

Association of Jumping Mechanography-Derived Indices of Muscle Function with Tibial Cortical Bone Geometry

Charlotte Verroken¹ · Hans-Georg Zmierzak¹ · Stefan Goemaere¹ · Jean-Marc Kaufman¹ · Bruno Lapauw¹

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Abstract Jumping mechanography has been developed to estimate maximum voluntary muscle forces. This study assessed associations of jumping mechanography-derived force and power measurements with tibial cortical bone geometry, compared to other estimates of muscle mass, size, and function. Healthy men ($n = 181$; 25–45 years) were recruited in a cross-sectional, population-based sibling-pair study. Muscle parameters include isokinetic peak torque of the quadriceps, DXA-derived leg lean mass, mechanography-derived peak jump force and power, and pQCT-derived mid-tibial (66 %) muscle cross-sectional area (CSA). Mid-tibial cortical bone parameters were assessed by pQCT. In age, height, and weight-adjusted analyses, jump force and power correlated positively with cortical bone area, cortical thickness, and polar strength-strain index (SSIp) ($\beta = 0.23$ – 0.34 , $p \leq 0.001$ for force; $\beta = 0.25$ – 0.30 , $p \leq 0.007$ for power) and inversely with endosteal circumference adjusted for periosteal circumference (EC_{PC}) ($\beta = -0.16$, $p < 0.001$ for force; $\beta = -0.13$, $p = 0.007$ for power). Force but not power correlated with cortical over total bone area ratio ($\beta = 0.25$, $p = 0.002$). Whereas leg lean mass correlated with all cortical parameters except cortical over total bone area ratio ($\beta = 0.25$ – 0.62 , $p \leq 0.004$), muscle CSA only correlated with cortical bone area, periosteal circumference, and SSIp ($\beta = 0.21$ – 0.26 , $p \leq 0.001$), and quadriceps torque showed no significant correlations with the bone parameters. Multivariate models indicated that leg

lean mass was independently associated with overall bone size and strength reflected by periosteal and endosteal circumference and SSIp ($\beta = 0.32$ – 0.55 , $p \leq 0.004$), whereas jump force was independently associated with cortical bone size reflected by EC_{PC}, cortical thickness, and cortical over total bone area ratio ($\beta = 0.13$ – 0.28 ; $p \leq 0.002$). These data indicate that jumping mechanography provides relevant information about the relationship of muscle with bone geometry.

Keywords Jumping mechanography · Peak force · Mechanical loading · Bone geometry · Bone strength · Male · Pqct

Introduction

The strength of a bone depends on its material properties on the one hand and on the amount of bone tissue and its distribution in the bone organ (architectural properties or bone geometry) on the other hand [1]. In healthy subjects the material properties vary little with age and are only in part affected by external factors, whereas the amount of bone tissue and its geometry largely depend on lifelong modeling processes activated by mechanical load-induced deformations (strains) [2, 3], besides factors such as hormone exposure, inflammatory status, co-morbidities, and drug use. In everyday life, the largest strains result from regional muscle contractions [4–7]. When investigating functional muscle–bone relationships, it is therefore important to evaluate the maximum forces that can be produced by the muscles acting on the bone in question [8]. However, since maximum intrinsic muscle forces cannot be directly measured under in vivo conditions, estimates of muscle mass or size (e.g., muscle volume, cross-sectional

✉ Charlotte Verroken
charlotte.verroken@ugent.be

¹ Unit for Osteoporosis and Metabolic Bone Diseases, Department of Endocrinology, Ghent University Hospital, De Pintelaan 185, 9K12IE, 9000 Ghent, Belgium

area (CSA), or lean mass) as well as estimates of isokinetic muscle function (e.g., peak torque) have been frequently used as surrogate markers. Nonetheless, their reflection of maximum voluntary muscle force or their practical use is often limited and as such, the use of these assessments in the evaluation of muscle–bone relationships is rather questionable. More recently, jumping mechanography has been proposed as a more accurate method to estimate the maximum intrinsic forces that can be voluntarily generated in the leg musculature, by measuring ground reaction forces [8]. This technique is highly reproducible and can be safely used in populations covering a wide range of age and body size [9–12].

