J Musculoskelet Neuronal Interact 2010; 10(2):136-141

Hylonome

Original Article

Muscle cross sectional area and grip torque contraction types are similarly related to pQCT derived bone strength indices in the radii of older healthy adults

A.W. Frank, A.L. Lorbergs, P.D. Chilibeck, J.P. Farthing, S.A. Kontulainen

College of Kinesiology, University of Saskatchewan, Canada

Abstract

Objectives: We sought to identify the variance in radius bone strength indices explained by forearm muscle cross sectional area (MCSA) and isometric (ISO), concentric (CON), or eccentric (ECC) grip torque in healthy men and postmenopausal women when gender and body size were controlled for. Additionally we assessed variance in various grip contractions explained by MCSA. **Methods:** pQCT estimated bone strength of the radius and forearm MCSA were measured from 45 healthy adults (59.4 ± 7.2 yrs). Isokinetic dynamometry was used to assess peak grip torque. Regressions were adjusted for gender and radius length. **Results:** Peak grip torques were not independent predictors (p>0.05) of distal radius bone strength in compression (bone strength index; BSI_c) when gender was included in the prediction model. Gender was not a contributor to any model that included MCSA (p>0.05). At the diaphysis all torque measures, MCSA, gender, and length, significantly contributed to predict similar portions (79-80%) of the stress strain index (SSI_p; strength in torsion). MCSA accounted for 68-76% of variance in grip torque (p<0.05). **Conclusions:** When estimating radius bone strength, forearm MCSA is a comparable predictor to CON, ISO, & ECC grip torques and is also a good surrogate of these contraction types.

Keywords: Bone strength, Osteoporosis, pQCT, Concentric Torque, Eccentric Torque

Introduction

The distal radius (wrist) is a common site of osteoporotic fractures, accounting for 1.7 million annual fractures worldwide[1]. The increased incidence of wrist fractures coincides with a reduction in forearm bone mass and muscle force output with ageing[2-6]. However, less is known about the role of forearm muscle size and different muscle contraction types in determining estimated bone strength of the radius in older individuals.

Due to the considerable strains that hand gripping exerts on the bones of the forearm, handgrip measures have been used to assess the muscle-bone relationship at the radius[7-11]. However, all previous studies have used hand-held *isometric* gripping devices for their convenience and portability. These devices are limited to isometric force measures, neglecting both concentric (muscle shortening) and eccentric (muscle lengthening) dynamic contractions. Eccentric contractions produce the greatest muscle tension, which may place enough strain on the bone tissue to illicit an osteogenic response[12-14].

Bone strength variables are highly associated with body size (e.g. stature) and muscle force measures[15]. Both men and women have shown significant relationships for isometric grip force and polar Strength Strain Index (SSI_p) at the radius diaphysis[11], but less is known about the relationship between concentric or eccentric grip force and estimated bone strength at the distal radius[16]. For convenience, muscle cross sectional area (MCSA) is commonly used as a surrogate for muscular force[17-19]. In the forearm, MRI derived MCSA significantly (p<0.05) correlated (r=0.41) with variables of radius bone strength[20]. In the lower body, MCSA was correlated with isometric[17] as well as concentric and eccentric torques[18,19], however the utility of MCSA as a surrogate of these contraction types in the forearm is unknown. Furthermore, the relationship between muscle and bone strength does not appear to vary be-

The authors have no conflict of interest.

Corresponding author: S.A. Kontulainen, College of Kinesiology, University of Saskatchewan, 87 Campus Drive, Saskatoon, SK S7N5B2 Canada
E-mail: saija.kontulainen@usask.ca

Edited by: J. Rittweger
Accepted 3 March 2010

tween the genders in early to mid adulthood[21,22], however less is known about the influence of gender on this relationship in the forearm over age 40.

