The Human Muscle Size and Strength Relationship. Effects of Architecture, Muscle Force and Measurement Location.

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Title page

Title:
THE HUMAN MUSCLE SIZE AND STRENGTH RELATIONSHIP: EFFECTS OF ARCHITECTURE, MUSCLE FORCE AND MEASUREMENT LOCATION

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Abbreviated title for running head:
MUSCLE SIZE AND STRENGTH RELATIONSHIP

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Key words
Magnetic resonance imaging
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Physiological cross-sectional area

1   **Abstract**

2   *Purpose:* This study aimed to determine the best muscle size index of muscle strength

3   by establishing if incorporating muscle architecture measurements improved the human muscle

4   size-strength relationship. The influence of calculating muscle force, and the location of

5   anatomical cross-sectional area (ACSA) measurements on this relationship were also

6   examined.

7   *Methods:* Fifty-two recreationally active males completed unilateral isometric knee

8   extension strength assessments and MRI scans of the dominant thigh and knee to determine

9   quadriceps femoris (QF) size variables (ACSA along the length of the femur, maximum ACSA

10   [$ACSA_{MAX}$] and volume [VOL]) and patellar tendon moment arm. Ultrasound images (2 sites

11   per constituent muscle) were analyzed to quantify muscle architecture (fascicle length,

12   pennation angle), and when combined with VOL (from MRI), facilitated calculation of QF

13   effective PCSA ($_{EFF}PCSA$) as potentially the best muscle size determinant of strength. Muscle

14   force was calculated by dividing maximum voluntary torque (MVT) by the moment arm and

15   addition of antagonist torque (derived from hamstring EMG).

16   *Results:* The associations of $_{EFF}PCSA$ (r=0.685), $ACSA_{MAX}$ (r=0.697), or VOL

17   (r=0.773) with strength did not differ, although qualitatively VOL explained 59.8% of the

18   variance in strength, ~11-13% greater than $_{EFF}PCSA$ or $ACSA_{MAX}$. All muscle size variables

19   had weaker associations with muscle force than MVT. The association of strength-ACSA at

20   65% of femur length (r=0.719) was greater than for ACSA measured between 10-55% and 75-

21   90% (r=-0.042-0.633) of femur length.

22   *Conclusions:* In conclusion, using contemporary methods to assess muscle architecture

23   and calculate $_{EFF}PCSA$ did not enhance the muscle strength-size association. For

24   understanding/monitoring muscle size, the major determinant of strength, these findings

25   support the assessment of muscle volume, that is independent of architecture measurements,

26   and was most highly correlated to strength.

Introduction

Muscular strength, the maximum voluntary torque (MVT) a muscle group can produce, influences the performance of athletic events (1) and functional activities of daily life (2), is a risk factor for muscle injury (3), and is implicated in the development and progression of joint degeneration (i.e. osteoarthritis; (4, 5)). Knowledge of the factors underpinning strength and strength change are important in order to understand, assess/monitor and potentially modify the most important determinants. Whilst it is well known that muscle size is a key determinant of maximum strength (6–8), the most important muscle size determinant of strength is unclear. In fact the relationship of muscle size and strength may be influenced by both muscle size and strength measurements, with little investigation of the inclusion of muscle architecture assessment in the measurement of muscle size, the effect of calculating muscle force as the index of strength, which accounts for joint-level confounders (moment arm and antagonist co-activation), or the influence of muscle size measurement location (relative to segment length).

Theoretically, physiological cross-sectional area (PCSA) most accurately reflects the number of sarcomeres/myosin-actin cross-bridges arranged in parallel and thus able to generate tension between the tendons (9), and would be expected to be the strongest determinant of maximum strength (7, 10). However, studies comparing three common measures of muscle size have reported either maximum anatomical cross-sectional area ($ACSA_{MAX}$; (7)), muscle volume (VOL; (11)- elbow extensors), or PCSA ((11)- elbow flexors) to be the best correlate of strength. This inconsistency might be explained by the methodological limitations in the measurement of architecture and thus PCSA within these studies. Whilst $ACSA_{MAX}$ and VOL can be accurately assessed with T1-weighted magnetic resonance imaging (MRI), considered the gold standard technique (12), PCSA cannot be assessed directly by MRI alone. PCSA is typically calculated by dividing VOL (from MRI) by fascicle length (L_F), and further corrected

52 for the loss of force transmission to the aponeurosis/tendon in pennate muscle (i.e. pennation

53 angle, θ_P), sometimes referred to as effective PCSA ($_{EFF}$PCSA). Therefore, PCSA relies on

54 both the determination of VOL (via MRI) and the precise measurements of muscle architecture

55 (L_F and θ_P, via ultrasound).

56

57   Previous studies comparing associations between strength and different muscle size

58 indices (i.e. $ACSA_{MAX}$ vs. PCSA vs. VOL), have used the following muscle architecture (L_F

59 and θ_P) approximations for the calculation of PCSA: estimation from cadaveric data (7);

60 estimation based on muscle length ((11)– elbow flexors); or ultrasonographic measurements at

61 one site in one constituent muscle ((11)– elbow extensors). It is known that muscle architecture

62 varies both between and along constituent muscles of a muscle group (13, 14), therefore

63 performing multiple ultrasonographic measurements along the length of each constituent

64 muscle may better account for such variations. Furthermore, L_F has commonly been assessed,

65 and hence PCSA calculated, with relatively short ultrasound arrays that visualise ~30-50% of

66 L_F (40 mm array (15, 16); 45 mm (17); 60 mm (18)) and consequently, require prediction of

67 the remainder of the fascicular path in order to estimate L_F. This limitation can be minimized

68 by use of a longer ultrasound array, thereby reducing the proportion of overall fascicle length

69 that is extrapolated. Moreover, these issues in the assessment of L_F and θ_P, may provide a

70 methodological explanation for the variable findings as to the best muscle size index of

71 strength. It is conceivable that more careful architecture, and thus also PCSA, measurements,

72 could result in PCSA being the superior determinant of muscle strength and demonstrate the

73 utility of incorporating muscle architecture measurements within the assessment of human

74 muscle size. Finally, muscle thickness assessed with ultrasound imaging is often considered a

75 convenient, but somewhat crude index of muscle size. Perhaps surprisingly the relationship

76 between muscle thickness and strength has not been compared to that of MRI-derived measures

77 of muscle size (ACSA, PCSA and VOL) and strength.

78

79   The theoretical basis for a close association of cross-sectional area measurements

80 (ACSA and PCSA) and muscular strength, as opposed to VOL, is based on the assumption of

81 longitudinal transmission of force along the muscle from the cross-section of greatest area and

82 thus the largest amount of contractile material aligned in parallel. However, lateral force

83 transmission may provide an alternative means of transferring force from intermediate points

84 along muscle fibres (19), allowing a single muscle fibre to act as a series of independent force

85 generators each able to transmit force to the aponeuroses/tendons via radial structural proteins,

86 costameres, the sarcolemma and extra-cellular matrix (20); see Fig. 11 of reference (21).

87 Lateral force transmission might favor a stronger relationship between VOL, which

88 incorporates length, and strength compared to cross-sectional areas.

89

90   The assumption of predominantly longitudinal force transmission also underpins the

91 notion that the best measure of ACSA in relation to strength is the cross-section with the

92 greatest amount of contractile material in parallel (i.e. $ACSA_{MAX}$, usually calculated as the sum

93 of maximum ACSAs from each constituent muscle, typically occurring at different points

94 along the limb (7, 22, 23)). However, it has been suggested based on ultrasound measurements

95 that for the quadriceps femoris (QF) muscle group relatively proximal ACSA, may be more

96 strongly associated with strength (24) and strength gains after resistance training (25) than mid-

97 muscle measurements. To date there has been no MRI study of ACSA at set intervals along the

98 length of the muscle/bone in relation to strength or how location/length specific ACSA

99 measurements compare to $ACSA_{MAX}$.

100

101   The association between muscle size variables (i.e. $_{EFF}$PCSA, ACSA$_{MAX}$ and VOL) and

102   joint-level function (i.e. strength/MVT) may be somewhat diluted/confounded by joint

103   neuromechanical factors such as the leverage (moment arm) of the agonist muscles, as well as

104   co-activation and thus opposing torque from the antagonist muscles. It is possible that muscle

105   size variables could be very highly correlated with muscle force, as is the case for isolated

106   animal muscles (r=0.99; (8)), and thus explain a greater proportion of the variance in muscle

107   force than is the case for joint-level MVT. However, this has not been investigated.