According to the mechanostat theory [2], strains caused by muscle forces influence bone geometry, and therefore, mechanography-derived muscle force estimates might correlate better with bone geometry than regional muscle mass, volume, CSA, or peak torque. Although previous studies have indeed shown positive associations of peak jump force and/or power with bone size and strength [13–18], studies comparing jumping mechanography to other estimates of muscle size and function are scarce and inconclusive [13–15, 17]. Moreover, some of these studies used noncommercial ground reaction force plates [14–16] or suboptimal jump procedures [13–16], failed to account for body mass [14, 15, 17], or investigated specific populations [13, 18]. The present study therefore aims to examine the associations of mechanography-derived peak jump force and power, as compared to other commonly used muscle mass, size, and function estimates, with tibial cortical bone geometry in young, healthy men. We hypothesized that (1) peak jump force would correlate better with bone geometry than peak jump power, as strains are caused by force and not power, and that (2) peak jump force would correlate better with bone geometry and strength than other muscle size and function estimates only indirectly associated with strain.

Subjects and Methods

Subjects

This study is part of a population-based study (SIBLOS) designed to investigate determinants of peak bone mass in men, focusing on general lifestyle, sex hormone status, body composition, and genetic background. The detailed study design has been described previously [19]. Briefly, 1114 healthy men aged 25–45 years, who had a brother within the same age range also willing to participate, were recruited from the population registries of the semirural to urban communities around Ghent, Belgium, between March, 2002 and July, 2010. After implementation of the

exclusion criteria (including illnesses or medication use affecting body composition, sex hormone status, or bone metabolism), 1001 men were included in the study cohort. The study protocol was approved by the ethical committee of the Ghent University Hospital and written informed consent was obtained from all participants. As jumping mechanography assessments were implemented in the study protocol in 2008, the current study is based on data of the 181 men included from January, 2008 onward. Physical activity was scored using the questionnaire as proposed by Baecke et al. [20]. All assessments were performed by a well-trained and dedicated study team.

Anthropometry and Estimates of Muscle Size and Function

Body weight was measured to the nearest 0.1 kg in light indoor clothing without shoes. Standing height was measured to the nearest 0.1 cm using a wall-mounted Harpenden stadiometer (Holtain Ltd., Crymch, UK). Body composition was measured using dual-energy X-ray absorptiometry (DXA) with a Hologic QDR-4500A device (software version 11.2.1; Hologic, Bedford, MA, USA), with leg lean mass (kg) defined as the lean mass from both lower limbs including thigh musculature. The coefficient of variation (CV) for whole-body calibration phantoms was <1 % as calculated from weekly measurements; CVs for outcome variables have not been calculated. Muscle CSA (cm²) was assessed at the dominant tibial shaft (66 % of bone length from distal end) using a peripheral quantitative computed tomography (pQCT) device (XCT-2000; Stratec Medizintechnik, Pforzheim, Germany) as described below, with CV for the calibration phantom <1 % as calculated from daily measurements. Isokinetic peak torque of the quadriceps muscle (Nm) was assessed during knee extension movements of the dominant limb at a preset constant angular velocity of 60°/s, using an isokinetic dynamometer (Biodex, New York, NY, USA). Three trial efforts and five maximal efforts with no rest were allowed to produce five overlying curves, and peak torque was derived from the effort with the highest value. Jumping mechanography was performed using a Leonardo Mechanography Ground Reaction Force Platform (software version 4.2; Novotec Medical GmbH, Pforzheim, Germany). As recommended by the manufacturer, peak jump force (kN) was assessed during multiple 1-legged hopping (m1LH) on the dominant limb, whereas peak jump power (kW) was assessed during single 2-legged jumps (s2LJ). For the m1LH, participants were instructed to bounce on the ball of the foot with the knee almost straight and the ankle joint as stiff as possible, aiming to achieve a maximum ground reaction force. The jump with the highest vertical ground reaction force was selected for analysis. The s2LJ was performed as a

countermovement jump for which individuals were asked to jump as high as possible, producing a maximal elevation of the center of mass. This jump was repeated 3 times and the recording with the highest jump height was analyzed. Both jump procedures were performed with freely moving arms. The CV for peak jump power was 5.08 % as calculated from 3 repeated jumps for all participants; CV for peak jump force has not been calculated.

Bone Geometry

Geometric bone parameters and estimates of bone strength were determined at the dominant lower leg (tibial shaft, 66 % of bone length from distal end) using pQCT. Single tomographic slices of 2.0 mm thickness were taken at a voxel size of 0.8 mm and a scan speed of 20 mm/s. Imaging and the calculation of numerical values were performed using the manufacturer's software package (version 5.4). The following parameters were assessed: total bone area (mm²), cortical bone area (mm²), periosteal circumference (mm), endosteal circumference (mm), cortical thickness (mm), and polar strength-strain index (SSIP, mm³). CSA of the tibia was determined after detecting the outer bone contour at a threshold of 280 mg/cm³. Periosteal and endosteal circumference and cortical thickness were estimated using a circular ring model, with cortical thickness as the difference between the outer and inner radius. The cortical over total bone area ratio (%) was calculated as cortical bone area divided by total bone area. Whereas we considered the total bone area and periosteal circumference as indicators of overall bone size, the cortical over total bone area ratio and cortical thickness rather reflect the amount of cortical bone. Muscle CSA was estimated using a threshold below water equivalent linear attenuation set at 0.22/cm. This threshold eliminated skin and fat mass with lower linear attenuation in the cross-sectional slice. From the remaining area, bone area was subtracted, showing the muscle at its maximum CSA. The CV for the calibration phantom was <1 % as calculated from daily measurements; CVs for outcome variables have not been calculated.