Thus, our primary objective was to investigate the variance in radial bone strength indices (SSI_p and compressive bone strength index; BSI_c) explained by forearm MCSA and isometric, concentric or eccentric grip torque in men and postmenopausal women over the age of 50. Our secondary objective was to assess forearm muscle area as a surrogate for forearm muscle torque by determining the variance in isometric, concentric or eccentric grip torque that was explained by a measure of MCSA in older adults. We hypothesized that each of the grip torque contraction types and MCSA would similarly improve the prediction of radius bone strength when gender and radius length are accounted for. It was further hypothesized that the predictive contribution of gender would be significant after including the parameters of either contraction torque or MCSA.

Age (yrs)	59.4 ± 7.2
Weight (kg)	76.6 ± 12.8
Height (cm)	166.6 ± 6.9
Rad. Length (mm)	256.9 ± 12.3
ISO (N·m)	60.7 ± 19.3[a]
CON (N·m)	45.6 ± 15.3[a]
ECC (N·m)	82.1 ± 24.5[a]
MCSA (mm^2)	3542.4 ± 911.5
BSI_C (mg^2/mm^4)	33.65 ± 17.12
SSI_p (mm^3)	319.9 ± 91.1
[a]*Grip torques significantly different from one another (p<0.001)*	

Table 1. Participant Characteristics (Mean ± SD); ISO: isometric torque, CON: concentric torque, ECC: eccentric torque, MCSA: muscle cross sectional area, BSI_c: bone strength index for compression, SSI_p: polar stress strain index.

Methods

Participants

Participants were recruited from the Saskatoon area via newspaper advertisements. We included participants who were 50 years of age or older; postmenopausal (defined as an absence of menstruation for at least 12 months); had forearm bone mineral density T-score (as measured by DXA, Hologic Inc.) above the osteoporotic threshold[23]; had no previous fragility fractures or musculoskeletal conditions (i.e. arthritis or carpal tunnel syndrome); and were not involved in strength training or racquet sports. Initially 58 participants were recruited for study. Informed consent was obtained from all participants prior to testing and approval was obtained from the University of Saskatchewan Biomedical Research Ethics Board.

Anthropometric Measures

Subject height was measured by a wall-mounted stadiometer accurate to ± 1 mm and weight (lightly clothed) from a digital scale accurate to ± 0.05 kg. Forearm length was measured using an anthropometric tape measure from the lateral border of the proximal head of the radius to the distal end of the of the radius styloid process (Stylon)[24]. All anthropometric landmarks were palpated, measures were repeated three times, and the mode or median value was recorded.

Muscle Torque Measures

We measured maximum voluntary contractions of each hand with isokinetic dynamometry (Humac NORM, CSMi, Stoughton, MA). Participants were tested in a standing position to better resemble a typical hand-held isometric grip force measure. Participants stood with feet shoulder width apart and the isokinetic dynamometer positioned with the handle in a comfortable position alongside the body. The arm and shoulder joints were in a slightly flexed position and the forearms neutral. No straps were utilized to secure participants, but postural compensations were monitored and corrected by the technician. Two measures were taken on separate days to control for practice effects and calculate precision (CV_{rms}, %) for the protocol. The isokinetic dynamometry protocol included isometric (ISO), concentric (CON, 15˚/s, [0.262 rad/s]), and eccentric (ECC, 15˚/s) handgrip contractions administered in a randomized order, with each test trial preceded by a practice contraction. Three maximum exertions were performed for each contraction type. Thirty seconds rest was provided after the practice contraction and thirty-second rest intervals were given between each recorded repetition. The highest peak torque (N·m) for each contraction type was used for analysis. Precision for this protocol was calculated from measures of three separate exertions within the same 20 participants. The lab precision (CV_{rms}, %) for isometric, eccentric, and concentric handgrip peak torques was 7.3, 6.6, and 8.2%, respectively.

Bone Measures

Peripheral quantitative computed tomography (pQCT; Stratec, XCT 2000) was used to measure estimated bone strength of the non-dominant and dominant radius. All measurements and analyses were performed by one trained operator. Planar scout views over the joint line were used to place the reference line at the medial tip of the distal radius endplate. Distal to the reference line, we scanned a single 2.4 mm thick tomographic slice at the distal radius (4% of forearm length) and radius shaft (65% of forearm length). These sites were selected for their clinical relevance and anatomical suitability for our bone and muscle variables[22].

