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Greater association of peak neuromuscular performance with cortical bone geometry, bone mass and bone strength than bone density: A study in 417 older women

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ABSTRACT

Background: We evaluated which aspects of neuromuscular performance are associated with bone mass, density, strength and geometry.
Methods: 417 women aged 60–94 years were examined. Countermovement jump, sit-to-stand test, grip strength, forearm and calf muscle cross-sectional area, areal bone mineral content and density (aBMC and aBMD) at the hip and lumbar spine via dual X-ray absorptiometry, and measures of volumetric vBMC and vBMD, bone geometry and section modulus at 4% and 66% of radius length and 4%, 38% and 66% of tibia length via peripheral quantitative computed tomography were performed. The first principal component of the neuromuscular variables was calculated to generate a summary neuromuscular variable. Percentage of total variance in bone parameters explained by the neuromuscular parameters was calculated. Step-wise regression was also performed.
Results: At all pQCT bone sites (radius, ulna, tibia, fibula), a greater percentage of total variance in measures of bone mass, cortical geometry and/or bone strength was explained by peak neuromuscular performance than for vBMD. Sit-to-stand performance did not relate strongly to bone parameters. No obvious differential in the explanatory power of neuromuscular performance was seen for DXA aBMC versus aBMD. In step-wise regression, bone mass, cortical morphology, and/or strength remained significant in relation to the first principal component of the neuromuscular variables. In no case was vBMD positively related to neuromuscular performance in the final step-wise regression models.
Conclusion: Peak neuromuscular performance has a stronger relationship with leg and forearm bone mass and cortical geometry as well as proximal forearm section modulus than with vBMD.

1. Introduction

It is well established that bone mineral density (BMD) is related to, or can be modulated by, physical activity [1,2], local muscular force generation capacity [3,4], local muscle size [5–8] and peak explosive power [5]. This has been investigated in a number of populations such as children [5,6,8], adolescents [6], young adults [1], athletes [7] and individuals up into their 9th decade of life [2–4].

However, differences in bone properties are not adequately explained by bone mineral density alone as bone geometry plays an important role [6]. This dependency has been investigated in some cross-sectional studies. For example in pre-pubertal children [5], measures of muscle size and power were related to the derived polar strength-strain index, but not to volumetric BMD (vBMD) as measured via peripheral quantitative computed tomography (pQCT) of the tibial shaft. In female tennis players [7], muscle area was associated with total bone and cortical area and polar second moment of area at the humeral shaft as measured by magnetic resonance imaging and dual X-ray absorptiometry (DXA). In another study of pre-pubertal girls [8], lean tissue mass was the most predictive of bone strength, geometry and areal bone mineral content (BMC) versus other muscle related factors as measured by DXA at the femoral neck. In children, adolescents and

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adults up to the age of 35 [9], muscle CSA, muscle force, body weight, physical activity were independently associated with polar section modulus, periosteal circumference and cortical area of the tibial shaft but none of the load co-variates were associated with tibial shaft vBMD as measured by pQCT. Whilst the relationship of bone density to physical capacity has been relatively well investigated, further work is needed to better understand the relationship to broader bone characteristics. Specifically, we wanted to better understand which aspects of bone density, mass and geometry are most related to, or most influenced by, neuromuscular function.

In the current investigation we considered the relationship between physical capacity (grip strength, jumping), forearm and calf muscle size to bone mineral density, bone mass, bone geometry and derived measures of bone strength in women aged 60 to 95 years of age. This investigation was conducted on the basis of data collected as part of the larger "Bus-tour" study [10].

2. Material and methods

2.1. Study-design, setting, participants and ethical clearance

The study was designed to recruit a representative cross-sectional database of the female population aged 60 to 95 years in Germany [10]. For this purpose, all testing devices were loaded onto a truck and a team from the Center of Muscle and Bone Research toured through twenty German cities. The cities were spread throughout Germany. Subjects were recruited via the local media and came to the testing facility for screening and subsequent testing. Subjects were excluded if they used any kind of walking aid, had bilateral hip replacement, or underwent current or prior fluoride therapy. The study was approved by the ethical committee of the Charité University Medical School Berlin and the radiological examinations were approved by the German Federal Agency for Radiation Protection. All subjects gave their informed written consent prior to participation in the study.

We aimed to include at least 180 women in each of the age ranges 60–64 years, 65–70 years, 70–74 years, 75–79 years and 80 years and above. A total of 1211 subjects were included in the study. 947 subjects completed both functional testing and DXA measures with 417 subjects also completing pQCT measures. We report on these 417 subjects who completed all measures. Subject descriptive characteristics are reported in Supplementary Tables 1 to 3. Selecting the 947 subjects that completed all DXA and functional measures for the analysis did not change the main outcomes for the DXA data (see Supplementary Table 4).