Statistics

Descriptives are expressed as mean \pm standard deviation (SD). Visual inspection of histograms and quantile–quantile (QQ) plots and Shapiro–Wilk tests were performed to assess normality. Linear mixed-effects modeling with a variance components residual correlation structure for random effects was used to evaluate cross-sectional relationships and differences between the participants who did and those who did not perform jumping mechanography, taking the interdependence of measurements within

families into account. Continuous variables were standardized in order to obtain standardized regression coefficients. Parameters of fixed effects were estimated using maximum likelihood estimation and reported as standardized regression coefficients (β) with their respective 95 % confidence intervals (CI). Unless stated otherwise, analyses are adjusted for age, height, and weight. Analyses including endosteal circumference were additionally adjusted for periosteal circumference to provide an estimate of endosteal expansion independently of bone size (EC_{PC}) [18]. To determine the independent associations of the different muscle parameters with each of the bone parameters, multivariate models were constructed with one of the bone parameters as the dependent and all muscle parameters showing a significant correlation with the considered bone parameter as the predictor variables, with additional adjustment for age, height, and weight ('Enter' method). No multicollinearity issues were detected based on the correlation coefficients between the predictors, 95 % CIs, and since linear mixed models do not provide collinearity diagnostics, collinearity diagnostics derived from linear regression models performed in a random sample including one participant from every family. Considering the large number of statistical tests, the significance level for associations was arbitrarily set at $p < 0.01$; all p values were two-tailed. R^2 statistics were derived from models considering one of the bone parameters as the dependent and one of the muscle parameters in addition to age, height, and weight as the predictor variables and were calculated as $R^2 = 1 - \exp(-2(\log L_m - \log L_0)/n)$, where $\log L_m$ denotes the log-likelihood of the model of interest, $\log L_0$ denotes the log-likelihood of an intercept-only model, and n denotes the number of observations [21]. The relative quality of these models was assessed by comparing Akaike Information Criteria (AIC), with the lowest AIC indicating the best fitting model. All analyses were performed using SPSS version 22.0 (IBM Corp., Armonk, NY, USA).

Results

Description of the Study Population

The study population comprised 181 participants who performed jumping mechanography, including 73 brother pairs, 2 triplets, and 29 singles. Their general characteristics as well as estimates of muscle size and function and parameters reflecting bone geometry are summarized in Table 1. All participants completed the s2LJ, and 178 participants completed the mLH. Leg lean mass, muscle CSA, and quadriceps peak torque were available for 178, 181, and 174 participants, respectively. The majority of the participants (63.5 %) had a normal BMI, 11.0 % were

Table 1 General characteristics, estimates of muscle size and function, and parameters reflecting bone geometry and strength ($n = 181$)

	Mean \pm SD
<i>General characteristics</i>	
Age (year)	34.1 \pm 5.4
Weight (kg)	79.4 \pm 11.1
Height (cm)	180.3 \pm 6.9
BMI (kg/m ²)	24.4 \pm 3.2
Mean activity index (score)	2.64 \pm 0.40
<i>Muscle parameters</i>	
Maximum jump height (m)	0.52 \pm 0.09
Peak jump power (kW)	4.0 \pm 0.7
Relative peak jump power (W/kg)	51 \pm 8
Peak jump force (kN)	2.3 \pm 0.4
Relative peak jump force (times Fg)	2.9 \pm 0.4
Quadriceps peak torque (Nm)	197 \pm 42
Muscle CSA at tibial shaft (cm ²)	83 \pm 12
Leg lean mass (kg)	19.9 \pm 2.7
<i>Bone parameters</i>	
Cortical bone area (mm ²)	367 \pm 45
Cortical over total bone area ratio (%)	44 \pm 5
Periosteal circumference (mm)	97 \pm 6
Endosteal circumference (mm)	69 \pm 7
Cortical thickness (mm)	4.4 \pm 0.5
SSI _p (mm ³)	3051 \pm 522

Fg Gravitational force, CSA cross-sectional area, SSI_p polar strength-strain index

overweight (BMI 25–30 kg/m²), and 6.7 % were obese (BMI \geq 30 kg/m²). As compared to the participants who did not perform jumping mechanography, participants included in this study had somewhat higher periosteal (97 \pm 6 vs. 95 \pm 6 mm, $p < 0.001$) and endosteal (69 \pm 7 vs. 67 \pm 7 mm, $p < 0.001$) circumferences. No other relevant differences were detected.