108

109   Therefore, the aim of this study was to determine the effect of incorporating muscle

110   architecture measurements, calculating muscle force, and ACSA measurement location on the

111   human muscle size-strength relationship. Specifically by comparing: (i) the relationships of

112   four distinct QF muscle size measures (ACSA$_{MAX}$ and VOL from MRI, $_{EFF}$PCSA from the

113   combination of MRI with ultrasound measurements of architecture, and muscle thickness from

114   ultrasound) with knee extensor strength in a large cohort of healthy young men; (ii) the

115   association of these muscle size measures with muscle force as opposed to joint-level MVT;

116   and (iii) the relationship of strength to ACSA, according to the site of ACSA measurements

117   along the femur. We hypothesised that: rigorous muscle architecture measurements (L$_F$ and/or

118   θ_P), at eight sites throughout the QF, in combination with high resolution MRI, would facilitate

119      $_{EFF}$PCSA, rather than ACSA$_{MAX}$ or VOL, being the most powerful determinant of knee

120   extension MVT; that higher associations would be found between muscle size indices with

121   muscle force, than with MVT, once joint-level confounders were accounted for; and that the

122   MVT-ACSA relationship would be influenced by the location of the ACSA measurement along

123   the femur length.

124

125

126   **Materials and Methods**

127   *Participants*

128   Fifty-two young, healthy men (age 25 ± 2 years, height 1.76 ± 0.07 m, body mass $72 \pm$

129   9 kg) free from musculoskeletal injury provided written informed consent prior to participation

130   in this study that was approved by the Loughborough University Ethical Advisory Committee.

131   All participants were recreationally active (2200 ± 1355 metabolic equivalent min/wk; assessed

132   with the short format International Physical Activity Questionnaire; (26)), were not completing

133   any form of systematic physical training, and had not completed lower-body strength training

134   for >18 months. Only male participants were included in order to prevent the potential

135   confounding influence of sex differences in specific tension (force per muscle area: in vivo-

136   (27, 28); and in vitro [i.e. single muscle fibre specific tension]- (29)) on the muscle strength

137   and size relationships investigated in this study.

138

139   *Overview*

140   Participants completed a familiarisation session and two neuromuscular function

141   measurement sessions of their dominant leg, 7-10 days apart at a consistent time of day (starting

142   between 1200 and 1900), and an imaging session (within ± 7 days of the second function

143   measurement session). Familiarisation involved participants completing knee extension and

144   flexion maximum voluntary contractions (MVCs) to become accustomed to these assessments.

145   Function measurement sessions involved assessment of unilateral isometric knee extension

146   strength (i.e. MVT) and antagonist co-activation (hamstrings EMG), as well as knee flexion

147   MVCs for EMG normalization. Musculoskeletal imaging of the dominant limb involved

148   acquisition of magnetic resonance T1-weighted axial plane images (1.5 T) of the QF to assess:

149   ACSA along the length of each constituent muscle, VOL, and in combination with ultrasound-

150   derived muscle architecture measurements, $_{EFF}$PCSA. Ultrasonographic images were recorded

151 at two locations along the length of each constituent muscle of the QF to assess L_F, θ_P, and

152 muscle thickness using a 92-mm wide transducer that was typically able to visualise ~80-90%

153 of total L_F (see Fig. 1A). Sagittal plane MRI scans of the knee were also acquired and analyzed

154 to determine patellar tendon moment arm (PT_{MA}) which was used (along with antagonist EMG

155 during knee extension) to calculate muscle force.

156

157 *Torque recording*

158   Knee extension and flexion torque was recorded whilst participants were seated on a

159 rigid custom-made isometric dynamometer (see Fig. 6B of reference (30)) with knee and hip

160 angles of 115° and 126° (180° = full extension), respectively. This knee joint angle was selected

161 as the angle of peak torque (31). Extraneous bodily movement was minimized by fastening

162 adjustable straps across the pelvis and shoulders. An S-beam strain gauge with a low baseline

163 noise range (<0.1% MVT; Force Logic, Swallowfield, UK) mounted to the dynamometer was

164 positioned posterior and perpendicular to the tibia and then secured around the participant's

165 leg at ~15% of tibial length (distance from lateral malleolus to knee joint space) above the

166 medial malleolus with an ankle strap (35 mm width reinforced canvas webbing). The analog

167 force signal from the strain gauge was amplified (x370) and sampled at 2,000 Hz using an

168 external analog-to-digital (A/D) converter (Micro 1401; CED, Cambridge, UK) and recorded

169 with Spike 2 computer software (CED, Cambridge, UK). In offline analysis, force data were

170 low-pass filtered at 500 Hz using a fourth-order, zero-lag Butterworth filter (32), gravity

171 corrected by subtracting baseline force, and multiplied by lever length, the distance from the

172 knee joint space to the center of the ankle strap, to calculate torque values.

173

174

175

EMG recording

Surface EMG was recorded from the medial and lateral hamstring muscles using a wireless EMG system (Trigno; Delsys Inc., Boston, MA). Hamstring EMG measurements were performed to allow estimation of muscle force during knee extension MVT (see "Moment arm and calculation of muscle force" section of methods below). Prior to sensor placement skin preparation (shaving, abrading, and cleansing with 70% ethanol) was conducted. Single differential Trigno Standard EMG sensors (Delsys Inc., Boston, MA; fixed 1-cm interelectrode distance) were then positioned on the medial (semitendinosus and semimembranosus) and lateral (biceps femoris long head) hamstring muscles using adhesive interfaces at 45% of thigh length (above the popliteal fossa). The location of the sensors was determined by palpating the borders of the biceps femoris long head and the medial hamstrings (semitendinosus and semimembranosus) respectively. Each sensor was then placed at 50% of the mediolateral muscle width and parallel to the presumed orientation of the underlying fibres. The isometric dynamometer had a section of the seat removed to accommodate the placement of Hamstring EMG sensors on the skin without compression. EMG signals were amplified at source (x300; 20- to 450-Hz bandwidth) before further amplification (overall effective gain, x909), and sampled at 2,000 Hz via the same A/D converter and computer software as the force signal, to enable data synchronization. In offline analysis, EMG signals were corrected for the 48-ms delay inherent to the Trigno EMG system.

Knee extension maximum voluntary contractions.

Following a brief warm-up of the dominant leg knee extensors [3 s contractions at 50% (x3), 75% (x3), and 90% (x1) of perceived maximum] participants performed 3-4 MVCs with the instruction to "push as hard as possible" for 3-5 s. MVCs were separated by ≥30 s of rest. Biofeedback was provided by placing a horizontal cursor on the torque-time curve with a

201 horizontal cursor indicating the greatest torque obtained within that session, and verbal

202 encouragement was provided during all MVCs. Knee extensor MVT was defined as the

203 greatest instantaneous torque achieved during any MVC during that measurement session.

204 RMS EMG from each of the hamstring sites during knee extension MVT (i.e. over a 500-ms

205 time period, 250-ms either side of instantaneous knee extension MVT) was normalized to that

206 measured during knee flexion MVT (knee flexion EMG_{MAX}; see below) and then averaged

207 across the two hamstring sites (normalized antagonist HEMG). Knee extension MVT had a

208 between-session within-participant coefficient of variation (calculated as: [SD ÷ mean] x 100)

209 value of 3.0%.

210

211 *Knee flexion maximum voluntary contractions*

212   Knee flexion MVCs were then performed in the same manner as knee extension MVCs,

213 following prior warm-up contractions. Knee flexion MVT was defined as the greatest

214 instantaneous torque achieved during any MVC during that measurement session. RMS

215 hamstring EMG for a 500-ms epoch at knee flexion MVT (250-ms either side) was analyzed

216 for each site (knee flexion EMG_{MAX}); this approach was intended to capture muscle activity

217 measures during the 500-ms period with the highest mean torque during the plateau phase of

218 the 3-5 s MVC where torque is relatively stable.

