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Local architecture of the vastus intermedius is a better predictor of knee extension force than that of the other quadriceps femoris muscle heads

Ryosuke Ando[1], Akira Saito[1,2], Yoshihisa Umemura[3] and Hiroshi Akima[1,4]

[1]Graduate School of Education and Human Development, Nagoya University, Nagoya, [2]Japan Society for the Promotion of Science, Tokyo, [3]School of Health and Sport Sciences, Chukyo University, and [4]Research Center of Health, Physical Fitness & Sports, Nagoya University, Nagoya, Japan

Correspondence
Ryosuke Ando, Graduate School of Education and Human Development, Nagoya University, Furo, Chikusa, Nagoya, Aichi 464-8601, Japan
E-mail: ando@nagoya-u.jp

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Summary

The purpose of this study was to determine whether the muscle architecture of each head of the quadriceps femoris (QF) at multiple regions can be used to predict knee extension force. Muscle thickness and pennation angle were measured using sonographic images from multiple regions on each muscle of the QF with the knee flexed to 90°. The fascicle lengths of the rectus femoris (RF), vastus lateralis (VL) and vastus intermedius (VI) muscles were estimated based on sonographic images taken along the length of the thigh. The muscle architecture of the vastus intermedius was determined in two separate locations using sonographic images of the anterior (ant-VI) and lateral portions (lat-VI). The maximal voluntary contraction (MVC) was measured during isometric knee extension at a knee joint angle of 90°. The relationship between MVC force and muscle architecture was examined using a stepwise linear regression analysis with MVC force as the dependent variable. The muscle thickness of the ant-VI was selected as an independent variable in the first step of the linear regression analysis ($R^2 = 0{\cdot}66$, $P<0{\cdot}01$). In the second step, pennation angle of the lat-VI was added to the model ($R^2 = 0{\cdot}91$, $P<0{\cdot}01$). These results suggest that among the four muscles that make up the QF, the muscle architecture of the VI is the best predictor of knee extension force.

Introduction

The human quadriceps femoris (QF) consists of four muscles: the vastus intermedius (VI), vastus lateralis (VL), vastus medialis (VM) and rectus femoris (RF). Of these four, we have recently reported that the VI may make the greatest contribution to knee extension during dynamic contractions under heavy load (Akima & Saito, 2013b). Furthermore, the VI is the primary knee extensor during submaximal isometric contraction (Zhang *et al.*, 2003). Finally, the VI occupies approximately 30% of the volume of the QF muscle (Akima *et al.*, 2007), and the physiological cross-sectional area (PCSA) of the VI is the largest of any muscle within the QF (Friederich & Brand, 1990; O'Brien *et al.*, 2010), both of which play an important role in generating force during knee extension.

Despite the important role played by the VI, it has been overlooked in the majority of studies examining the muscle architecture of QF using ultrasonography (Fukunaga *et al.*, 1997; Ichinose *et al.*, 1997; Kubo *et al.*, 2001; Reeves *et al.*, 2004; Austin *et al.*, 2010; Csapo *et al.*, 2011; Guilhem *et al.*, 2011). In a recent examination of the VL and RF muscles, Moreau *et al.* (2010) concluded that the architecture of the VL was the best predictor of knee extension torque. Taken together, the above findings suggest that adding architectural information on the VI may result in models that more accurately predict the function of the knee during extension. This would allow for more accurate estimates of muscle strength in individuals with a muscle injury or disease that precludes a maximal effort. Further, enhanced understanding of the relationship between muscle architectural properties and muscle function may help to develop superior resistance training regimens for elderly individuals and patients with muscle atrophy.

Because of its time resolution and low cost, ultrasound is widely used to assess muscle architecture in both research and clinical fields. Blazevich *et al.* (2006) and O'Brien *et al.* (2010) measured muscle architecture of the QF muscles at proximal, middle and distal portions of each muscle using ultrasonography, concluding that muscle architecture differs greatly across scanning sites. Therefore, there is a need to investigate which ultrasonography measurement site is most closely associated with muscle function.