Table 2 displays correlations between the different muscle parameters. The strongest associations were seen between leg lean mass and peak jump power and between leg lean mass and muscle CSA, whereas the weakest correlation was observed between muscle CSA at the tibial shaft and quadriceps torque. Overall, the strength of the correlations was moderate with a maximal correlation coefficient of 0.69 between leg lean mass and peak jump power.

Associations of Jumping Mechanography with Bone Geometry

In unadjusted analyses, both peak jump force and power were positively associated with cortical bone area ($\beta = 0.42$ for force; $\beta = 0.42$ for power, both $p < 0.001$), cortical thickness ($\beta = 0.31$, $p < 0.001$ and $\beta = 0.23$, $p = 0.002$), periosteal circumference ($\beta = 0.28$ and $\beta = 0.39$, both $p < 0.001$), and SSI_p ($\beta = 0.35$ and $\beta = 0.44$, both $p < 0.001$) and negatively with EC_{PC} ($\beta = -0.16$ and $\beta = -0.13$, both $p < 0.001$) (Fig. 1). In addition, power but not force displayed a positive correlation with endosteal circumference ($\beta = 0.24$, $p = 0.001$), whereas force but not power tended to be associated with the cortical over total bone area ratio ($\beta = 0.16$, $p = 0.022$). As shown in Table 3, the associations of force and power with cortical bone area, cortical thickness, SSI_p, and EC_{PC} as well as the association of force with the cortical over total bone area ratio remained significant after adjustment for age, height, and weight, whereas the correlations of force and power with periosteal circumference and the correlation of power with endosteal circumference weakened and lost significance. For cortical bone area, cortical thickness, EC_{PC}, and SSI_p, models including peak jump force fitted better than models including peak jump power, with R^2 values 40.5 versus 35.4 %, 23.6 versus 15.3 %, 26.2 versus 20.3 %, and 48.9 versus 46.7 %, respectively. Moreover, when force and power were both included in the regression models, only force was

Table 2 Correlations between muscle size and function estimates

	pPs2LJ		pFm1LH		Leg lean mass		Quadriceps torque	
	β (95 % CI)	p	β (95 % CI)	p	β (95 % CI)	p	β (95 % CI)	p
Muscle CSA	0.39 (0.26; 0.51)	<0.001	0.42 (0.30; 0.55)	<0.001	0.61 (0.50; 0.71)	<0.001	0.23 (0.09; 0.36)	0.001
Quadriceps torque	0.38 (0.24; 0.51)	<0.001	0.35 (0.21; 0.50)	<0.001	0.43 (0.29; 0.57)	<0.001		
Leg lean mass	0.69 (0.59; 0.79)	<0.001	0.59 (0.47; 0.70)	<0.001				
pFm1LH	0.46 (0.34; 0.57)	<0.001						

Analyses are unadjusted. Dependent and predictor variables were standardized in order to obtain standardized regression coefficients (β) pPs2LJ peak jump power (single 2-legged jump), pFm1LH peak jump force (multiple 1-legged hopping), CSA cross-sectional area