219

220 *Fascicle length, pennation angle and muscle thickness*

221   L_F, θ_P and muscle thickness of the constituent QF muscles (vastus lateralis (VL), vastus

222 intermedius (VI) vastus medialis (VM), and rectus femoris (RF)) were measured using a B-

223 mode ultrasonography machine (EUB-8500, Hitachi Medical Systems UK Ltd,

224 Northamptonshire, UK) and a 92-mm, 5-10 MHz linear-array transducer (EUP-L53L) coated

225 with water soluble transmission gel. To match the knee joint angle during MVCs, these images

226   were collected whilst participants sat at rest in the same isometric dynamometer and joint

227   configuration used for maximum strength testing. Images were captured at rest at two sites

228   along the length of each constituent muscle of the QF. Specifically, ultrasound images were

229   recorded at 50% of superficial medio-lateral muscle width at the following locations along the

230   length of the femur from the knee joint space: 30% and 50% of femur length (VI), 50 and 70%

231   of femur length (VL); 20% and 40% of femur length (VM); 55% and 75% of femur length

232   (RF). The locations of these ultrasound recordings were largely adopted from prior research

233   incorporating multiple ultrasound measurements along the length of each constituent muscle

234   of the QF (33). The transducer was positioned parallel to the long axis of the thigh and

235   perpendicular to the skin, the position of the transducer was then subtly adjusted to align with

236   the plane of the fascicles at each site so that an image with the deep and superficial aponeuroses

237   and the trajectory of several fascicles was clearly identifiable with minimal pressure applied to

238   the dermal surface. Video output from the ultrasound machine was transferred to a computer

239   (via an S-video to USB converter) and images recorded using ezcap video capture software.

240   Images were subsequently imported into public domain software and analyzed (Image J, v1.48,

241   National Institutes of Health, Bethesda, USA).

242

243   θ_P at each individual recording site was measured as the angle of insertion of the muscle

244   fascicles into the deep aponeurosis (Fig. 1A), except for the VI where θ_P was measured as the

245   angle between the proximal end of each fascicle and the femur. L_F was measured as the length

246   of the fascicular path between the insertions into the superficial and deep aponeurosis (Fig.

247   1A). When the fascicular path extended beyond the acquired image the missing portion of the

248   fascicle was estimated by extrapolating linearly the fascicular path and the aponeurosis (18,

249   34). L_F and θ_P at each measurement site were taken as the mean of three individual fascicles.

250   L_F and θ_P of each constituent muscle was averaged across the two measurement sites of that

251 muscle. Overall QF L_F and θ_P were calculated as the mean of the four constituent muscles.

252 Muscle thickness at each measurement site (i.e. 2 per muscle) was quantified as the mean of

253 the distance between the deep and superficial aponeurosis at each end, and the middle of the

254 image before being averaged across sites within each muscle (Fig. 1A). Finally, the muscle

255 thickness for each constituent muscle was summed to quantify overall QF muscle thickness.

256

257 *MRI scan and analysis procedures for muscle size and patellar tendon moment arm*

258 **Muscle size variables.** Participants reported for their MRI scan (1.5 T Signa HDxt,

259 GE) having not completed any strenuous physical activity in ≥36 h, and had received prior

260 instruction to arrive in a relaxed state having eaten and drunk normally. Upon arrival

261 participants sat quietly for 15 min prior to their MRI scan. Participants lay resting supine at a

262 knee joint angle of 163° (180° = full extension) whilst MR imaging was conducted. A receiver

263 8-channel whole body coil allowed axial T1-weighted images (time of repetition/time to echo

264 550/14, image matrix 512 x 512, field of view 260 x 260 mm, pixel size 0.508 x 0.508 mm,

265 slice thickness 5 mm, inter-slice gap 0 mm) of the dominant leg to be acquired from the anterior

266 superior iliac spine to the knee joint space in two overlapping blocks. Oil filled capsules placed

267 on the lateral side of the thigh allowed alignment of the blocks during analysis (OsiriX

268 software, Version 6.0, Pixmeo, Geneva, Switzerland). The constituent muscles (VM, VL, VI,

269 and RF) were manually segmented in every third image (i.e. every 15 mm; Fig. 1B) starting

270 from the most proximal image in which the muscle appeared. The number of images (slices)

271 manually segmented along the length of each constituent muscle was (mean ± SD): VL, 24 ±

272 2 (range 21-28); VI, 24 ± 1 (range 21-28); VM, 23 ± 2 (range 20-26); RF, 22 ± 1 (range 20-

273 25).

274

275 The ACSA values measured along the length of each muscle were expressed relative

276 to femur length (defined by the number of axial slices between the proximal greater trochanter

277 (100% femur length) and the knee joint space (0% femur length)). Cubic spline interpolation

278 (1000 point; GraphPad Prism 6; GraphPad Software) was then used to quantify ACSAs for

279 each constituent muscle at 5% intervals along the length of the femur, and overall QF ACSA

280 at each 5% interval calculated by summation. QF $ACSA_{MAX}$ was calculated as the summation

281 of the maximal measured ACSA from each constituent muscle and the location relative to

282 femur length was also recorded.

283

284 The volume of each constituent QF muscle was calculated as the area under the ACSA-

285 femur length curve following cubic spline interpolation, and the constituent muscle volumes

286 summed for overall QF VOL. The $_{EFF}PCSA$ of each individual QF muscle was calculated as:

287 muscle volume (cm^3) divided by L_F multiplied by the cosine of θ_P. L_F and θ_P were mean values

288 from two ultrasound measurement sites along the length of each individual QF muscle. Overall

289 QF $_{EFF}PCSA$ was calculated via the summation of the individual QF muscle $_{EFF}PCSAs$.

290

291 **Moment arm and calculation of muscle force.** Immediately after thigh imaging, a

292 lower extremity knee coil was used to acquire sagittal images (time of repetition/time to echo

293 480/14, image matrix 512 x 512, field of view 160 x 160 mm, pixel size 0.313 x 0.313, slice

294 thickness 2 mm, inter-slice gap 0 mm) of the knee joint. Sagittal plane images were used to

295 determine PT_{MA}, the perpendicular distance from the patellar tendon line of action to the tibio-

296 femoral contact point, which was approximately the mid-point of the distance between the

297 tibiofemoral contact points of the medial and lateral femoral condyles (Fig. 1C). The tibio-

298 femoral contact point was used as an approximation of the joint centre of rotation (35). Due to

299 constraints in the size of the knee coil, sagittal images were acquired in an extended knee

300   position (~163°). PT_{MA} length was then corrected to that during MVC by estimating moment

301   arm at 115° from previously published data fitted with a quadratic function (36) scaled to each

302   participant's measured moment arm length at 163°. Internal muscle force was subsequently

303   calculated as follows: (external knee extensor MVT + estimated antagonist knee flexor torque)

304       $\div$ corrected PT_{MA}. Antagonist knee flexor torque at knee extension MVT was estimated by

305   expressing the antagonist HEMG amplitude during knee extensor MVT relative to the knee

306   flexor EMG_{MAX} (normalized antagonist HEMG) and multiplying by the knee flexor MVT

307   (assuming a linear relationship between EMG amplitude and torque).

308

309   *Statistics*

310   All statistical analyses were conducted using SPSS Version 26.0 (IBM Corp., Armonk,

311   NY, USA), unless stated. Significance was defined as $P < 0.05$. MVT (knee extension and

312   flexion) and normalized antagonist HEMG from each of the duplicate test sessions was

313   averaged for each participant to produce criterion values for the calculation of muscle force

314   and statistical analysis. Knee extension MVT, muscle force, QF size (VOL, $ACSA_{MAX}$,

315       $_{EFF}PCSA$, and muscle thickness), PT_{MA}, QF L_F and QF θ_P were tested for outliers using the

316   Grubbs' test, also referred to as the ESD method (extreme studentized deviate;

317   https://www.graphpad.com/quickcalcs/grubbs1/ (36)), and no outliers were detected. Values

318   presented for group level results are Mean ± SD. Data normality was assessed using the Shapiro

319   Wilk test. MVT was the only variable found to not be normally distributed and was transformed

320   (log 10) to meet parametric statistical testing requirements of normality prior to further

321   statistical analysis. Pearson's product moment bivariate correlations were conducted between

322   MVT / muscle force and the different measures of overall QF size (VOL, $ACSA_{MAX, EFF}PCSA$,

323   and muscle thickness). To statistically assess differences between Pearson's product moment

324   bivariate correlations (e.g. MVT vs. QF VOL compared to MVT vs. QF $ACSA_{MAX}$, MVT vs.