We analyzed total bone density and area from the 4% site using Contour mode 1 (including voxels with densities ≥480 mg/cm^3). Distal radius bone strength at the 4% site was estimated by calculating bone strength index in compression (BSI_c, mg^2/mm^4)[16]. BSI_c is a product of squared total bone density and total area[16,25].

	BSI_C (mg^2/mm^4)			SSI_p (mm^3)		
	R^2 Adj.	ß	$r_{partial}$	R^2 Adj.	ß	$r_{partial}$
Model	**0.40**			**0.76**		
Length		0.10	0.10		0.41[a]	0.56
Gender		-0.59[a]	-0.52		-0.56[a]	-0.67
ISO Model	**0.38**			**0.79**		
Grip force		0.09	0.07		0.33[a]	0.40
Length		0.07	0.07		0.32[a]	0.47
Gender		-0.53[a]	-0.39		-0.35[a]	-0.43
CON Model	**0.39**			**0.80**		
Grip force		0.16	0.12		0.39[a]	0.45
Length		0.06	0.06		0.32[a]	0.49
Gender		-0.48[a]	-0.35		-0.30[a]	-0.38
ECC Model	**0.42**			**0.79**		
Grip force		0.29	0.25		0.32[a]	0.42
Length		0.02	0.02		0.32[a]	0.48
Gender		-0.42[a]	-0.35		-0.38[a]	-0.49
MCSA Model	**0.43**			**0.80**		
MCSA		0.45	0.28		0.46[a]	0.45
Length		-0.004	-0.004		0.31[a]	0.47
Gender		-0.26	-0.175		-0.23	-0.25

[a]Significance ($p<0.05$) Males =1 Females =2

Table 2. Adjusted coefficients of determination (R^2 Adj.), standardized beta values (ß) and partial correlation coefficients ($r_{partial}$) for isometric (ISO), concentric (CON), eccentric (ECC) grip torque, and muscle cross-sectional area (MCSA) prediction models for the dependent variables bone strength index (BSI_C) at the distal radius and strength strain index (SSI_P) at the shaft.

At the 65% shaft, we analyzed cortical bone area with Separation mode 4 (including voxels with densities ≥480 mg/cm^3) and estimated bone strength with stress strain index in torsion (SSI_p, mm^3) calculated from cortical bone area by pQCT software (Stratec XCT 6.0)[26,27].

We determined MCSA by subtracting both radius and ulna total areas from the whole limb cross sectional area that was determined with Contour mode 1 (including voxels ≥40 mg/cm^3). We used muscle filter C02 to enhance muscle area detection. Precision of bone and muscle measures was calculated from duplicate scans of 49 adults. Repeatability (CV_{rms}, %) of pQCT derived BSI_c, SSI_p, and MCSA at the forearm were approximately 11.7%, 4.3%, and 1.4% respectively.

Statistical Analysis

Statistical analysis was performed using SPSS v.17.0 for Windows. Measures of the right and left arm were averaged for each subject and both genders were pooled together. It has been shown that gender has no effect on the muscle-bone strength relationship in young adults[21,22], however the influence of gender in older adults is unknown. Therefore a forced entry multiple regression analysis included both gender and radius length to account for any variation gender, and body size[28] in these older adults. MCSA, ISO, CON, or ECC peak grip torques were independently added to the model to explain variance in the BSI_c and SSI_p. Similarly, the ability of MCSA to predict ISO, CON and ECC grip peak torque was assessed with multiple regression models including both gender and radius length into the model prior to entering MCSA. Peak torque values from the three grip contraction types were compared with a repeated measures ANOVA. An alpha level <0.05 was considered significant in all statistical comparisons.

