characteristics were analyzed in the radius 4% site only whereas total and cortical bone analyses were performed at the radius 66% and femur 50% sites. At the radius 4% site, the loaded limb had significantly ($p<0.05$ and $p<0.01$) greater total BMC and trabecular vBMD compared to the non-loaded radius. At the 66% site, no differences between limbs were found except in cortical vBMD ($p<0.05$). Analysis of the femur 50% site revealed significant inter-limb differences in total and cortical BMC, total and cortical bone area, as well as cortical thickness in favor of the loaded femur (slide leg). No significant ($p>0.05$) differences between limbs were found for MCSA at either the radius 66 or femur 50% sites.

Forearm MCSA and arm ABFLBM were both significantly related ($p<0.05$) to most bone variables in the 4% and 66% site of the forearm with the exception of total vBMD at both sites and cortical vBMD and cortical thickness at the 66% site. However, forearm MCSA was more strongly correlated with total and trabecular content (r=0.883, 0.940) and total and trabecular area (r=0.876, 0.801) at the 4% site, respectively. At the 66% site, forearm MCSA shared the strongest relationship with total and cortical content (r=0.815, 0.684) and total and cortical area (r=0.893, 0.772). At the femur 50% site, thigh MCSA had the strongest correlation with the measured bone parameters (r=0.657-0.742) with the exception of total and cortical vBMD, which were not significantly correlated ($p>0.05$).

Discussion

To the best of our knowledge, this is the first investigation that has examined muscle and bone adaptations to mechanical

Variable	Loaded	Non-Loaded	% Diff	*p* value
Radius 4%				
Total BMC (g/mm)	135.44±35.3	130.02±33.4	4.1±3.5	0.006
Total vBMD (g/cm^3)	419.33±64.7	414.98±54.5	0.8±6.1	0.599
Total Area (mm^2)	327.38±83.5	316.06±77.1	3.6±7.9	0.228
Trab BMC (g/mm)	62.03±24.7	57.78±25.7	9.7±15.2	0.135
Trab vBMD (g/cm^3)	258.84±57.1	247.78±57.2	4.8±5.9	0.025
Trab Area (mm^2)	235.76±73.8	225.78±65.3	4.6±12.4	0.346
Radius 66%				
Total BMC (g/mm)	115.51±27.1	111.68±23.6	3.3±7.5	0.187
Total vBMD (g/cm^3)	734.81±97.4	719.88±97.8	2.4±7.9	0.341
Total Area (mm^2)	160.51±47.1	156.86±36.2	1.6±12.5	0.579
Cort BMC (g/mm)	103.91±21.9	99.49±20.8	4.9±8.3	0.110
Cort vBMD (g/cm^3)	1128.96±38.6	1115.1±47.6	1.3±1.7	0.041
Cort Area (mm^2)	92.32±20.9	89.21±18.9	3.5±7.7	0.198
Cort Thickness (mm)	2.53±0.4	2.45±0.4	3.7±8.2	0.174
MCSA (mm^2)	4575.75±1252.8	4326.59±1233.1	6.6±10.9	0.108
Femur 50%				
Total BMC (g/mm)	555.80±108.1	514.99±98.6	8.2±9.3	0.029
Total vBMD (g/cm^3)	893.16±66.4	870.24±60.4	2.7±4.3	0.072
Total Area (mm^2)	624.11±121.7	593.52±114.2	5.2±5.3	0.015
Cort BMC (g/mm)	528.53±105.9	487.79±96.4	8.7±10.4	0.039
Cort vBMD (g/cm^3)	1123.85±18.4	1132.78±16.2	-0.8±1.4	0.117
Cort Area (mm^2)	470.40±94.2	431.18±88.6	9.6±10.8	0.028
Cort Thickness (mm)	7.14±1.1	6.57±0.90	9.0±10.8	0.028
MCSA (mm^2)	12950.46±2839.7	13058.34±2925.3	-0.7±4.7	0.574

Trab: Trabecular; Cort: Cortical; vBMD: Volumetric Bone Mineral Density; MCSA: Muscle Cross-sectional Area.