325 QF VOL compared to muscle force vs. QF VOL, or MVT vs. ACSA at 50% of femur length

326 compared to MVT vs ACSA at 70% of femur length) an online resource

327 (http://comparingcorrelations.org; (37) was used to implement Meng et al.'s (38) z test (two

328 dependent groups [i.e., same group], overlapping [i.e. one variable in common], two-tailed test,

329 alpha level= 0.05, confidence value= 0.95, null value= 0). Pearson's product moment bivariate

330 correlations were also calculated between MVT and location specific QF ACSA measurement

331 at 5% intervals between 10 and 90% of femur length. Between-participant coefficient of

332 variation (CV_B) for all variables was calculated as follows: [cohort SD ÷ cohort mean] x 100.

333 L_F and θ_P were compared between muscles (i.e. once mean values had been derived across two

334 measurement sites within each muscle) using a one-way ANOVA with stepwise multiple

335 comparison corrected least significant difference (LSD) post-hoc testing.

336

337 **Results**

338 *Group level muscle strength, size and architecture*

339 Knee extension MVT was 246 ± 42 Nm (range: 173-396 Nm; CV_B 17.3%) and QF

340 muscle force was 5874 ± 960 N (range: 3886-8681 N; CV_B 16.3%), respectively. Whole QF

341 $_{EFF}$PCSA, VOL, and $ACSA_{MAX}$ were 167 ± 19 cm^2 (range: 124-206 cm^2; CV_B 11.4%), 1838 $\pm$

342 263 cm^3 (range: 1254-2573 cm^3; CV_B 14.3%), and 90 ± 12 cm^2 (range: 68-125 cm^2; CV_B

343 13.8%), respectively. QF muscle thickness was 92 ± 11 mm (range: 74-123 mm; CV_B 11.5%).

344 Constituent QF muscle size variables are reported in Table 1.

345

346 Overall QF L_F was 106.6 ± 8.9 mm (range: 87.8-125.5 mm; CV_B 8.4%), and QF θ_P was

347 $15.5 \pm 1.8°$ (range: 12.2-19.0°; CV_B 11.5%). L_F (i.e. mean of 2 sites) differed between

348 constituent QF muscles (ANOVA P<0.001). Specifically, VI L_F (98.7 ± 9.7 mm) was shorter

349 than that of the VM (105.8 ± 15.2 mm), VL (113.1 ± 11.7 mm) and RF (108.9 ± 14.7 mm; LSD

350 0.001≤P<0.019) and VM L_F was shorter than that of VL (LSD P=0.019). L_F did not differ

351 between any other individual QF muscles (LSD 0.211≤P≤0.221). θ_P differed between

352 constituent QF muscles (One-way ANOVA P<0.001). Post-hoc testing revealed that θ_P

353 differed between all individual QF muscles (LSD [all] P<0.001; VL $16.0 \pm 3.2°$; VI $13.4 \pm$

354 $3.3°$; VM $19.2 \pm 3.9°$; and RF $13.5 \pm 2.6°$) except between VI and RF (LSD P=0.814). PT_{MA}

355 was 4.41 ± 0.30 cm (range: 3.65-5.16 mm; CV_B 6.7%).

356

357 *Correlation of muscle size variables with maximum voluntary torque and muscle force.*

358   MVT was correlated with all four QF size variables with the bivariate correlation

359 between MVT and VOL producing the highest r-value (r=0.773, P<0.001), followed by

360 $ACSA_{MAX}$ (r=0.697, P<0.001), $_{EFF}PCSA$ (r=0.685, P<0.001) and muscle thickness (r=0.406,

361 P=0.003; Fig. 2A-D). Statistical comparisons revealed no differences between the bivariate

362 correlation coefficients of MVT and MRI-derived measures of muscle size: MVT with VOL

363 or $ACSA_{MAX}$ (z=1.614, P=0.107), MVT with VOL or $_{EFF}PCSA$ (z=1.555, P=0.120), MVT

364 with $ACSA_{MAX}$ or $_{EFF}PCSA$ (z=0.151, P=0.880). However, correlation coefficients between

365 MVT with VOL (z=3.699, P<0.001), $ACSA_{MAX}$ (z=2.417, P=0.015), or $_{EFF}PCSA$ (z=2.393,

366 P=0.017) were each greater than the correlation coefficient between MVT and muscle

367 thickness.

368   Muscle force was correlated with, or had a tendency to be correlated with, all four QF

369 muscle size variables but with lower correlation coefficients than for MVT (VOL r=0.627,

370 P<0.001; $ACSA_{MAX}$ r=0.598, P<0.001; $_{EFF}PCSA$ r=0.575, P<0.001; and muscle thickness

371 r=0.269, P=0.054; Fig. 3A-D). The correlation coefficients produced for each muscle size

372 variable with muscle force were lower than for with MVT: VOL with muscle force or MVT

373 (z=3.306, P<0.001), $ACSA_{MAX}$ with muscle force or MVT (z=2.069, P=0.039), $_{EFF}PCSA$ with

374 muscle force or MVT (z=2.252, P=0.024), and muscle thickness with muscle force or MVT

375 (z= 2.275, P=0.023). In summary, muscle size variables explained 9.2 to 20.4% more of the

376 variance in MVT than in muscle force. For context we also calculated the correlation between

377 PT_{MA} and MVT finding a weak, significant relationship (r=0.285; P=0.041).

378

379 *Anatomical cross-sectional area along the length of the femur*

380 The $ACSA_{MAX}$ of each of the four constituent muscles occurred at $28.4 \pm 3.6\%$ (VM),

381 $57.1 \pm 5.1\%$ (VL), $57.9 \pm 4.3\%$ (VI) and $68.2 \pm 5.7\%$ femur length (RF; Fig. 4A). Considering

382 location/femur length specific ACSA of the whole QF (i.e. sum of all 4 constituents at each

383 femur length), the highest ACSA occurred at 55% femur length (71 ± 10 cm^2; Fig. 4B). As the

384 association between muscle force and muscle size measures were weaker than that for MVT

385 (see previous paragraph), only bivariate correlations between location specific ACSA measures

386 and MVT were conducted. Significant correlations were observed between MVT and QF

387 ACSA measurements at 25-85% of femur length, with the highest correlation (r= 0.719,

388 P<0.001) occurring at 65% of femur length (i.e. more proximal than the position of highest

389 location specific ACSA; Fig. 4C). In fact, ACSA measured at 65% femur length and two

390 adjacent locations (60 and 70%) had marginally, but not significantly ($0.0688 \leq z \leq 0.4744$,

391 $0.6352 \leq P \leq 0.9452$), higher correlation coefficients with MVT (r=0.701 to 0.719) than

392 $ACSA_{MAX}$ (r=0.697). Statistical comparisons between correlation coefficients revealed that the

393 association between MVT and ACSA at 65% of femur length was: greater than the association

394 between MVT and ACSA at 10-45% of femur length ($1.979 \leq z \leq 4.457$, $0.001 \leq P \leq 0.048$) and

395 75-90% of femur length ($2.093 \leq z \leq 3.493$, $0.001 \leq P \leq 0.036$); and had a tendency to be greater

396 than 50-55% of femur length (z= 1.711-1.843, P=0.065-0.087). The association of MVT-

397 ACSA at 65% of femur length did not differ compared to the that between MVT-ACSA at 60%

398 or 70% of femur length ($0.556 \leq z \leq 0.656$, $0.512 \leq P \leq 0.579$).

399

Discussion

This study examined the relationship between QF size measures (VOL, $_{EFF}$PCSA, ACSA$_{MAX}$ and muscle thickness) and both knee extensor strength (MVT) and internal muscle force in a large cohort of healthy young men, as well as the influence of ACSA location along the femur on the relationship with strength. Our first two hypotheses were refuted as incorporating thorough muscle architecture measurements when determining $_{EFF}$PCSA did not result in this index of QF size becoming the pre-eminent muscle size determinant of MVT, and muscle force was not more strongly associated with muscle size variables than joint-level MVT. In agreement with our final hypothesis the MVT-ACSA relationship was influenced by ACSA measurement location with stronger correlations at specific locations of 60-70% of femur length than for other locations.

