Short Communication

Relationships between lower body muscle structure and isometric mid-thigh pull peak force

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Objectives: To explore relationships between aspects of vastus lateralis (VL) and medial gastrocnemius (MG) muscle structure (muscle thickness, fascicle length and pennation angle) and isometric mid-thigh pull (IMTP) peak force capacity.

Design and Methods: Fifteen male collegiate athletes (height 1.79 ± 0.05 m; body mass 82.8 ± 8.1 kg, age 23.2 ± 3.4 years), from a wide range of field-based sports, had sonographic images of their VL and MG musculature (for the dominant leg) recorded at rest before participating in a standardized maximal IMTP protocol.

Results: Intraclass correlation coefficients (≥ 0.91, $p < 0.001$) and coefficient of variation percentages ($\leq 2.5\%$) showed excellent reliability of the muscle structure and IMTP peak force measurements. A large positive relationship was found between VL muscle thickness and absolute IMTP peak force ($r = 0.62$, $p < 0.01$, power = 0.89). Moderate, but non-significant, relationships were observed between VL pennation angle and both absolute ($r = 0.41$, $p = 0.06$, power = 0.60) and relative ($r = 0.39$, $p = 0.08$, power = 0.46) IMTP peak force. A small non-significant correlation was noted between VL muscle thickness and relative IMTP peak force ($r = 0.26$, $p = 0.19$). No aspect of MG muscle structure was significantly correlated with IMTP peak force.

Conclusion: The VL muscle thickness of male collegiate athletes' dominant leg is largely correlated to their bilateral absolute IMTP peak force capacity (demonstrating 38% shared variance). Practitioners should, therefore, develop hypertrophy of male collegiate athletes' VL musculature through appropriately designed strength training programs.

(*Journal of Trainology* 2015;4:43-48)

Key words: muscle thickness ■ pennation angle ■ fascicle length ■ force ■ strength

INTRODUCTION

Structural properties of human skeletal muscle (e.g. muscle thickness, fascicle length and pennation angle) directly influence force, velocity, and thus power production during athletic tasks.[1] For example, greater muscle thickness and pennation angles result in an increase in force capacity whereas longer fascicles can produce greater fibre shortening velocities, leading to increased power output.[1] Each of the aforementioned aspects of muscle structure can be reliably[2] and noninvasively quantified for multiple upper and lower body muscles via ultrasonography. This notion has led to muscle structure assessments forming part of a range of recently conducted cross-sectional[3-7] and intervention studies[8-11]. Correlational analyses conducted as part of many of these studies have linked distinct aspects of lower body muscle architecture to peak force and power measured during several dynamic[3, 4, 7] and isometric[3, 8] tasks thought to be beneficial to athletic performance.

The bilateral vastus lateralis (VL) muscle thickness of elite male surfers was, for example, found to be significantly correlated to peak force ($r = 0.53$-0.60, $p \leq 0.04$) produced during the isometric mid-thigh pull (IMTP) and during both the squat jump (SJ) and countermovement jump (CMJ) ($r = 0.54$-0.77, $p \leq 0.04$).[3] Furthermore, the lateral gastrocnemius (LG) pennation angle of this groups' left leg (i.e. the dominant leg for 13 of the 15 athletes tested) was significantly correlated with peak force ($r = 0.53$, $p = 0.04$) attained in the SJ and both absolute ($r = 0.70$, $p < 0.01$) and relative ($r = 0.63$, $p = 0.01$) peak force produced in the IMTP.[3] Large correlation coefficients were also observed between bilateral VL muscle thickness and IMTP peak force ($r = 0.67$, $p < 0.01$) in junior competitive male and female surfers, with bilateral LG muscle thickness ($r = 0.54$, $p < 0.01$) and VL pennation angle ($r = 0.46$, $p < 0.01$) also demonstrating large and moderate associations, respectively, with IMTP peak force for this cohort.[12] Similar trends were also found in young competitive track and field throwers (6 males and 6 females) in that VL muscle thickness and pennation angle were related to isometric leg press peak force ($r = 0.64$-0.85, $p < 0.05$).[8]