Finally, we should not overlook differences in knee joint angle during assessments using ultrasound imaging and knee extension strength in previous studies (Moreau et al., 2010; Strasser et al., 2013) that modify the fascicle length and pennation angle (Fukunaga et al., 1997; Ichinose et al., 1997). Ultrasound scanning is generally performed with the knee joint in the extended position (0–20°; Blazevich et al., 2007; Moreau et al., 2010; O'Brien et al., 2010; Strasser et al., 2013). However, knee extension strength is measured at knee joint angles in the range of 60–90° (Freilich et al., 1995; Blazevich et al., 2009; Moreau et al., 2010; Akima et al., 2012; Strasser et al., 2013). This important difference between the two methodologies could impair our understanding of the relationship between the architectural and functional properties of QF muscles.

The purpose of this study was to determine whether the muscle architecture parameters, such as muscle thickness, pennation angle and fascicle length, of each head of the QF group at multiple regions can be used to predict knee extension force. We hypothesized that knee extension force would be more highly correlated with muscle thickness and pennation angle of the VI than with the other muscles that make up the QF.

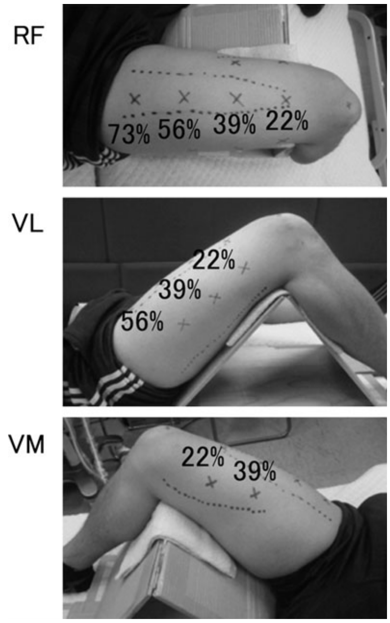

Figure 1 Scanning sites of the thigh. Crosses identify scanning sites, dots mark the border between muscles. The percentages 22%, 39%, 56% and 73% represent the length from the superior border of the patella to the anterior superior iliac spine (Blazevich et al., 2006). RF, rectus femoris; VL, vastus lateralis; VM, vastus medialis. The vastus intermedius was identified in sonographic images of scanning sites of the RF and the VL.

Methods

Participants

Eleven healthy men (age: 21·9 ± 0·9 years; height: 174·3 ± 6·2 cm; weight: 65·1 ± 9·3 kg) volunteered for this study. The participants had not been involved in any type of resistance training for several years. Before the experiment, the purpose, procedures and risks associated with the study were explained and written informed consent was obtained from all participants. All experimental protocols were approved by the Ethics Committee of the Research Center of Health, Physical Fitness and Sports, Nagoya University.

Ultrasound scanning

Participants were placed in the supine position on an examination bed with a knee joint angle of 90° to match the angle during force measurement. We identified scanning sites on the skin surface of the right thigh according to the procedures used by Blazevich et al. (2006) (Fig. 1). Sites were located at 22%, 39%, 56% and 73% of the length from the superior border of the patella to the anterior superior iliac spine (Blazevich et al., 2006).

The muscle shape, including muscle length and the bulky region of the muscle belly, of each head of the QF group is different along the length of the thigh (Morse et al., 2007; Ward et al., 2009). We accounted for these differences in architecture at the sonographic measurement sites. Muscle architecture of the RF was measured using sonographic images that were taken at 39%, 56% and 73% scanning sites. The VL was measured from sonographic images that were taken at 22%, 39% and 56%. The VM was measured using sonographic images that were taken at 22% and 39%. The VI was divided into anterior (ant-VI) and lateral (lat-VI) segments, identified using sonographic images on the RF and VL, respectively, using scanning sites 22%, 39% and 56%.

Longitudinal sonographic images were acquired using Logiq 5 Pro ultrasound scanner (General Electric, Duluth, GA, USA) with a 3·8 cm linear array probe. A water-soluble gel was applied to the scanning head of the probe to achieve acoustic coupling, and extra care was taken to avoid deformation of the muscle architecture. The probe was oriented perpendicular to the skin and parallel to the estimated fascicle direction.