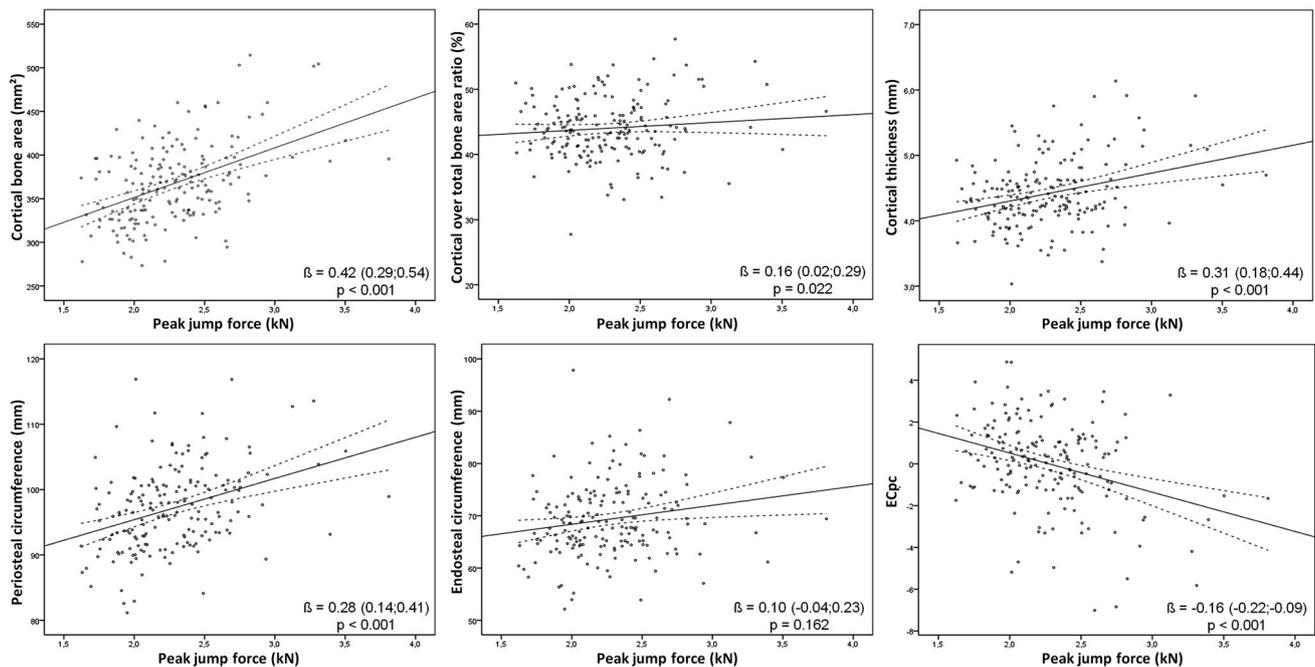


Fig. 1 Scatter plots with regression lines and 95 % confidence intervals representing unadjusted associations between mechanography-derived peak jump force and bone geometry

independently associated with these bone parameters ($\beta = 0.29$ for cortical area, $\beta = 0.30$ for cortical thickness, $\beta = -0.14$ for EC_{PC} and $\beta = 0.12$ for SSI_p , all $p < 0.001$). Additional adjustment for physical activity level did not alter the results (data not shown).

Associations of Other Muscle Parameters with Bone Geometry

In unadjusted analyses, muscle CSA, quadriceps torque, and leg lean mass correlated positively with cortical bone area ($\beta = 0.37$, $p < 0.001$ for muscle CSA; $\beta = 0.25$, $p = 0.001$ for quadriceps torque; $\beta = 0.56$, $p < 0.001$ for leg lean mass), periosteal ($\beta = 0.34$; $\beta = 0.36$ and $\beta = 0.64$, all $p < 0.001$) and endosteal circumference ($\beta = 0.21$, $p = 0.002$; $\beta = 0.27$, $p < 0.001$ and $\beta = 0.45$, $p < 0.001$), and SSI_p ($\beta = 0.38$; $\beta = 0.33$ and $\beta = 0.64$, all $p < 0.001$). In addition, muscle CSA and leg lean mass correlated positively with cortical thickness ($\beta = 0.18$, $p = 0.008$ and $\beta = 0.23$, $p = 0.001$) and negatively with EC_{PC} ($\beta = -0.10$, $p = 0.002$ and $\beta = -0.19$, $p < 0.001$). No associations were found between any of the muscle parameters and the cortical over total bone area ratio. After adjustment for body weight, height, and age, the associations of muscle CSA with cortical bone area, periosteal circumference, SSI_p , and EC_{PC} weakened but remained significant (borderline for EC_{PC}), whereas the associations with endosteal circumference and cortical thickness lost significance (Table 3). The associations of leg lean mass

with cortical bone area, cortical thickness, and EC_{PC} became somewhat stronger, whereas those with periosteal and endosteal circumference and SSI_p weakened but remained significant. None of the correlations between quadriceps torque and the bone geometry parameters remained significant.

Independent Associations of the Different Muscle Parameters with Bone Geometry

Table 4 displays the results of the multivariate analyses assessing the independent relations of the muscle parameters with bone geometry. Whereas leg lean mass correlated independently with periosteal and endosteal circumference and SSI_p , peak jump force was independently associated with the cortical over total bone area ratio, cortical thickness, and EC_{PC} . Both force and leg lean mass were independently associated with cortical bone area.