The influence of lower body muscle structure on the dynamic and isometric performances noted in the aforementioned studies are not exclusive to highly trained or elite athletes, however. LG muscle thickness was, for example, a significant predictor ($R^2 = 0.12$-0.20) of absolute power produced by recreationally (strength and power) trained males during the SJ, CMJ and drop jump, whereas LG pennation angle was a significant predictor ($R^2 = 0.17$-0.26) of relative power produced during these jumps.[5] Similarly, VL muscle thickness was correlated to peak power attained during the CMJ in both physically active men ($r = 0.55$, $p = 0.04$) and women ($r = 0.81$, $p < 0.01$), while VL fascicle length was also found to be related to this parameter in women ($r = 0.65$, $p = 0.01$).[7] Several studies

Received September 27, 2015; accepted November 5, 2015
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have also reported that VL muscle thickness is related to other performances that require high force and power outputs, such as one repetition maximum (1-RM) values attained for the back squat[9, 13] and weightlifting derivatives (e.g. power clean and hang power clean) [6, 8].

The assessment of peak force in particular is of paramount importance to athletic development, given that peak force capacity (in both absolute terms and relative to body mass) is known to influence sprint[14, 15], jump[3, 15-18] and change of direction[14, 19] performances. Peak force capacity was assessed in each of the aforementioned studies via the performance of maximal IMTPs, which was first introduced by Haff et al.[20] and has since become an increasingly popular assessment measure due to its high reliability[14, 21, 22], even when quantified using low sampling frequencies (e.g. 500 Hz).[23] Like VL muscle thickness[6, 9, 13], IMTP peak force has also been reported to be related to 1-RM back squat ($r = 0.97$, $p < 0.05$)[24] and power clean ($r = 0.74$, $p \leq 0.05$)[16] performances. Therefore, IMTP peak force assessments can also lend insight into athletes' dynamic force producing capacity during these fundamental strength and power exercises.[25]

Identifying which aspects of muscle architecture and, indeed, which muscles relate to maximal lower body force capacity is important for practitioners, as this may help with talent identification and could facilitate athletic program design.[3] Given that the IMTP is an established method of determining maximal lower body force capacity[14, 20-23], exploring relationships between lower body muscle structure and IMTP peak force is an interesting concept. Although the associations of IMTP peak force with both VL and LG muscle structure have been recently explored in elite and junior surfers[3, 12], this population represent a very specific athletic group and thus the relationships noted may lack transferability. Furthermore, medial gastrocnemius (MG) muscle activation was recently reported to be around 10.5% greater than LG activation across various dynamic and isometric tasks[26] and so establishing relationships between MG muscle structure and IMTP peak force may be of greater interest to practitioners. The aims of the present study were, therefore, to explore whether aspects of VL and MG muscle structure were related to the IMTP peak force capacity of collegiate athletes from a variety of sports. It was hypothesized that IMTP peak force would be positively correlated to muscle thickness and pennation angle of both the VL and MG.

METHODS

Experimental Design

This study utilized a cross-sectional design, whereby subjects were required to attend a single testing session to have three ultrasound images of both their VL and MG musculature recorded at rest before participating in a standardized maximal IMTP protocol.

Subjects

Fifteen male collegiate athletes (height 1.79 ± 0.05 m; body mass 82.8 ± 8.1 kg, age 23.2 ± 3.4 years), from a wide range of team sports (Table 1), volunteered to take part in this study. All subjects were involved in structured resistance programs, had ≥ 2 years Olympic lifting experience and were competent with correct IMTP technique (as determined by a qualified strength and conditioning coach). Subjects were provided with full participant information and all provided written informed consent. The study protocol was approved by the institutional review board and conformed to the principles of the World Medical Association's Declaration of Helsinki (1983).

Table 1 Athletes' Sport Categories

Sport	Number of Athletes
Rugby Union	2
Rugby League	3
Soccer	6
Basketball	2
Cricket	2

Procedures

The VL and MG musculature of the subject's self-reported dominant leg (right leg for all subjects) was imaged using a 7.5 MHz, 100 mm linear array, B-mode ultrasound probe (MyLab 70 XVision, Esaote, Genoa, Italy) with a depth resolution of 67 mm.[6] The VL images were taken at the half-way point between the greater trochanter and the VL distal muscle-tendon junction (as derived via ultrasound recordings) while subjects lay in a relaxed supine position (for approximately 5 minutes) with their knee at full extension.[6, 27] Resting images of the MG were recorded at the half-way point between medial femoral condyle and the MG distal muscle-tendon junction while subjects lay in a pronated position with the foot hanging off the back of the examination table in a neutral position and the knee fully extended. Three images of both the VL and the MG musculature were taken to establish the reliability of the measurements.[6, 27, 28]

Muscle structural properties were subsequently analyzed using ImageJ software (Wayne Rasband National Institute of Health, Bethesda, MD, USA). Muscle thickness was measured as the vertical distance between the superficial aponeurosis and the deep aponeurosis taken at the centre of the image.[9] Fascicle length was measured directly from the superficial to the deep aponeurosis and pennation angle was measured directly as the angle between the fascicle and the deep aponeurosis.[29] Three recordings of each muscle structural parameter were recorded for each image taken for both the VL and MG and the average measurement was used for further statistical analyses.