Knee extension task

The isometric knee extension task was performed using a custom-made dynamometer (Takei Scientific Instruments Co. Ltd, Niigata, Japan) attached to a force transducer (LTZ-100KA; Kyowa Electronic Instruments, Tokyo, Japan). The hip was fixed to the seat by straps and the ankle was attached to a pad by straps. The hip and knee joint angles were flexed to 70° and 90° respectively. The lever arm consisted of a vertical aluminium bar and a horizontal padded aluminium bar. The length of the vertical aluminium bar was adjusted to the length of each participant's leg. The horizontal padded aluminium bar was attached to a force transducer, which was in line with the applied force. The participants were asked to grab handles mounted on the sides of the seat to help stabilize the upper body. After the warm-up, the participant performed two maximal voluntary contractions (MVC) with ≥1 min of rest between trials. If the two MVC forces differed by more than 5%, an additional trial was performed. The MVC consisted of a force-rising phase (1–2 s), a sustained phase (≥3 s) and a relaxation phase. Signals from the force transducer were sampled using an A-D converter (PowerLab; ADInstruments, Melbourne, Vic., Australia).

Test–retest reliability

One week after the initial testing, nine of 11 participants came back to the laboratory to assess test–retest reliability of the ultrasound measurement and MVC tests. The procedures used during the follow-up tests were identical to those used during initial testing.

Data analysis

All images were analysed using public domain image-processing software (ImageJ, version 1.46; National Institutes of Health, Bethesda, MD, USA). Muscle thickness in the superficial muscles (RF, VL and VM) was defined as the distance between the superior border of the subcutaneous fascia and the deep aponeurosis. In the deep muscle (VI), muscle thickness was defined as the distance between the inferior border of the superficial aponeurosis and the superior border of the femur (Fig. 2). Pennation angle of superficial muscles was measured as the angle between the fascicle and its deep aponeurosis and that of deep muscle was measured as the angle between the fascicle and its superficial aponeurosis (Rutherford & Jones, 1992; Ema *et al.*, 2013a; Fig. 2).

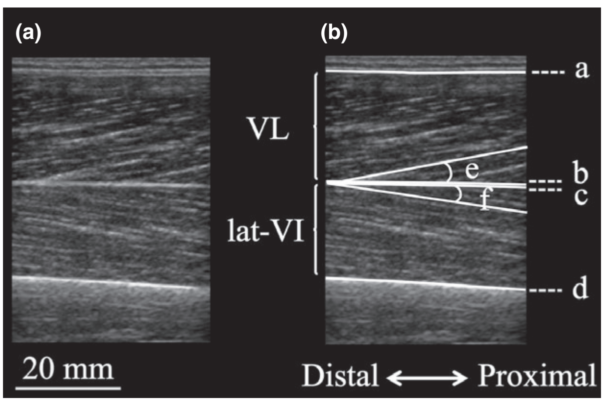

Figure 2 Representative sonographic image of the VL and lat-VI without mark-up (a) and with anatomical landmarks identified (b). VL, vastus lateralis; lat-VI, lateral vastus intermedius; a, superficial aponeurosis of the VL; b, deep aponeurosis of the VL; c, superficial aponeurosis of the VI; d, superior border of femur; e, pennation angle of the VL; f, pennation angle of the lateral VI.

Fascicle length was measured using linear extrapolation technique (Blazevich *et al.*, 2009; Ema *et al.*, 2013b; Ando *et al.*, 2014), because the full fascicle could not be seen in the sonographic image. Fascicle length was measured at the mid-portion of each quadriceps muscle, and no measurement was performed for VM because there was large fascicle curvature and angle between the superficial aponeurosis and deep aponeurosis in all participants. Pennation angle and fascicle length values were measured for three different fascicles that were clearly seen in a sonographic image and these three values were averaged to obtain a representative value for each muscle.

The MVC force was sampled and averaged over 1 s in the sustained phase during each contraction using Chart 5.5 software (ADInstruments). The average of the two highest MVCs was used as the representative MVC force.