Discussion

The present study showed that mechanography-derived peak jump force and, albeit not independently from force, power correlate positively with parameters reflecting cortical bone geometry and strength at the tibial shaft. This correlation seems driven by an association with decreased endosteal expansion rather than increased periosteal apposition, as reflected by the inverse correlations with

Table 3 Associations of muscle parameters with bone geometry

	pPs2LJ		pFmILH		Muscle CSA		Quadriceps torque		Leg lean mass	
	β (95 % CI)	<i>p</i>								
Cortical bone area	0.28 (0.12; 0.44)	0.001	0.33 (0.19; 0.47)	<0.001	0.26 (0.13; 0.40)	<0.001	0.08 (-0.06; 0.23)	ns	0.62 (0.41; 0.82)	<0.001
Cortical over total bone area ratio	0.16 (-0.02; 0.35)	ns	0.25 (0.09; 0.41)	0.002	0.02 (-0.14; 0.18)	ns	-0.07 (-0.23; 0.09)	ns	0.10 (-0.15; 0.35)	ns
Periosteal circumference	0.13 (-0.02; 0.27)	ns	0.11 (-0.02; 0.25)	ns	0.21 (0.09; 0.33)	0.001	0.15 (0.02; 0.28)	ns	0.56 (0.38; 0.74)	<0.001
Endosteal circumference	-0.002 (-0.17; 0.16)	ns	-0.06 (-0.21; 0.09)	ns	0.12 (-0.02; 0.26)	ns	0.10 (-0.04; 0.24)	ns	0.32 (0.11; 0.54)	0.004
EC _{PC}	-0.13 (-0.21; -0.04)	0.003	-0.16 (-0.23; -0.09)	<0.001	-0.09 (-0.16; -0.02)	ns	-0.01 (-0.08; 0.06)	ns	-0.25 (-0.36; -0.13)	<0.001
Cortical thickness	0.25 (0.07; 0.44)	0.007	0.34 (0.18; 0.49)	<0.001	0.15 (-0.01; 0.31)	ns	0.01 (-0.15; 0.17)	ns	0.37 (0.12; 0.61)	0.003
SSIp	0.30 (0.10; 0.51)	0.003	0.23 (0.10; 0.36)	0.001	0.26 (0.14; 0.38)	<0.001	0.13 (-0.0002; 0.26)	ns	0.61 (0.44; 0.79)	<0.001

Analyses are adjusted for age, height and weight. Dependent and predictor variables were standardized in order to obtain standardized regression coefficients (β)
pPs2LJ Peak jump power (single 2-legged jump), *pFmILH* peak jump force (multiple 1-legged hopping), *CSA* cross-sectional area, *EC_{PC}* endosteal circumference additionally adjusted for periosteal circumference, *SSIp* polar strength-strain index, *ns* nonsignificant

EC_{PC}. Regarding other muscle mass, size, and function estimates, leg lean mass strongly correlates with parameters reflecting overall as well as cortical bone size and bone strength, while the associations of muscle CSA and especially quadriceps torque with bone geometry seem less consistent. Multivariate modeling revealed that whereas leg lean mass is independently associated with overall bone size and strength, peak jump force specifically and independently correlates to cortical bone size. These data thus suggest that as compared to other commonly used muscle size and function estimates, jumping mechanography provides a better estimation of the maximum voluntary muscle forces affecting cortical bone parameters.

Confirming our hypothesis and broadly consistent with previous studies [13–18], peak jump force was a stronger predictor of bone geometry than peak jump power. In contrast, some authors observed similar or stronger correlations of bone size and strength with power than with force [13, 15], although their use of single two-legged jumps to assess jump force may have resulted in an underestimation of peak forces [8]. To our knowledge, only one other study investigated the associations of peak jump force and power with endosteal expansion, reporting an inverse relationship of endosteal expansion with peak jump power but not force [18]. However, they studied a more heterogeneous population including a large number of high bone mass-cases, who differ from the general population in their cortical phenotype [22]. Moreover, we found higher mean values for peak jump power and force, explained by our younger and only male study population. More evidence supporting the hypothesis of a particular association between muscle force and endosteal expansion results from studies on physical activity and bone geometry, demonstrating that vigorous but not moderate or light habitual physical activity is associated with reduced endosteal expansion [23] and that sports requiring very high muscle forces (e.g., hurdling and triple jump), as compared to lower intensity sports, are associated with larger differences in cortical area and thickness than in total cross-sectional bone area [24, 25]. As such, locally exerted strains, as reflected by peak jump force, particularly appear to affect cortical bone geometry.