Table 4. Limb differences in pQCT variables.

loading using competitive ten-pin bowling athletes as a unilateral model. DXA and pQCT analyses revealed significant differences in several bone and muscle measurements between the loaded and non-loaded limbs of competitive ten-pin bowlers.

Ten-pin bowling is mostly enjoyed by the general public as a recreational league sport or an entertaining weekend activity. However, competitive bowlers train for their sport like any other athlete. This results in repetitive unilateral loading of the throwing arm as well as the slide leg. In order to generate a high revolution rate on the 6.81-7.27 kg bowling ball, the athlete must forcefully slide step followed by an abrupt planting of the slide leg as all body weight is transferred to the slide leg in order to release the ball down the lane[13]. Force data from the United States Bowling Congress's (USBC) biomechanics lab has shown that the slide leg is under considerable strain up to five times body weight (personal communication). The results of our lower limb analyses indicate that the slide leg adapts to these forces by changing bone mass and size. Compared to the non-loaded leg, aBMD of the total hip, trochanter, and femoral neck was significantly greater in the slide leg. Additionally, pQCT analyses revealed that the slide leg had greater total and cortical BMC as well as total and cortical bone area, and cortical wall thickness at the femur 50% diaphyseal site. Few sports entail unilateral loading of a lower limb. For this reason, studies examining side to side differences of the lower extremities in athletes are scarce. Wu and Colleagues (1998) found that the take-off hip of female gymnasts had 4-9% higher aBMD compared to the opposite hip and that ground reaction forces (GRF) were greater during take-off than landing. More recently, the femoral mid-diaphyses of the dominant leg in world class fencers were shown to have greater cortical wall thickness when compared to the non-dominant leg, an adaptation likely due to strain caused by the act of lunging[10]. These results taken with those of our study suggest that the diaphyses of the lower limbs adapt to mechanical strain, such as that experienced in lunging and bowling, by increasing bone area and cortical thickness. This would be a favorable adaptation, as an increase in bone area away from the center axis will increase its resistance to bending and torsion[15].

Several studies have been conducted examining bone adaptations to mechanical loading using side by side upper limb comparisons of competitive racquet and squash players. In competitive ten-pin bowlers, the aBMD of the loaded radius was only greater at the distal site with no difference at the mid-shaft site. This is in contrast to Haapasalo et al. (1994) and Kannus et al. (1994) who both reported 6-8% inter-limb differences in aBMD of the loaded radial mid-shaft of tennis and squash players[3,16]. Interestingly, using pQCT we found that cortical vBMD of the radial shaft was significantly greater (1.3%) in the loaded radius with no differences in bone area (total or cortical) or wall thickness. Again, this is different than what has been observed in studies employing pQCT to measure bone adaptations of the radius in tennis athletes. Ashizawa et al. (1999) reported that cortical vBMD was significantly lower (-0.08%) in the mid-shaft of the loaded radius whereas Haapasalo et al. (2000) found no difference between mid-shafts[7,8]. Furthermore, these authors reported large differences in bone geometry and size at the mid-shaft of the radius in the racquet arm. In a cross-sectional study between competitive female weight lifters and recreationally active counterparts, Heinonen and colleagues (2002) found that the weight lifters had significantly larger mid-shafts (cortical bone area and cortical wall thickness), but no difference in vBMD[17]. Several possibilities exist to why our data are not in line with others. The difference in limb loading patterns between ten-pin bowling and racquet sports, training volume and frequency, as well as starting age are all possible factors. Nara-Ashizawa and colleagues (2002) conducted a cross-sectional study using recreational tennis players who initiated playing after bone maturation had already occurred (>30yrs of age) and found that the adaptations in the loaded radius were different than in competitive tennis players who had started at a young age[18]. The tennis players who started playing after the age of 30 years did not have the markedly enlarged shaft, but instead had 8% higher cortical vBMD compared to the non-loaded limb. Although the results of our mid-shaft analyses are similar, the average age of our subjects was 30.6 years and average years of competition was 13.2 (Table 2), therefore our subjects had likely initiated bowling before skeletal maturation had occurred. Additionally, our subjects trained on average 3.5 days per week. It is most likely that the observed differences in the mid-shaft between our study and those evaluating competitive tennis players who started playing at a young age is due to the different mechanical loading patterns between the two activities. Tennis playing results in repetitive high-impact activity to the muscles and bones of the forearm through contact between the ball and racquet[19]. In bowling, the primary forces acting on the forearm bones are from muscle contractions during stabilization of the ball in backswing as well as the exaggerated supination to pronation required to generate high revolution rates on the bowling ball. One recent engineering study reported that some highly trained bowlers can generate up to 305 revolutions per minute on the bowling ball immediately before release[20]. While we are reporting a significant difference in cortical vBMD, it must be noted that this difference could be influenced by the partial volume effect. At the radial 66% shaft site, cortical thickness has been shown to affect the outcome of cortical vBMD with thin cortices resulting in underestimations of true cortical vBMD[21]. However, Prevrhal and colleagues (1999) found that cortical density measurements become inaccurate once cortical thickness drops below 2.2-2.5 mm[22]. Since the average cortical thickness of the dominant and non-dominant shafts (Table 4) in our bowlers are within this range, we believe this data has merit.