2.2. Peripheral quantitative computed tomography

An XCT 2000 (Stratec Medizintechnik, Pforzheim, Germany) was used to obtain pQCT scans from the left lower leg and the left forearm. An earlier publication [11] describes the measurement and analysis approach in detail. In short, scout-views were generated in the frontal plane to identify the tibio-talar and radio-carpal clefts to position the reference line. Sectional images were then obtained at 4% (distal epiphysis), 38% (diaphysis; lower-leg only) and 66% (diaphysis) of tibia and 4% and 66% of ulnar length. At the 4% site, total vBMC, total vBMD and total bone area were measured. At more proximal sites (38% and 66% at the lower-leg, 66% at the forearm) total vBMC, total vBMD, total bone area, cortical vBMD, cortical area, cortical thickness, endosteal circumference, periosteal circumference, derived section modulus and muscle area were measured. The radius, ulna, tibia and fibula were assessed. The analysis was done using software version 6.2 with the default parameter settings.

2.3. Dual X-ray absorptiometry

The lumbar spine (L1–L4 in anteroposterior projection), proximal femur (total) and femoral neck were measured via dual X-ray absorptiometry (DXA) with a Lunar Prodigy (General Electric Company, Waukesha, Wisconsin, USA). Areal bone mineral content (aBMC in g) density (aBMD in g/cm^2) and the T-score at each region were calculated. The left hip was measured. If a prior hip replacement was present on the left side, then the right hip was scanned. All scans were performed according to the manufacturer's standard operating protocol.

2.4. Neuromuscular function

2.4.1. Grip strength

Testing was performed in standing using a digital hand dynamometer (Takei Scientific Instruments Co. Ltd., Tokyo, Japan). The shoulder was placed in an adducted and neutrally rotated position with the elbow in full extension [12]. Three repetitions were performed on the left hand with a 30 s break between tests. The highest value (in kilograms) from the three attempts was used in further analysis.

2.4.2. Countermovement jump

Maximal countermovement jump testing was performed on a ground reaction force platform (Leonardo Mechanograph GRFP, Novotec GmbH, Pforzheim, Germany). Subjects first stood on the 66 × 66 cm testing platform with their hands resting on their hips. Before the first jump, the subject's body mass was measured for use in subsequent calculations. Subjects were then instructed to perform a countermovement (i.e. a brief squat beforehand) jump and encouraged to jump as high as possible. The subject was instructed to retain their hands on their hips. Three jumps were performed during each testing session with a break of 1 min between each jump. Software provided by the manufacturer (Leonardo Mechanography version 2.01) was used for recording and storage of data and for subsequent calculation of the variables of interest. The peak jump power was calculated.

2.4.3. Sit-to-stand

Five repetitions from a seated-to-standing posture beginning at 45 cm seated height were performed as quickly as possible [13]. Subjects were required to cross their arms on their chest and complete knee extension had to be performed for each repetition. Tests were performed from a sitting surface anchored on the ground reaction platform used in the countermovement jump testing. The same software as in countermovement jump testing was used to measure the total duration of time required to perform the task. The operator supervised correct performance of the test. The operator also counted the repetition number loudly for the subjects and encouraged them to perform tests as quickly as possible. The test was performed once. A test was stopped and repeated once if (a) the subject did not maintain the required arm position and so used arm momentum to aid the sit-to-stand motion, or (b) the knee or hip were not completely straightened in standing. Total time in seconds for the five repetitions was used in further analysis.

2.5. Principal component analysis and statistical analyses

To reduce the potential impact of collinearity in the analysis, the first principal component of the neuromuscular variables was calculated. Following the rationale presented by Calavalle et al. [14], the neuromuscular variables (grip strength, sit-to-stand time, countermovement jump power, calf muscle area, forearm muscle area) were pooled using varimax principal component analysis (PCA) scaling the individual values to a mean of 0, and variance of 1. The first principal component is reported as a summary descriptor of neuromuscular performance, and was calculated for each individual from the factor loadings as $C = A * B$, where C = a N by 1 column vector of the 1st principal component values for the individuals, A = N by 5 matrix of individual values in neuromuscular performance scaled to a mean of 0 and a variance of 1, B = a 5 by 1 column vector of varimax 1st principal component loadings, and N = number of participants. The first principal component correlated most strongly with grip strength (Pearson's $r = 0.54$, $p <$