Leg lean mass and muscle CSA were associated with parameters reflecting cortical as well as overall bone geometry, which is largely in line with previous studies [3, 13–15, 17, 19, 26–34]. However, the associations of muscle CSA with bone geometry were not independent of jump force or leg lean mass, and quadriceps torque showed no correlations with bone geometry at all. Stronger associations of bone strength and size with peak jump force than with muscle CSA have also been described by Anliker et al. [17], but possibly due to the use of less indicative jump procedures, could not or only in part be confirmed by

Table 4 Independent associations of muscle parameters with bone geometry

	pPs2LJ		pFm1LH		Muscle CSA		Leg lean mass	
	β (95 % CI)	<i>p</i>	β (95 % CI)	<i>p</i>	β (95 % CI)	<i>p</i>	β (95 % CI)	<i>p</i>
Cortical bone area	0.06 (−0.11; 0.23)	ns	0.22 (0.08; 0.36)	0.002	0.08 (−0.07; 0.23)	ns	0.42 (0.16; 0.68)	0.002
Cortical over total bone area ratio	–		0.25 (0.09; 0.41)	0.002	–		–	
Periosteal circumference	–		–		0.02 (−0.12; 0.16)	ns	0.55 (0.33; 0.77)	<0.001
Endosteal circumference	–		–		–		0.32 (0.11; 0.54)	0.004
EC _{PC}	−0.04 (−0.13; 0.05)	ns	−0.13 (−0.20; −0.05)	0.001	–		−0.16 (−0.29; 0.03)	ns
Cortical thickness	0.10 (−0.10; 0.30)	ns	0.28 (0.11; 0.44)	0.001	–		0.18 (−0.09; 0.45)	ns
SSI _p	0.02 (−0.14; −0.17)	ns	0.12 (−0.01; 0.25)	ns	0.08 (−0.08; 0.19)	ns	0.51 (0.27; 0.75)	<0.001

Models include one of the bone parameters as the dependent and the indicated muscle parameters as the independent variables and are additionally adjusted for age, height, and weight. Inclusion of the muscle parameters was based on their significant correlation with the dependent variable in age, height, and weight-adjusted analyses. Dependent and predictor variables were standardized in order to obtain standardized regression coefficients (β)

pPs2LJ Peak jump power (single 2-legged jump), *pFm1LH* peak jump force (multiple 1-legged hopping), *CSA* cross-sectional area, *EC_{PC}* endosteal circumference additionally adjusted for periosteal circumference, *SSI_p* polar strength–strain index, *ns* nonsignificant

other authors [13–15]. Differences in the explanatory capacity of jump force versus muscle CSA and quadriceps torque with respect to cortical bone geometry might be explained by several factors. First, muscle CSA and quadriceps torque are poor surrogate markers of muscle force as they correlate only moderately to peak jump force and power. On the one hand, although isokinetic dynamometry theoretically represents a good method for the evaluation of leg muscle function, as maximum muscle forces are generated during eccentric contractions [8, 17], it is a rather impractical technique yielding a large variability in peak torque output due to methodological difficulties [8, 35]. On the other hand, the use of muscle size measurements such as muscle CSA as a surrogate of maximum intrinsic muscle force is limited, because the mechanical potential of a muscle depends not only on morphology but also on muscle fiber type and muscle composition [36]. As known from biopsies, spectroscopy, and MRI studies, fatty infiltration of muscles can already be noticed in young, healthy subjects, confounding the relationship between the size of a muscle and the forces that can be generated by its fibers [37, 38]. Moreover, peak jump force is determined by factors such as Achilles tendon elasticity and joint size. Since joint size is determined at the end of puberty and afterward cannot be enhanced, peak joint forces must be controlled in order not to exceed those that the joints had adapted to at that time, to avoid rupturing of the tendons. Increases in muscle mass or size may therefore not lead to increases in maximum muscle force in healthy, non-deconditioned adults [8, 39]. Second, the peak torque measurements in this study were derived from the quadriceps

muscle, whereas the bone geometry was assessed at the tibia, and the absence of any association may therefore not be entirely unexpected. Third, besides being a (poor) marker of muscle force, muscle CSA is also a surrogate of lean mass, which might affect bone geometry in a different way than muscle force. Indeed, in contrast to muscle CSA and quadriceps torque and in line with the results of Binkley et al. [13], leg lean mass was strongly associated with peak jump force and power as well as with bone geometry and strength. Moreover, and as opposed to our hypothesis, it was the only muscle parameter independently associated with periosteal circumference and thus overall bone size. Although strong correlations of (appendicular) lean mass with bone geometry have been previously described, the mechanisms underlying these associations are incompletely understood [13, 32, 33, 40]. In general, DXA-derived estimates of leg lean mass reflect a combination of both potential local muscle activity and the overall individual's health status, body composition, and physical activity level. We speculate that total leg lean mass better represents local muscle activity than a single-cross-sectional measurement of the muscle, even if the latter is assessed in the same area as the bone geometry. In addition, the muscle secretes a variety of cytokines and growth factors collectively referred to as myokines, which might modulate bone metabolism through endocrine and other signaling pathways [41]. Furthermore, certain regulatory pathways and associated factors, such as androgens, affect both skeletal muscle mass and (directly or indirectly) bone size, and evidence exists that myogenic progenitor cells may play a role in bone formation [42].