Statistical analyses

All data are presented as mean ± SD. Muscle thickness and pennation angle were compared between scanning sites for each muscle using a one-way analysis of variance (ANOVA). When Levene's test showed unequal variance for muscle thickness and pennation angle for any muscle, we used a paired t-test with Bonferroni correction ($\alpha = 0{\cdot}0167$) to compare the three scanning sites. Fascicle length was compared among muscles using factorial ANOVA. When a significant difference was observed in any ANOVA, a Tukey's *post-hoc* test was performed. Relationships between MVC force and muscle thickness, pennation angle and fascicle length were examined using a Pearson product moment correlation. A stepwise linear regression analysis was performed to create a predictive model of MVC force. Muscle thickness, pennation angle and fascicle length of all scanning sites for each muscle were entered into the stepwise regression as independent variables if they represented a significant contribution to the explained variance (P to enter $\leq 0{\cdot}05$, P to remove $\geq 0{\cdot}10$). Intraclass correlation coefficients (ICC) were used to assess the test–retest reliability of muscle architecture measurements while between-day coefficient of variation (CV) was calculated for MVC. The level of significance was set at $P<0{\cdot}05$; however, it was adjusted by Bonferroni correction when appropriate. Statistical analyses were performed using the IBM SPSS Statistics software (version 20.0; IBM, Tokyo, Japan).

Results

The ICC values of muscle thickness (0·966) and pennation angle (0·949) were very high, although they were slightly lower for fascicle length (0·836). The MVC between-day CV was 6·7%.

Muscle thickness and pennation angle of the RF, ant-VI, VL, lat-VI and VM at each scanning site are presented in Fig. 3. For muscle thickness, regional differences were observed for all muscles except the VM. Pennation angle of the RF, VL, lat-VI and VM was significantly different among scanning sites. Fascicle length of the RF, ant-VI, VL and lat-VI was not significantly different between muscles (Table 1).

The average MVC force at a knee joint angle of 90° was 538·7 ± 92·8 N. A significant positive correlation was observed between MVC force and muscle thickness at 56% ant-VI (r = 0·74, P<0·01; Fig. 4), and pennation angle at 39% lat-VI (r = 0·68, P<0·05; Fig. 5). In contrast, there was no significant correlation between MVC force and fascicle length for any muscle.

Table 2 shows a summary of the stepwise linear regression analysis. In step 1, muscle thickness at 56% ant-VI entered the model with a coefficient of determination of 0·66 (P<0·01). Pennation angle at 56% lat-VI entered the model in step 2, increasing the coefficient of determination to 0·91 (P<0·01). No other variables were added or retained in the model.

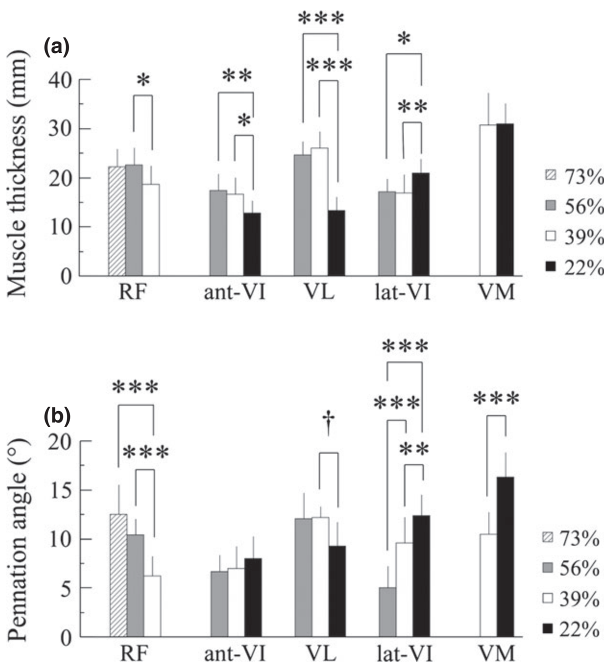

Figure 3 Muscle thickness (a) and pennation angle (b) of the RF, ant-VI, VL, lat-VI and VM at each scanning site. The percentages 22%, 39%, 56% and 73% represent the length from the superior border of the patella to the anterior superior iliac spine (Blazevich *et al.*, 2006). RF, rectus femoris; ant-VI, anterior vastus intermedius; VL, vastus lateralis; lat-VI, lateral vastus intermedius; VM, vastus medialis. Mean ± SD. *Significantly different, P<0·05. **Significantly different, P<0·01. ***Significantly different, P<0·001. †Significantly different P<0·0167.

Table 1 Mean fascicle length of the RF, ant-VI, VL and lat-VI.