Results

Of the 58 participants recruited for the study, 12 did not meet the inclusion criteria. A total of 46 participants completed all measurements. Regression diagnostics indicated a participant with a standardized residual for the prediction of SSI_p exceeding ±3SD and she was removed from our data. Therefore data from 15 healthy males (mean age 63.9 ± SD 7.5 yrs) and 30 healthy females (57.2 ± 6.0 yrs) were included in the current cross-sectional comparison. The mean peak torques recorded for ISO, CON, and ECC contractions were significantly different ($p<0.001$) from one another, with ECC>ISO>CON (Table 1).

BSI_c and Handgrip Measures

The three direct measures of handgrip torque (ISO, CON, & ECC peak torque) were not significant ($p<0.05$) contributors to their respective prediction models for BSI_c at the radial epiphysis (Table 2). In these models only gender was a significant predictor of BSI_c. Radius length did not contribute ($p>0.05$) to any of the BSI_c prediction models. The independent contribu-

Dependent	R^2 Adj.	Independent	ß	$r_{partial}$
ISO (N·m)	**0.74**			
		MCSA	0.65^a	0.53
		Length	0.12	0.18
		Gender	-0.16	-0.16
CON (N·m)	**0.76**			
		MCSA	0.68^a	0.56
		Length	0.07	0.12
		Gender	-0.17	-0.18
ECC (N·m)	**0.68**			
		MCSA	0.72^a	0.53
		Length	0.12	0.16
		Gender	-0.04	-0.04
[a]Significance (p<0.001) Males =1 Females =2				

Table 3. Adjusted coefficients of determination (R^2 Adj.), standardized beta values (ß) and partial correlation coefficients ($r_{partial}$) of muscle cross-sectional area (MCSA) prediction models for isometric (ISO), concentric (CON) and eccentric (ECC) grip force measures.

tion of MCSA for predicting variance in BSI_c, approached significance (p=0.07). However, none of the predictor variables, including gender (p=0.26) were significant contributors in the MCSA model. The MCSA and ECC models predicted 43% and 42% of the variance in distal radius BSI_c. The ISO and CON models both predicted 38% and 39% of the variance in distal radius BSI_c, respectively.

SSI_p and Handgrip Measures

Contrary to the prediction models for BSI_c, in the direct handgrip models, gender, forearm length, ISO, CON, and ECC significantly (p<0.05) contributed to the prediction of SSI_p at the radius diaphysis (Table 2). This was also true of MCSA and radius length in the MCSA model, however gender was not a significant (p<0.05) contributor to the prediction of SSI_p. The CON, ECC, ISO, and MCSA models each predicted 79-80% of the variance in radius SSI_p.

MCSA and Handgrip Peak Torque

MCSA contributed significantly (p<0.001) to each of the handgrip contraction types (Table 3). The MCSA, length and gender model predicted 76% of the variance CON grip peak torque, as well as 74% and 68% of the variance in ISO and ECC grip peak torque respectively (Table 3). Neither radius length nor gender were significant (p>0.05) predictors for the handgrip peak torques.

Discussion

Our primary objective was to investigate the variance in radius bone strength indices (SSI_p & BSI_c) explained by forearm muscle area and isometric, concentric or eccentric grip torque in men and postmenopausal women over the age of 50. To the best of our knowledge, this is the first study to examine the relationships between the three types of handgrip contractions and the surrogate force measure of MCSA in the forearm. The additional grip torque measures are of clinical importance because unlike concentric and isometric torque, the capacity for eccentric torque is better maintained with advancing age[29-32], making eccentric exercises attractive for potential exercise interventions aiming to prevent bone fragility.

At the distal radius all measures of grip torque and MCSA were unable to significantly contribute to multiple regression models that included both gender and radius length as prediction variables. This is particularly interesting because our sample of men and women demonstrated the expected hierarchy of contraction forces (ECC>ISO>CON)[33]. Our results also demonstrated that while no variable significantly contributed, the combination of MCSA, length, and gender was capable of predicting up to 43% of the variance in BSI_c at the 4% distal radius site.