In a very simplified model, it can be assumed that under physiological conditions, factors such as hormones and myokines acting in an endocrine manner and/or through specific tissue–tissue transport mechanisms mainly influence overall bone size, whereas the detailed shaping of bones involved in motion is mainly controlled locally through strain-sensing by osteocytes and consecutive effector mechanisms (in turn probably modulated by systemic factors). Further, while overall bone size, as reflected by periosteal circumference, in adult life mainly reflects influences of the past (e.g., during growth), cortical area, cortical thickness and endosteal circumference are much more subject to change. Possibly, leg lean mass reflects the systemic factors and past influences on the tibia better than the other examined muscle parameters, whereas peak jump force may be the better indicator of strain-mediated adaptive changes. This might explain the pronounced independent association of leg lean mass with overall bone size as opposed to the association of jump force with cortical bone size.

Our findings imply that jumping mechanography and leg lean mass measurements should be considered advantageous methods in future studies investigating functional muscle–bone relationships, given their distinct associations with cortical and overall bone geometry. Clearly, further research is needed to elucidate to what extent interventions addressing peak voluntary muscle force influence cortical bone geometry and fracture risk, as this would have an impact on rehabilitation programs or other interventions for patients with suspected bone deficits. Given the fact that fracture risk seems to be mainly predicted by cortical rather than overall bone size [43–48], we speculate that increasing peak voluntary muscle force would benefit bone health and fracture risk more than increasing (leg) lean mass.

A major strength of this study is the well-defined population-based sample of healthy men. Since all study subjects were between 25 and 45 years of age, we assume that they had already reached peak bone mass but were not yet subjected to major degenerative alterations of the skeletal or the muscular system at the time of the study. Moreover, we used several methods to estimate muscle size and function including jumping mechanography, which enabled us to compare this more recent technique with other commonly used measurements. In contrast to previous studies, peak jump force, muscle CSA, and bone parameters were assessed at the same (dominant) limb. Our study also has limitations. Obviously, the cross-sectional design does not allow to draw conclusions about causality. Although our sample size was relatively small compared to some studies focusing on traditional muscle function measurements and bone parameters, only two studies using

jumping mechanography investigated larger, but also more heterogeneous populations [16, 17]. Furthermore, the peak torque measurements were derived during knee extension and therefore mainly reflect muscles at the upper leg, whereas the bone parameters were measured at the tibial shaft. Torque measurements derived from ankle plantarflexion might have been more informative and more strongly correlated to tibial bone strength and geometry; however, such measurements were not available in our study population. The relation of bone strength with peak jump force as well as with ankle plantarflexion torque has been assessed in one study, observing stronger associations of plantarflexion torque with compressive bending strength but not overall bone strength [14]. Nonetheless, as mentioned earlier, the use of two-legged instead of one-legged hopping to assess jump force might have led to an underestimation of peak forces in this study.

In conclusion, our results indicate that out of several commonly used muscle mass, size, and function estimates, leg lean mass independently correlates with overall bone size and strength at the tibial shaft, whereas the forces exerted on the bone, as represented by mechanography-derived peak jump force, specifically correlate with cortical bone size. As compared to other muscle parameters, jumping mechanography thus provides relevant additional information about the relationship of muscle with cortical bone geometry.

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Author Contributions Jean-Marc Kaufman, Hans-Georg Zmierczak, and Stefan Goemaere designed the study. Hans-Georg Zmierczak, Stefan Goemaere, Bruno Lapauw, and Jean-Marc Kaufman collected the data. Charlotte Verroken was responsible for statistical analysis of the data and wrote the first draft of the paper. She is guarantor. All authors revised the paper critically for intellectual content and approved the final version. All authors agree to be accountable for the work and ensure that any questions relating to the accuracy and integrity of the paper are investigated and properly resolved.

Compliance with Ethical Standards

Conflict of interest Charlotte Verroken, Hans-Georg Zmierczak, Stefan Goemaere, Jean-Marc Kaufman, and Bruno Lapauw declare that they have no conflict of interest.

Human and animal rights and informed consent The study was conducted in accordance with the 1964 Helsinki declaration and its later amendments and the study protocol was approved by the ethical committee of the Ghent University Hospital. Written informed consent was obtained from all individual participants included in the study.

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