Knowledge of the muscle size measurements underpinning strength and strength change are important in order to understand, assess/monitor and potentially modify the most important determinants. Surprisingly, in the current study determination of $_{EFF}$PCSA involving comprehensive MRI scanning along the length of the constituent QF muscles, and the incorporation of two ultrasonographic muscle architecture measurements per muscle did not result in $_{EFF}$PCSA being the highest correlate of MVT. In fact, comparisons of correlation coefficients revealed no difference between the association of $_{EFF}$PCSA, ACSA$_{MAX}$, or VOL with MVT, although qualitatively VOL explained 59.8% of the variance in MVT, which was ~11-13% greater than either $_{EFF}$PCSA (46.9%) or ACSA$_{MAX}$ (48.6%). As far as we are aware the current study involved the most thorough in vivo investigation to date with: (i) a large cohort (n=52 vs. n=19 (17), n=26 (11), n=39 (7)); (ii) a relatively homogenous cohort (low-moderate physically active males, as opposed to mixed sex and training status groups that might introduce other variables); (iii) duplicate measurements of knee extension strength on

425 two occasions with a highly reliable dynamometer and protocol (between-session within-

426 participant coefficient of variation of 3.0% in the current experiment). In addition, specific to

427 the $_{EFF}$PCSA measurements we took multiple ultrasonographic measurements at two sites for

428 each constituent muscle with a long ultrasound array to provide a rigorous assessment of

429 muscle architecture, as opposed to estimation from cadaveric data (7) or muscle length ((11)–

430 elbow flexors), or single site ultrasound measurements ((11)– elbow extensors). In keeping

431 with previous literature (39) this revealed that muscle architecture (θ_P and. L_F) differed between

432 the constituents QF muscles indicating that all four muscles should be assessed to accurately

433 determine $_{EFF}$PCSA of each muscle and thus also of the whole muscle group. Despite these

434 attempts to improve the $_{EFF}$PCSA measurement, the current study provides robust evidence that

435 with these techniques $_{EFF}$PCSA is not more strongly associated with strength than VOL or

436 ACSA$_{MAX}$, and qualitatively VOL actually explained ~13% more variance than $_{EFF}$PCSA. Our

437 finding that VOL was qualitatively the greatest correlate of muscular strength over cross-

438 sectional area measurements ($_{EFF}$PCSA and ACSA$_{MAX}$) was consistent with one previous

439 report ((11)– elbow extensors), but not others that found $_{EFF}$PCSA ((11)– elbow flexors) or

440 ACSA$_{MAX}$ (7) to be pre-eminent, but these studies did not complete statistical comparisons of

441 these associations. Only one previous report did a statistical comparison, also finding VOL to

442 be a superior, but not statistically greater, determinant of muscular strength than ACSA (17).

443 Overall, the differences between these three indices of muscle size ($_{EFF}$PCSA, ACSA$_{MAX}$,

444 VOL) in predicting strength appear relatively subtle, but with 3 of 5 datasets indicating VOL

445 maybe marginally superior.

446

447   The statistically equivalent but qualitatively weaker association of $_{EFF}$PCSA with

448 strength, compared to VOL, appears contrary to classic physiological theory that $_{EFF}$PCSA best

449 represents the number of actin-myosin cross bridges in parallel and able to generate tension

450   between tendons. There seem to be four possible explanations for this finding. Firstly, our

451   ability to assess complex muscle architecture, and thus accurately determine $_{EFF}$PCSA, may be

452   limited with the use of two-dimensional ultrasonography. Employing more sophisticated three-

453   dimensional muscle architecture imaging techniques (i.e. diffusion tensor MRI) for the

454   determination of $_{EFF}$PCSA seems a logical progression for future research. Secondly, it seems

455   likely that VOL can be measured with less error than $_{EFF}$PCSA, given the calculation of PCSA

456   involves the combination of multiple variables with the potential for accumulated measurement

457   error that might reduce the association with MVT. Thirdly, classic physiology assumes purely

458   longitudinal force transmission. However, evidence for the existence and importance of lateral

459   force transmission has been documented in both amphibian myofibers (19) and mammalian

460   whole muscle (40, 41). Therefore, lateral force transmission, potentially between fibres,

461   fascicles and even constituent muscles (20, 42, 43) could mean that $_{EFF}$PCSA is not the only

462   geometric determinant of contractile force production. Specifically, due to lateral force

463   transmission the length and/or shape of a muscle/muscle group may also influence force

464   production and explain why VOL qualitatively explained the largest amount of variance in

465   muscular strength in the current study. Finally, whilst PT$_{MA}$ was a weaker predictor of isometric

466   strength in this study (r=0.285) than in some previous reports (17, 24, 44–46; r= 0.400 to

467   0.790), it is possible that VOL, which incorporates muscle length as well as cross-sectional

468   area, may provide a (better) proxy for body size and PT$_{MA}$, potentially explaining the higher

469   correlation of VOL with MVT than cross-sectional areas.

470

471   Muscle thickness measured with ultrasound was a statistically weaker correlate of MVT

472   (r=0.406) than the MRI measures of muscle size (i.e. VOL, ACSA$_{MAX}$, or $_{EFF}$PCSA; r= 0.685-

473   0.773). Similar (r= 0.411-0.470; (47, 48), and greater (r= 0.550-0.700 (49, 50)) associations

474   between QF muscle thickness and muscular strength have been reported in the research

475 literature. However, these prior studies measured only one site per muscle and several

476 measured only two of the four constituent QF muscles (47, 48, 50). Overall, the measurement

477 of muscle thickness with ultrasound appears to be a substantially weaker determinant of

478 isometric strength than MRI-based measures of muscle size, in this study explaining >30% less

479 variance in strength (explained variance: 16.5% for MT vs 46.9-59.8% for MRI measures).

480 Thus, while ultrasound measures of muscle thickness have the advantages of convenience and

481 low cost they are significantly less informative about the functional capacity of the quadriceps

482 and thus may have limited utility in comparing or monitoring individuals (i.e. during training,

483 disuse or aging).

484

485   We had anticipated that the joint-level relationship between muscle size and strength

486 may be limited by the influence of other neuromechanical factors (i.e. moment arm and

487 antagonist activation/torque) that might dilute/confound this relationship, and thus removal of

488 these factors would lead to a stronger relationship between muscle force and size variables.

489 However, the relationships between muscle force and muscle size variables were consistently

490 and statistically lower than for joint-level MVT (i.e. explaining 9.2 to 20.4% less variance). In

491 essence contrary to our hypothesis removal of the confounding factors (moment arm and

492 antagonist torque) weakened rather than strengthened the relationship of muscle size with

493 force/torque. Given the convincing evidence for a very high correlation between $_{EFF}$PCSA and

494 muscle force in isolated muscles (r=0.99; (8)), it seems our attempt to remove joint-level

495 neuromechanical factors may have further confounded rather than distilled the relationship

496 between muscle size and force/torque. This finding might question the validity of the moment

497 arm and antagonist measurements used in the current study, or suggest accumulated

498 measurement error when estimating muscle force via a calculation involving multiple

499 variables. Furthermore, the calculation of muscle force has been used as an intermediate step

500   for the assessment of specific tension (which subsequently involves dividing muscle force by

501   cross-sectional area; (51, 52)), and these results also query the validity of estimating specific

502   tension in this way.

503

504   It is possible that the contemporary methods that we employed are not sufficient to

505   accurately assess antagonist torque. Whilst we assessed activation of the largest of the knee

506   flexors (medial and lateral hamstrings), only two/three of nine knee flexor muscles were

507   measured; and antagonist torque was estimated based on an assumed linear relationship with

508   EMG (22), and this relationship may also be confounded by cross-talk from other muscles (53).

509   Improvements in the assessment of antagonist torque during knee extension seem warranted

510   and this may require more comprehensive assessment of antagonist co-activation. For example,

511   with the measurement of surface EMG of additional knee flexor muscles (i.e. the medial and

512   lateral gastrocnemius) and more careful determination of the torque-EMG relationship for

513   these muscles. In practice, however, antagonist torque was estimated as 5.3% of knee extension

514   MVT, and thus appeared to be a relatively modest correction within the calculation of

515   quadriceps muscle force. Given this modest influence of correcting for antagonist EMG on the

516   muscle force calculation, this may place particular concern on the functional validity of the

517   PT_{MA} measurement also used in the calculation of muscle force. Most contemporary studies,

518   including the current investigation, typically measure PT_{MA} in resting conditions to ensure

519   good image quality (i.e. no movement artefact), and at a relatively extended knee joint angle

520   due to space constraints within the bore of an MRI scanner. However, it is known that PT_{MA}

521   changes with contraction vs. rest (54) and joint angle (36). Although we corrected PT_{MA} values

522   according to the differences in knee joint angle between the imaging and the strength

523   measurements (52), it is possible that these confounding factors in the assessment of PT_{MA} may

524   have compromised the precision of this measurement.