Boonen et al. demonstrated that isometric grip force was not an independent predictor of trabecular density[34]; the primary component of the BSI_c. Our results expand the notion that ISO, as well as ECC and CON torques and the MCSA force surrogate are not significant independent contributors to the prediction of variance in BSI_c at the distal radius.

When predicting BSI_c at the distal radius gender appeared to be more influential than any grip contraction or radius length (an anthropometric surrogate for body size). Differences in the structure and density of trabeculae at the distal radius may explain the influence of gender on BSI_c. Khosla et al. utilized high-resolution pQCT on 602 individuals who were 21-97 years of age and found that men have thicker trabeculae than women across the adult life span with greater differences following menopause[35].

Our results at the 65% radius diaphysis demonstrated that MCSA, isokinetic and isometric grip torques similarly predicted the estimated resistance for torsional forces (SSI_p) in the radial shaft. These findings were in agreement with Kaji et al. who found significant (p<0.001) correlations (r=0.31 to 0.45) between isometric grip force and radial midshaft SSI_p in men and women[11]. Specker et al. also demonstrated significant grip force contributions to variance in female radius SSI_p[15]. Furthermore, with the exception of gender in our MCSA model, both gender and radius length significantly contributed to the prediction of SSI_p. While it was hypothesized that gender would have significant contributions to both grip torque and MCSA models, the inability of gender to significantly contribute to the diaphyseal MCSA model was not entirely surprising as both gender and SSI_p of the radius midshaft are highly related to MCSA[10]. However, our data suggested that this relationship is not limited to the radial midshaft and SSI_p. The inclusion of MCSA in our prediction models removed more than half of the base model unique variance accounted for by gender in both the BSI_c ($r_{partial}$= -0.52 to -0.175) and SSI_p ($r_{partial}$= -0.67 to -0.25). This is in agreement with claims that bone size (a factor in both BSI_c and SSI_p) is more dependent on MCSA and specific muscular tension than gender[21,22].

Our secondary objective was to assess forearm muscle area as a surrogate of forearm muscle torque by determining the variance in isometric, concentric or eccentric grip torques explained by MCSA in older adults. MCSA predicted 68-76% of the voluntary contraction torques, and neither gender nor forearm length were a significant contributor to the models (Table 3). These findings are in accordance with MCSA-torque relationships demonstrated in the lower extremity[17-19]. Furthermore, significant covariance between MCSA and all of the contraction types suggests a shared genetic action between them[36]. Based on our results, there is potential for MCSA to serve as a reliable surrogate of all three grip torque measures in adults over the age of 50.

It is important to note that cross-sectional design and small sample size are the main limitations of our study. A study with a larger sample size would be able to draw stronger conclusions regarding the relevance of MCSA and ISO, CON, and ECC contraction types in predicting radius bone strength. Randomized, controlled trials with contraction type specific resistance training are needed to assess the influence of muscle contraction types on pQCT-derived bone strength in the forearms of older adults.

Our results provide insight on the relationship between different measures of handgrip contraction torque and radius bone strength. Importantly, our findings demonstrated that MCSA at the 65% radius is a reliable surrogate of all three measures of grip torque. This information is useful for researchers and clinicians who use tomographic imaging for characterizing and comparing bone structure and strength in different aged populations.

Summary

Grip torques do not appear to be significant independent contributors to distal radius bone strength (BSI_c) when body size and gender are accounted for. The ability of forearm MCSA to significantly contribute to the prediction of variance in distal radius BSI_c requires further investigation. At the radius shaft MCSA and CON, ISO, ECC grip torques predicted bone strength (SSI_p) similarly. Forearm MCSA also predicted grip peak torque for all contraction types, and thus, forearm MCSA is a valid surrogate of peak grip torques in healthy older adults.

Acknowledgements

We thank all the volunteers for their participation to the study. Financial support to conduct of this study was provided by the Canadian Foundation for Innovation (CFI/LOF), the Saskatchewan Health Research Foundation (SHRF) and the Canadian Institutes of Health Research (CIHR).