In our bowlers, total BMC and trabecular vBMD were significantly greater in the loaded distal radius compared to the non-loaded distal radius. Similar findings in tennis players were reported by Ashizawa et al. (1999) and Kontulainen et al. (2002)[8,11]. However, they also found larger bone area in the distal site of the radius in the loaded forearm compared to the non-loaded forearm[8,11]. Total bone area was also larger (3.6%) in the loaded distal radius of the bowlers; however this difference was not statistically significant (Table 4).

An interesting finding in our bowlers was that ABFLBM was greater in the throwing arm compared to the non-throwing arm. However, no difference in ABFLBM was found between legs. It is possible that the weight of the bowling ball provides enough of a stimulus to result in increased lean mass in the arm after long term exposure to bowling. Interestingly, the increase in arm BFLBM was not reflected in the forearm MCSA measurement. This would suggest that hypertrophy may occur in the muscles of the upper arm, especially since during the back swing the deltoid and triceps are activated and responsible for completing the movement while working against gravity.

There are several limitations to our study. First, our statistical analyses may be underpowered due to the number of subjects (N=10). A power analyses for a statistical power of 80% conducted using previous studies that examined many of the same variables in tennis players[7] and gymnasts[6] revealed an N with a range between 9-45. Additionally, our subjects are composed of men and women. Menstrual status and history was not determined. Therefore, it is possible that the observed differences are sex specific. While a unilateral model for studying bone adaptation can control for several confounding factors, it must be pointed out that the use of a control group is needed to substantiate whether the inter-limb differences observed were significant. Nevertheless, we believe that the data presented are of value and that future research with this population should address these limitations.

Conclusion

To the best of our knowledge, this is the first investigation to report musculoskeletal adaptations of the extremities in competitive ten-pin bowlers. This athletic population provides a unique unilateral model to study bone adaptation. Compared to the non-loaded side, the femoral shaft of bowlers adapts by increasing total and cortical bone area as well as cortical wall thickness. In the loaded forearm, the shaft of the radius adapts by increasing vBMD and the distal site by increasing trabecular vBMD. ABFLBM is increased in the loaded arm but not in the slide leg. These results provide further evidence that periods of intermittent mechanical loading, such as that experienced in competitive ten-pin bowling, is beneficial for bone adaptation.

Acknowledgements

The authors would like to thank Nick Bohanan and the United States Bowling Congress for their efforts in recruitment and the use of force data from their biomechanics laboratory.

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