525   The relationship between MVT and ACSA in the present investigation was found to be

526   systematically influenced by the location of the ACSA measurement relative to femur length,

527   with r-values progressively increasing from 10% up to a peak at 65% of femur length (r=0.719)

528   before gradually declining between 65% and 90% of femur length. Thus the location showing

529   the largest association between MVT and ACSA (65% of femur length) was proximal of the

530   location with the largest location specific ACSA of the whole quadriceps, which had a

531   marginally lower correlation (55% of femur length, r=0.633). The correlation coefficient

532   between MVT and ACSA measured at 65% of femur length was found to be greater than, or

533   have a tendency to be greater than, all other ACSA measures along the femur other than those

534   directly adjacent (i.e. ACSA at 60 and 70% of femur length). Additionally, the r-value for the

535   association between MVT and ACSA at 65% femur length was also marginally superior, but

536   statistically equivalent to that of $ACSA_{MAX}$ (i.e. sum of maximum ACSA from each constituent

537   QF muscle, irrespective of location) and MVT (r=0.697). Therefore, this rigorous MRI

538   assessment at locations all along the femur supports the earlier suggestion based on ultrasound

539   measurements that proximal QF ACSA may be particularly important for the strength of this

540   muscle group (24). One practical implication of our observation that ACSA at 65% of femur

541   length had a similar association with MVT as $ACSA_{MAX}$ is that a single slice image at this one

542   location, which is a quicker, cheaper and analytically less laborious than the imaging of the

543   whole muscle needed to determine $ACSA_{MAX}$, may be as effective at predicting function.

544

545   It was notable that the location specific ACSA (65% of femur length) showing the

546   highest correlation with MVT was also proximal to the $ACSA_{MAX}$ of all three vastii muscles

547   (VM 28.4%; VL 57.1%; VI 57.9%) collectively comprising 87% of QF volume, with only the

548   RF having a more proximal $ACSA_{MAX}$ (68.2%). We are not aware of any reason that the RF

549   would have a disproportionate influence on knee extension strength. Alternative explanations

550 for this observation of proximal QF ACSA being most strongly related to strength may include

551 the differences between the imaging and strength measurements, in terms of both the state of

552 muscle contraction (resting for MRI vs. maximum contraction for MVT) and joint

553 configurations (hip and knee close to the anatomical position for MRI scanning vs. flexed hip

554 and knee at MVT for the isometric dynamometry). For example with the hip and knee flexed

555 in the dynamometer it might be expected that all four constituents of the QF would move

556 distally compared to the anatomical position in the MRI scanner (i.e. proximal muscle locations

557 [~ 65% of femur length] in the scanner may be closer to mid-thigh when seated on the

558 dynamometer). On the other hand, as the muscle contracts, even during an isometric

559 contraction the fibres and fascicles shorten considerably. We have previously found fascicle

560 length within the QF to shorten by 24% between rest and MVT, and as the muscle remains

561 isovolumetric, cross-sectional area shows a corresponding increase ($_{EFF}$PCSA +27% from rest

562 to MVT; (18)). In the QF this shortening of the muscle belly occurs in a non-symmetrical

563 manner primarily due to lengthening of the distal connective tissues, as for example the deep

564 VL aponeurosis at mid-thigh (50% femur length) has been shown to move ~17 mm proximally

565 from rest to 80% MVT (55). Therefore, the substantial increase in cross-sectional area, from

566 rest to MVT is likely accompanied by a proximal shift in the location of ACSA$_{MAX}$. In summary

567 the way in which these potentially competing effects of contraction state and joint

568 configuration combine to explain the apparent importance of proximal ACSA for isometric

569 strength measurements is unclear.

570

571 The current study was not without its limitations and it is important to acknowledge

572 them. The highly specific nature of the strength assessment (isometric contraction of the knee

573 extensors at a knee joint angle of 115°) used in the current investigation means that the results

574 presented cannot necessarily be generalized or assumed to be the same for other muscle groups,

575 modes of contraction (i.e. concentric or eccentric) or joint angles. Theoretically, as muscle

576 architecture is known to change substantially with contractile force (18) the most relevant

577 muscle architecture measurements for maximum contractile function would seem be those

578 measured at MVT. In practice, however, obtaining high quality architecture measurements at

579 MVT is highly challenging, and would not have been feasible for two sites of each of the four

580 individual muscles within the current study. Furthermore, based on our prior work the use of

581 architecture measurements made during MVCs, compared to resting measurements, did not

582 enhance the relationship between knee extension MVT and QF $_{EFF}$PCSA (18). Finally, the aim

583 of this study was to examine human muscle size-strength relationships and the influence of

584 some specific methodological considerations. We are conscious that other factors, beyond the

585 scope of this study, have also been suggested to influence strength (e.g. fibre type composition

586 (56) and agonist neuromuscular activation (57, 58)), and future work could examine

587 multifactorial determinants of strength.

588

589   In conclusion, despite incorporating comprehensive muscle architecture measurements

590 to enhance the determination of $_{EFF}$PCSA, statistical comparisons of correlation coefficients

591 revealed no differences between the association of $_{EFF}$PCSA, ACSA or VOL with MVT; and

592 VOL explained the highest variance in isometric knee extension MVT (~60%). This suggests

593 that with contemporary methods of muscle architecture measurements, $_{EFF}$PCSA offers no

594 advantage over purely MRI-derived indices of muscle size, and researchers interested in

595 understanding/explaining muscular strength may wish to use muscle volume as it does not

596 require additional architecture measurements and appears to explain marginally more variance

597 in strength. The location of ACSA measurements substantially effected the strength of the

598 association with MVT, with the highest association for ACSA measured at the relatively

599 proximal position of 65% of femur length. ACSA measured at this location was as strongly

600 associated with MVT as $ACSA_{MAX}$ despite requiring only a single slice/image in contrast to

601 scanning the whole muscle for $ACSA_{MAX}$.

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616 **AUTHOR CONTRIBUTIONS**

617 T.G.B., G.J.M, T.M.M.-W., and J.P.F. conception and design of research;

618 T.G.B., G.J.M., and T.M.M.-W. performed experiments;

619 T.G.B. and T.M.M.-W. analyzed data;

620 T.G.B. and J.P.F. interpreted results of experiments;

621 T.G.B. prepared figures;

622 T.G.B., and J.P.F. drafted manuscript;

623 T.G.B., G.J.M., T.M.M.-W., and J.P.F. edited and revised manuscript;

624 T.G.B., G.J.M., T.M.M.-W., and J.P.F. approved final version of manuscript.

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628

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777

FIGURE CAPTIONS

Fig. 1 Representative: (A) ultrasound images of vastus lateralis (VL; 50% of femur length), vastus intermedius (VI; 50% of femur length), rectus femoris (75% of femur length), and vastus medialis (VM; 40% of femur length; 0% is knee joint space); (B) axial magnetic resonance image of the thigh; and (C) sagittal magnetic resonance image of the knee joint. TFCP, tibio-femoral contact point.

Fig. 2 Scatterplots showing the relationships between knee extension maximum voluntary torque (MVT) and quadriceps femoris size measures: (A) muscle volume [VOL]; (B) maximum anatomical cross-sectional area [ACSA$_{MAX}$]; (C) effective physiological cross-sectional area [$_{EFF}$PCSA]; and (D) muscle thickness. Solid lines indicate the trend of the relationship between variables.