	Fascicle length (mm)
RF	103·7 ± 10·8
ant-VI	107·6 ± 12·4
VL	100·5 ± 11·9
lat-VI	108·5 ± 11·0

Values are means ± SD.
RF, rectus femoris; ant-VI, anterior vastus intermedius; VL, vastus lateralis; lat-VI, lateral vastus intermedius.

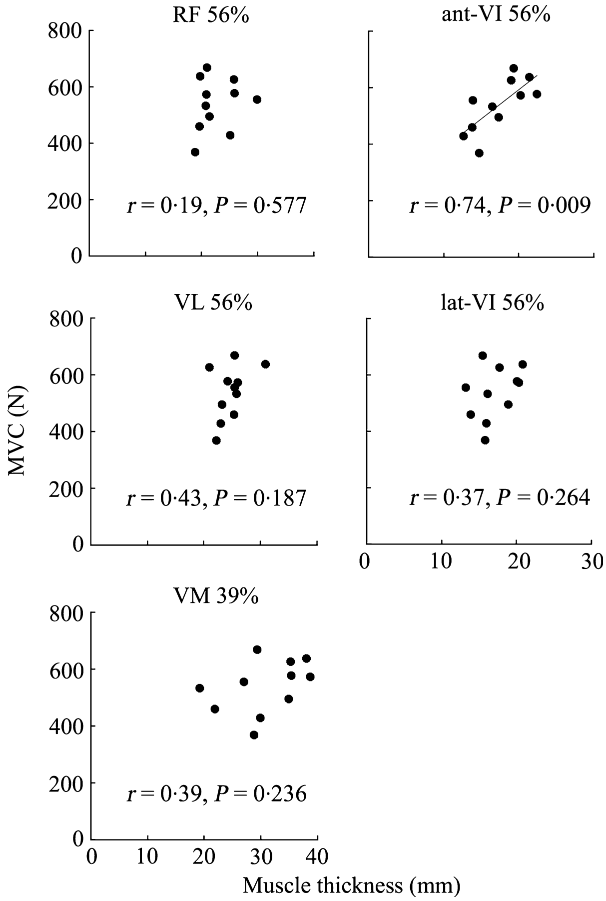

Figure 4 Correlations between MVC force and muscle thickness at a representative site for each quadriceps. MVC, maximal voluntary contraction; RF, rectus femoris; ant-VI, anterior vastus intermedius; VL, vastus lateralis; lat-VI, lateral vastus intermedius; VM, vastus medialis.

Discussion

The purpose of this study was to determine whether the muscle architecture parameters, such as muscle thickness, pennation angle and fascicle length, of each head of the QF group at multiple regions can be used to predict knee extension force. Both correlation and stepwise linear regression analyses suggested that there is a close relationship between knee extension force and the muscle thickness and pennation angle of the VI.

Consistent with previous studies, we observed regional differences in muscle thickness and pennation angle in the muscles that make up the QF (Blazevich *et al.*, 2006; O'Brien *et al.*, 2010). This finding was observed despite performing our measurements at a different knee joint angle than in previous reports. These results indicate that muscle architecture of the