References

1. Johnell O, Kanis JA. An estimate of the worldwide prevalence and disability associated with osteoporotic fractures. Osteoporosis Int 2006;17(12):1726-33.
2. Kritz-Silverstein D, Barrett-Connor E. Grip strength and bone mineral density in older women. J Bone Miner Res 1994;9(1):45-51.
3. Kallman DA, Plato CC, Tobin JD. The role of muscle loss in the age-related decline of grip strength: Cross-sectional and longitudinal perspectives. J Gerontol 1990; 45(3):M82-8.
4. Guglielmi G, De Serio A, Fusilli S, Scillitani A, Chiodini I, Torlontano M, et al. Age-related changes assessed by peripheral QCT in healthy Italian women. Eur Radiol 2000;10(4):609-14.
5. Butz S, Wuster C, Scheidt-Nave C, Gotz M, Ziegler R. Forearm BMD as measured by peripheral quantitative computed tomography (pQCT) in a German reference population. Osteoporosis Int 1994;4(4):179-84.
6. Gatti D, Rossini M, Zamberlan N, Braga V, Fracassi E, Adami S. Effect of aging on trabecular and compact bone components of proximal and ultradistal radius. Osteoporosis Int 1996;6(5):355-60.
7. Ducher G, Jaffre C, Arlettaz A, Benhamou CL, Courteix D. Effects of long-term tennis playing on the muscle-bone relationship in the dominant and nondominant forearms. Can J Appl Physiol 2005;30(1):3-17.
8. Tsuji S, Tsunoda N, Yata H, Katsukawa F, Onishi S, Yamazaki H, Relation between grip strength and radial bone mineral density in young athletes. Arch Phys Med Rehabil 1995;76(3):234-8.
9. Van Pottelbergh I, Goemaere S, Nuytinck L, De Paepe A, Kaufman JM. Association of the type I collagen alpha1 Sp1 polymorphism, bone density and upper limb muscle strength in community-dwelling elderly men. Osteoporos Int 2001;12(10):895-901.
10. Hasegawa Y, Schneider P, Reiners C. Age, sex, and grip strength determine architectural bone parameters assessed by peripheral quantitative computed tomography (pQCT) at the human radius. J Biomech 2001;34(4):497-503.
11. Kaji H, Kosaka R, Yamauchi M, Kuno K, Chihara K, Sugimoto T. Effects of age, grip strength and smoking on forearm volumetric bone mineral density and bone geometry by peripheral quantitative computed tomography: Comparisons between female and male. Endocr J 2005;52(6):659-66.
12. Frost HM. Vital biomechanics: Proposed general concepts for skeletal adaptations to mechanical usage. Calcif Tissue Int 1988;42(3):145-56.
13. Frost HM. Bone's mechanostat: A 2003 update. Anat Rec 2003;275a(2):1081.
14. Wright JE, Mawdsley RH, Braun J, Knapik JJ. Isokinetic, isotometric and isotonic strength relationships. Arch Phys Med Rehabil 1983;64(2):77.
15. Specker B, Binkley T, Fahrenwald N. Rural versus nonrural differences in BMC, volumetric BMD, and bone size: A population-based cross-sectional study. Bone 2004;35(6):1389-98.
16. Kontulainen SA, Johnston JD, Liu D, Leung C, Oxland TR, McKay HA. Strength indices from pQCT imaging predict up to 85% of variance in bone failure properties at tibial epiphysis and diaphysis. J Musculoskelet Neuronal Interact 2008;8(4):401-9.