Fig. 3 Scatterplots showing the relationships between quadriceps femoris muscle force and quadriceps femoris size measures: (A) muscle volume [VOL]; (B) maximum anatomical cross-sectional area [ACSA$_{MAX}$]; (C) effective physiological cross-sectional area [$_{EFF}$PCSA]; and (D) muscle thickness. Solid lines indicate the trend of the relationship between variables.

Fig. 4 Location specific anatomical cross-sectional area (ACSA) at 5% intervals along the length of the femur for (A) the constituent quadriceps femoris (QF) muscles and (B) overall QF muscle group. (C) Bivariate correlations between QF ACSA at 5% intervals along femur length and knee extension isometric maximum voluntary torque; 0% = distal, 100% = proximal. Significance of bivariate correlations are indicated as follows: * $P<0.05$, ** $P<0.01$, ***$P<0.001$. Data displayed in A and B are mean ± SD.

Fig. 1

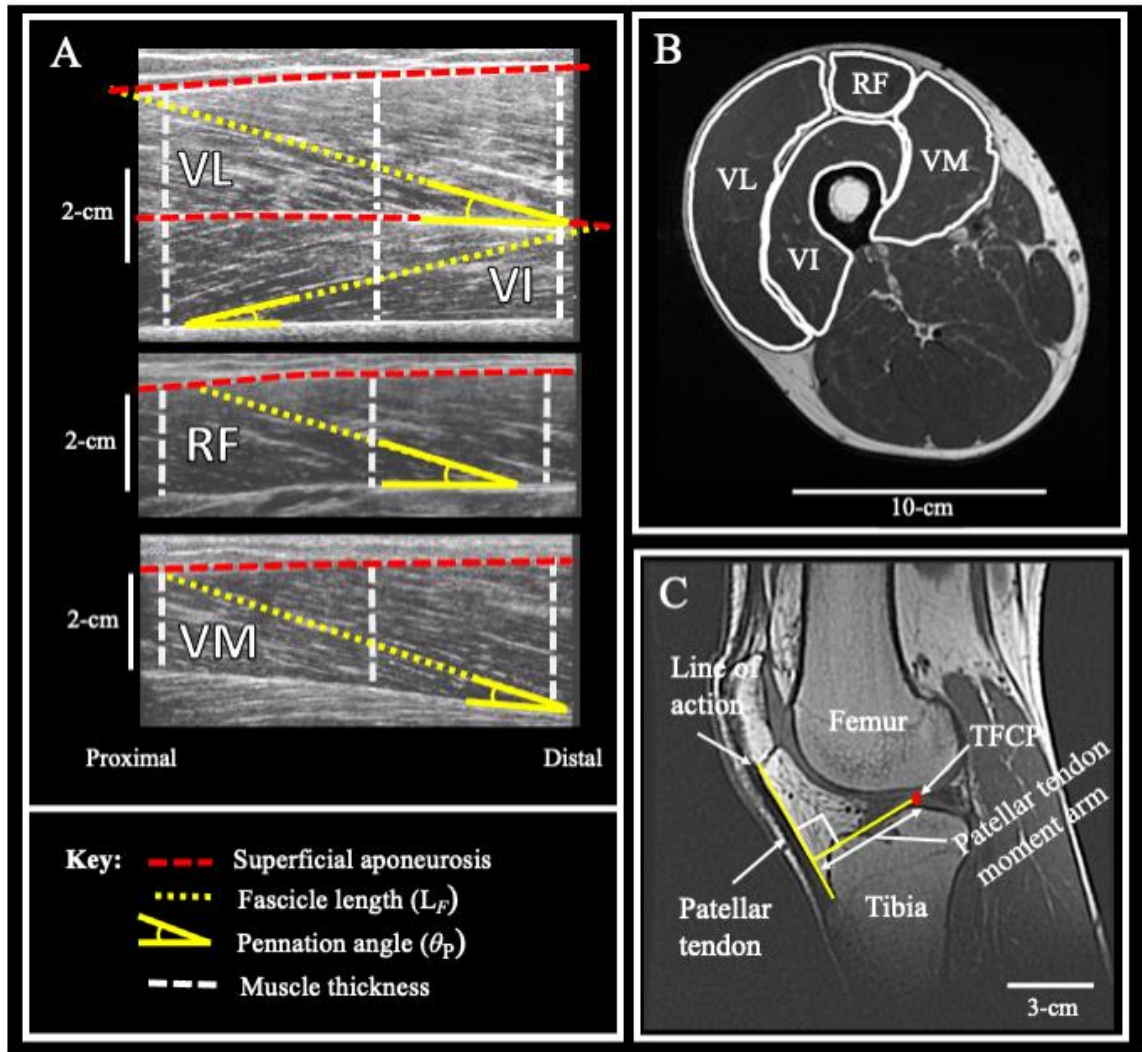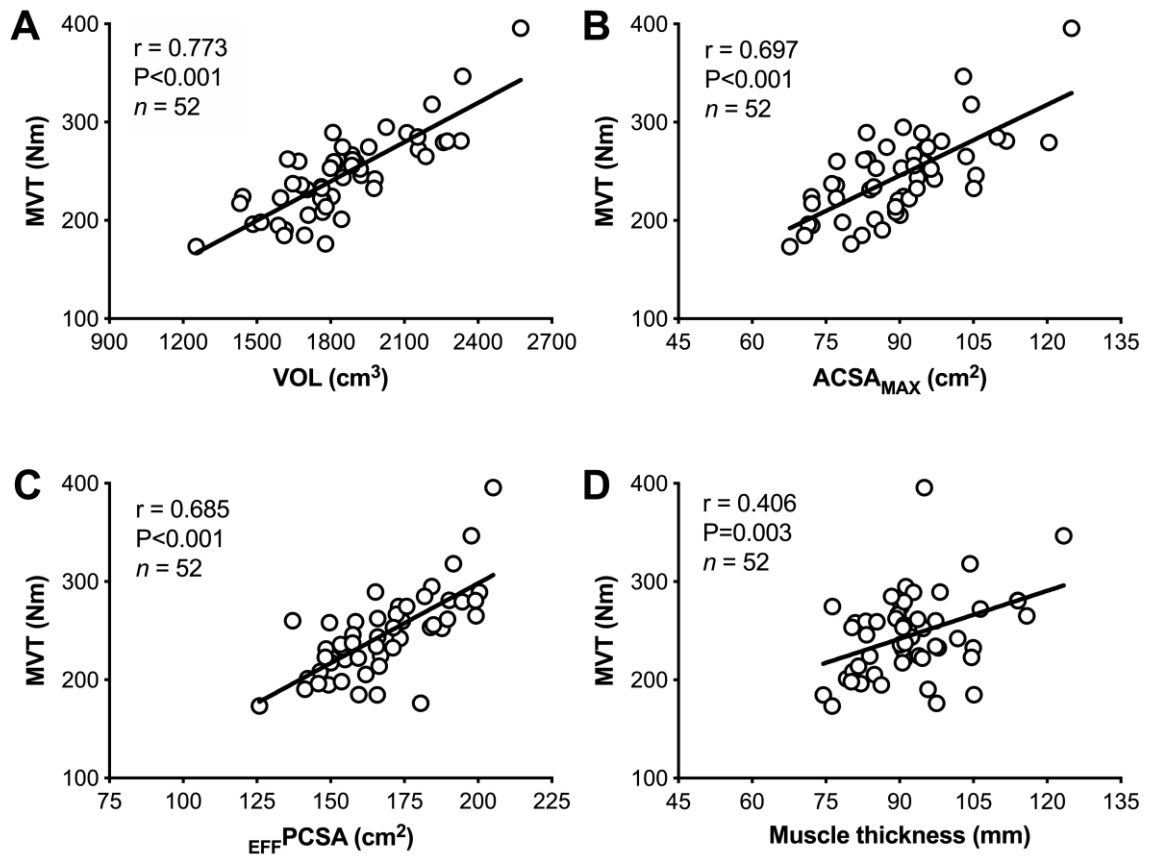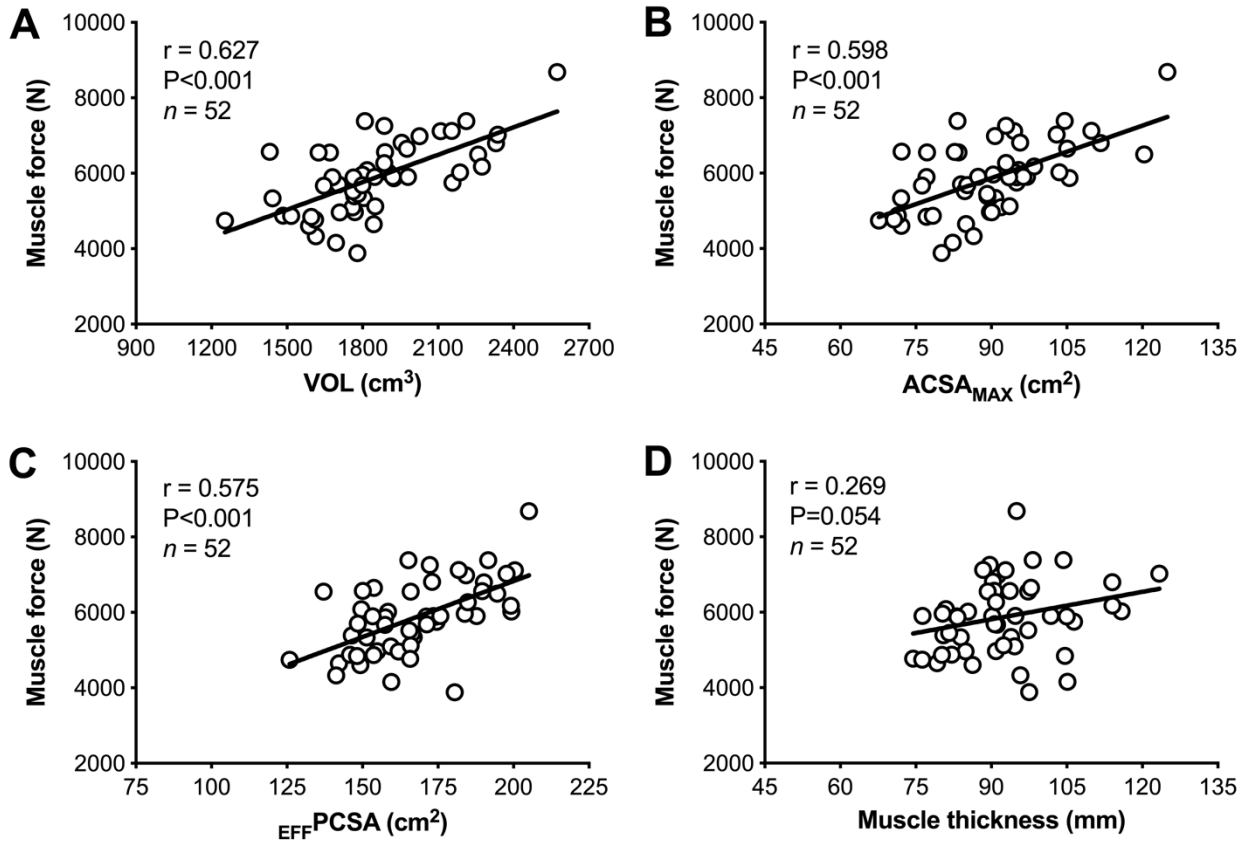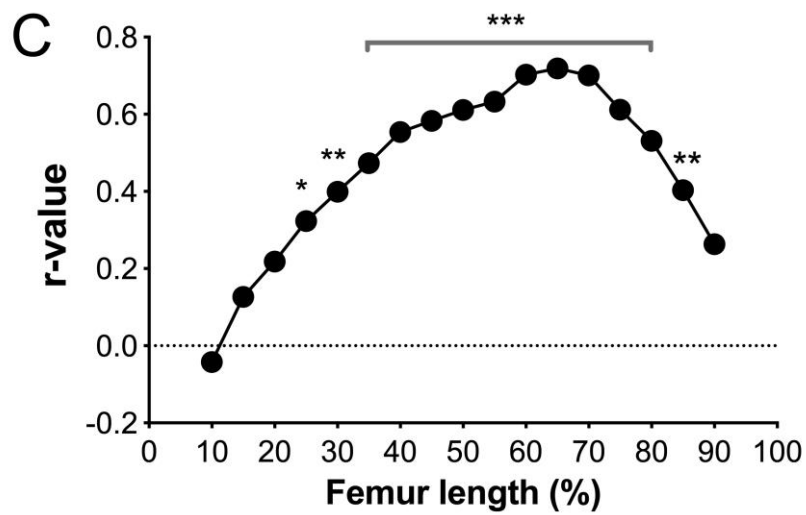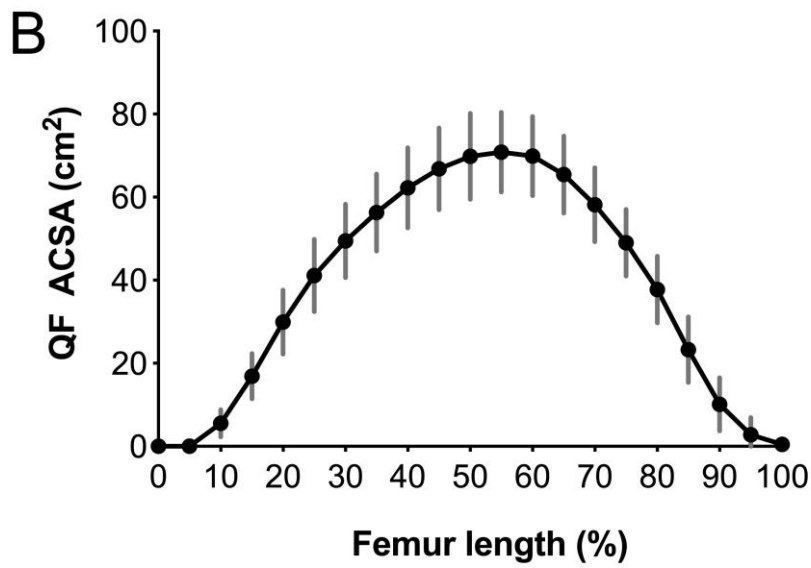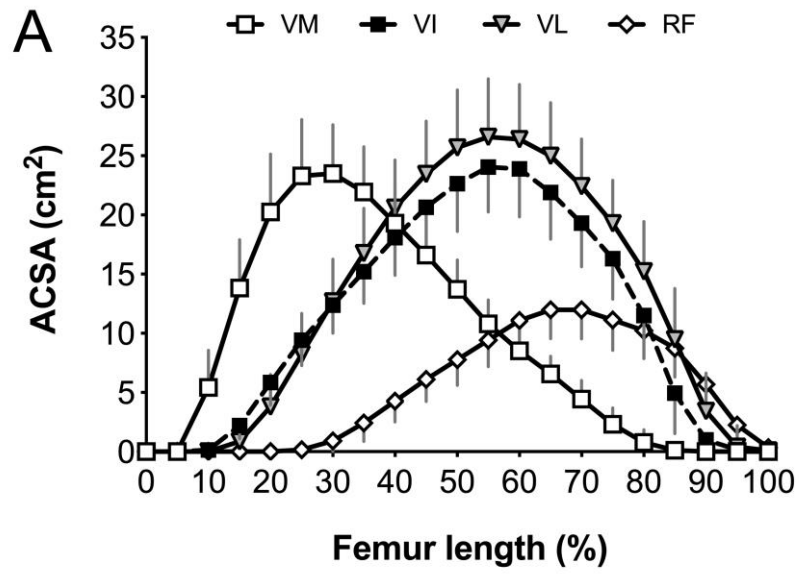Fig. 2

Fig. 3

Fig. 4

TABLES

Table 1. Muscle size of overall and constituent quadriceps femoris (QF) muscles

	Muscle volume (cm^3)	ACSA$_{MAX}$ (cm^2)	$_{EFF}$PCSA (cm^2)	Muscle thickness (mm)
VM	441 ± 68	25 ± 4	40 ± 7	26 ± 5
VI	547 ± 104	25 ± 4	54 ± 10	20 ± 4
VL	610 ± 98	28 ± 5	52 ± 8	25 ± 3
RF	240 ± 47	13 ± 2	21 ± 3	22 ± 3
QF	1838 ± 263	90 ± 12	167 ± 19	92 ± 11

Data are Mean ± SD. VM, vastus medialis. VI, vastus intermedius. VL, vastus lateralis. RF, rectus femoris.