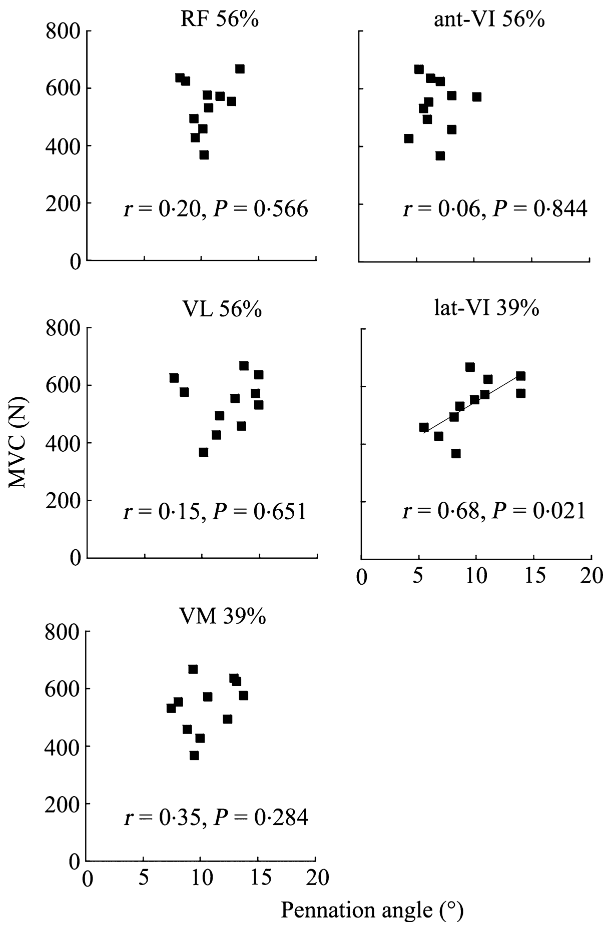

Figure 5 Correlations between MVC force and pennation angle at a representative site for each quadriceps. MVC, maximal voluntary contraction; RF, rectus femoris; ant-VI, anterior vastus intermedius; VL, vastus lateralis; lat-VI, lateral vastus intermedius; VM, vastus medialis.

Table 2 Stepwise linear regression analysis predicting MVC force of the knee extension.

Independent variables	Multiple regression equation	R	R^2	P
Step 1				
X_1: muscle thickness at 56% ant-VI	MVC = 110·4 + 24·1 X_1	0·81	0·66	0·004
Step 2				
X_1: muscle thickness at 56% ant-VI	MVC = 94·5 + 31·9 X_1−24·3 X_2	0·95	0·91	0·003
X_2: pennation angle at 56% lat-VI				

MVC, maximal voluntary contraction; ant-VI, anterior vastus intermedius; lat-VI, lateral vastus intermedius.

QF differs across scanning sites regardless of knee joint angle, and suggest that the relationship between muscle architecture and function are likely to differ across sites. This is supported by our observation of a significant positive correlation between MVC force and muscle thickness at 56% ant-VI (r = 0·74), and pennation angle at 39% lat-VI (r = 0·68), but not at other locations on the VI. Therefore, researchers and clinicians should consider the scanning site when using ultrasonography to estimate muscle function based on architectural properties.

A novel finding of this study was that muscle thickness and pennation angle of the VI were selected as predictors of knee extension force in a stepwise linear regression analysis, accounting for 91% of the variance in MVC force. This result conflicts with a previous study by Moreau *et al.* (2010) reporting muscle thickness of the VL as the best predictor of knee extension torque. However, it should be noted that Moreau *et al.* (2010) examined only the VL and RF muscles. Our results are supported by the studies of Lieb & Perry (1968) and Zhang *et al.* (2003). Lieb & Perry (1968) examined the transmission efficiency of tendon force by directly pulling the muscle head of each QF muscle in the amputated legs of cadavers. They found that, in comparison with other muscles, full extension of the knee joint was achieved using lower loads with the VI. Further, Zhang *et al.* (2003) showed that the VI was the primary knee extensor during submaximal contraction, and that VI tension was equivalent to 40–52% of the total knee extension moment. Taken together with these previous findings, our results suggest that the relative contribution of force generated by the VI during knee extension is larger than the other individual QF muscles.

Muscle thickness at 56% ant-VI was extracted as a predictor of MVC force in the first step of the stepwise linear regression analysis in the present study. Miyatani *et al.* (2002) have previously indicated that the muscle thickness (RF + VI) at mid-thigh measured using ultrasonography was useful for estimating the muscle volume of the QF, which is itself a predictor of MVC force. The location of the 56% ant-VI image in the present study was very close to the scanning site used previously by Miyatani *et al.* (2002). Therefore, the muscle thickness at 56% ant-VI would reflect muscle volume of the knee extensor. The anatomical cross-sectional area (ACSA) of the VI at mid-femur is larger than that of the proximal or distal region (Morse *et al.*, 2007). Further, a significant increase in the ACSA of the VI in response to isokinetic resistance training was observed only in this location (Housh *et al.*, 1992). These results from previous studies may help to explain our finding that muscle thickness at 56% ant-VI was the first predictor selected in the stepwise linear regression analysis of MVC force.

Pennation angle at 56% lat-VI was extracted in the second step of the stepwise linear regression analysis in this study. This indicates that pennation angle of the VI is also a significant contributor to the predictive model of knee extension force. In support of our findings, a previous study by Strasser *et al.* (2013) observed a significant relationship between the pennation angle of the VI, but not other muscles, and knee extension force (r = 0·68). Moreau *et al.* (2010) also showed that pennation angle of the VL and RF did not make a significant contribution to a predictive model of knee extension torque for children and adolescents, although they did not measure architectural properties of the VI.