17. Maughan RJ, Watson JS, Weir J. Strength and cross-sectional area of human skeletal muscle. J Physiol 1983;338:37-49.
18. Higbie EJ, Cureton KJ, Warren GL 3rd, Prior BM. Effects of concentric and eccentric training on muscle strength, cross-sectional area, and neural activation. J Appl Physiol 1996;81(5):2173-81.
19. Akima H, Kuno S, Takahashi H, Fukunaga T, Katsuta S. The use of magnetic resonance images to investigate the influence of recruitment on the relationship between torque and cross-sectional area in human muscle. Eur J Appl Physiol 2000;83(6):475-80.
20. Klein CS, Allman BL, Marsh GD, Rice CL. Muscle size, strength, and bone geometry in the upper limbs of young and old men. J Gerontol A Biol Sci Med Sci 2002;57(7):M455-9.
21. Rittweger J, Beller G, Ehrig J, Jung C, Koch U, Ramolla J, et al. Bone-muscle strength indices for the human lower leg. Bone 2000;27(2):319-26.
22. Neu C, Rauch F, Rittweger J, Manz F, Schoenau E. Influence of puberty on muscle development at the forearm. Am J Physiol Endocrinol Metab. 2002;283(1):E103-7.
23. Brown J, Josse R. 2002 clinical practice guidelines for the diagnosis and management of osteoporosis in Canada. CMAJ 2002;167(10 Suppl):S1.
24. International Society for the Advancement of Kinanthropometry. International standards for anthropometric assessment. Canberra: ISAK; 2001.
25. Carter DR, Bouxsein ML, Marcus R. New approaches for interpreting projected bone densitometry data. J Bone Miner Res 1992;7(2):137-45.
26. Schiessl H, Ferretti JL, Tysarczyk-Niemeyer G, Willnecker J. Noninvasive bone strength index as analyzed by peripheral quantitative computed tomography (pQCT). In: Schoenau E, editor. Paediatric osteology: New developments in diagnostics and therapy. Amsterdam: Elsevier; 1996. p. 141-6.
27. Ashe MC, Khan KM, Kontulainen SA, Guy P, Liu D, Beck TJ, et al. Accuracy of pQCT for evaluating the aged human radius: an ashing, histomorphometry and failure load investigation. Osteoporos Int 2006;17(8):1241-51.
28. Sumnik Z. The muscle-bone unit in adulthood: Influence of sex, height, age and gynecological history on the bone mineral content and muscle cross-sectional area. J Musculoskelet Neuronal Interact 2006;6(2):195-200.
29. Vandervoort AA, Kramer JF, Wharram ER. Eccentric knee strength of elderly females. J Gerontol 1990;45(4):B125.
30. Porter MM, Vandervoort AA. Standing strength training of the ankle plantar and dorsiflexors in older women, using concentric and eccentric contractions. Eur J Appl Physiol Occup Physiol 1997;76(1):62-8.
31. Porter MM, Vandervoort AA, Kramer JF. Eccentric peak torque of the plantar and dorsiflexors is maintained in older women. J Gerontol A Biol Sci Med Sci 1997; 52(2):B125-31.
32. Hortobagyi T, Zheng D, Weidner M, Lambert NJ, Westbrook S, Houmard JA. The influence of aging on muscle strength and muscle fiber characteristics with special reference to eccentric strength. J Gerontol A Biol Sci Med Sci 1995;50(6):B399-406.
33. Pousson M, Lepers R, Van Hoeke J. Changes in isokinetic torque and muscular activity of elbow flexors muscles with age. Exp Gerontol 2001;36(10):1687-98.
34. Boonen S, Cheng XG, Nijs J, Nicholson PH, Verbeke G, Lesaffre E, et al. Factors associated with cortical and trabecular bone loss as quantified by peripheral computed tomography (pQCT) at the ultradistal radius in aging women. Calcif Tissue Int 1997;60(2):164-70.
35. Khosla S, Riggs BL, Atkinson EJ, Oberg AL, McDaniel LJ, Holets M, et al. Effects of sex and age on bone microstructure at the ultradistal radius: a population-based noninvasive *in vivo* assessment. J Bone Miner Res 2006;21(1):124-31.
36. De Mars G, Thomis MA, Windelinckx A, Van Leemputte M, Maes HH, Blimkie CJ, et al. Covariance of isometric and dynamic arm contractions: Multivariate genetic analysis. Twin Res Hum Genet 2007;10(1):180-90.