Fascicle length is negatively related to MVC force, as increased fascicle length reduces the ratio of muscle volume-to-fascicle in the PCSA formula: PCSA = muscle volume/fascicle length. Increased fascicle length is also inversely related to muscle contraction velocity (Wickiewicz *et al.*, 1984; Burkholder *et al.*, 1994). In this study, fascicle length was not selected by stepwise linear regression analysis as an independent variable predicting MVC force. This result was likely due to the isometric nature of the contractions. Methodological limitations may have affected the reported relationships between the MVC force and the fascicle length of each individual muscle. Fascicle lengths were estimated based on a single ultrasound image using linear extrapolation, as was done in previous studies (Blazevich *et al.*, 2009; Erskine *et al.*, 2009; Ema *et al.*, 2013a). We confirmed that there is a close relationship between the extrapolated fascicle length, using the same methods performed in this study, and the fascicle length measured directly from the QF group in cadavers (ICC ranged from 0·813 to 0·853; Ando *et al.*, 2014). However, we obtained the ultrasound images at full knee extension in the previous study, and the length estimates were shorter than in this study. These shorter fascicle lengths may be associated with the differences in methodology and/or subject's demographics. Despite these differences, we found high reproducibility in fascicle length measurements on the different days in the present study (ICC = 0·836).

Our findings related to muscle thickness and MVC force are in contrast to those reported previously. Strasser *et al.* (2013) have shown a positive correlation between the thickness of individual QF muscles and knee extension strength. However, MVC force was associated only with VI in this study. This inconsistency could be due to measurements being taken at different knee joint angles across the two studies. Strasser *et al.* (2013) measured the muscle thickness in a supine position with the knee to flexed 10–20° from full extension. In this study, muscle architecture and knee extension force were measured at a knee joint angle of 90°. Several recent reports have illustrated the functional importance of the VI at flexed knee joint position (90–65°; Watanabe & Akima, 2011; Akima & Saito, 2013a,b). This functional importance is likely one of the reasons why VI muscle architecture was selected in the stepwise linear regression analysis in this study. On the other hand, the small sample size may be one reason why no significant correlations were found between MVC force and VL, VM and RF muscle thickness, even though these muscles are thought to be strong contributors to the production of knee extension torque. Their contributions might be masked by the close relationship between MVC force and muscle architecture in the VI. It is important to note that we achieved high statistical power, that is, 0·956, in the analysis of the relationship between MVC force and VI muscle thickness. This evidence supports the reported correlation coefficient between the two variables.

One limitation of this study was that the hip joint angle during ultrasound scanning (50°, 0° = anatomical position) was not exactly the same as during the strength measurement (70°), which might affect the muscle architecture of the RF. To the best of our knowledge, the muscle architecture of the RF has not been examined at various knee and hip joint angles in any previous study. According to published results on other muscles, a 20° difference in joint angle for a given muscle does not strikingly affect the muscle architecture. For example, the difference in VL pennation angle appears to be <1° between the knee joint at an angle of 15° and at rest (Ichinose *et al.*, 1997). Furthermore, Maganaris & Baltzopoulos (1999) showed that the muscle thickness of the tibialis anterior was very similar at four joint angles. They also showed only an approximately 4° change in pennation angle and 20 mm change in fascicle length as joint angle changed by 45°. Therefore, we expect that the effect of hip joint angle differences on the correlations found in this study was minimal.

In conclusion, we found that muscle thickness and pennation angle of the VI were closely related to knee extension force. In contrast, MVC force was not associated with muscle thickness or pennation angle of the other muscles that comprise the QF. These results suggest that the VI muscle architecture is a better predictor of knee extension force than that of the other QF muscle heads. The present findings may help to develop estimates of knee extensor strength that do not require a maximal effort among persons with or without injury (Akima *et al.*, 2008; Hioki *et al.*, 2013) or diseases such as muscular dystrophy (Akima *et al.*, 2012) and cerebral palsy (Moreau *et al.*, 2010).

Conflict of interest

The authors declare that there are no conflicts of interest.

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