A custom rack was used for the IMTP test (FT700 Ballistic Measurement System, Fitness Technology, Adelaide, Australia) which allowed for a fixed bar position and the ability to alter bar height for each subject accordingly. A 400-series force plate (Fitness Technology, Adelaide, Australia) was positioned under the rack sampling at 600 Hz and was integrated with computer software (Ballistic Measurement System; Fitness Technology, Adelaide, Australia). In accordance with previous research[14, 22], bar height was adjusted to align as close as possible with each subject's mid-thigh level and they all selected their preferred magnitude of knee and hip flexion so that the positioning of IMTP test represented the start position of the second pull phase of the clean as they would perform it during training.

Subjects were instructed to perform two standardized warm up IMTP repetitions (one at 50% and one at 75% of perceived maximum effort) with one minute of prescribed rest between repetitions. This preceded two maximal IMTP efforts performed using standard lifting straps, with a three minute rest interval allowed between repetitions. Audio cues such as "pull as fast and hard as possible"[30] were given for each of the maximal IMTP efforts and subjects maintained the application of maximal force for a five second time period.[14, 22] A third maximal IMTP trial was performed if the difference in peak force values between the initial two maximal IMTP trials was greater than 250 N.[3, 31] Each subject's best IMTP trial was determined as the trial which produced the highest peak force and then taken forward for correlational analyses along with relative peak force (i.e. peak force divided by bodyweight ($N.BW^{-1}$)).

Statistical Analyses

The intraclass correlation coefficient (ICC) and the percentage coefficient of variation (%CV) were used to assess relative and absolute reliability, respectively, between-images for the muscle structure measures and between-trials for the IMTP data. Normal distribution was assessed using Shapiro-Wilk's test of normality. Relationships between variables were then explored using Pearson's (r) or Spearman's correlation coefficients (ρ) based on data normality distribution. Correlation coefficients were interpreted as trivial (0.0-0.1), small (0.1-0.3), moderate (0.3-0.5), large (0.5-0.7), very large (0.7-0.9), and nearly perfect (0.9-1.0).[32] Additionally, the coefficient of determination (R^2) was calculated for all significant parametric relationships to highlight the magnitude of explained variance. SPSS software (version 20.0, IBM) was used for all the above calculations with an alpha level of $p = 0.05$ and post-hoc statistical power calculations were applied to all relationships using G.Power 3.1.[33]

RESULTS

The results demonstrated excellent between-image reliability for all muscle structure measurements, with ICCs ranging from 0.95-1.00 ($p < 0.001$) and CV ranging from 1.26-2.54% (Table 2). The overall mean VL muscle thickness, fascicle length and pennation angle measurements were 3.12 ± 0.54 cm, 8.04 ± 1.86 cm and 23.98 ± 5.54º, respectively. The overall mean MG muscle thickness, fascicle length and pennation angle measurements were 2.37 ± 0.24 cm, 6.16 ± 1.63 cm and 23.69 ± 4.88º, respectively. Between-trial reliability for IMTP peak force was also excellent (ICC = 0.914, $p < 0.001$; CV = 2.01%) with a mean absolute and relative IMTP peak force value of 3045 ± 497 N and 3.8 ± 0.6 $N.BW^{-1}$, respectively, achieved by the group.

As shown in Figure 1a, a large positive relationship was found between VL muscle thickness and absolute IMTP peak force ($r = 0.62$, $p < 0.01$, power = 0.89). Moderate relationships were observed between VL pennation angle and both absolute ($r = 0.41$, $p = 0.06$, power = 0.60) and relative ($r = 0.39$, $p = 0.08$, power = 0.46) IMTP peak force (Figures 1b and 1c, respectively), but these correlations were not statistically significant. A small non-significant correlation was noted between VL muscle thickness and relative IMTP peak force ($r = 0.26$, $p = 0.19$, power = 0.26). No aspect of MG muscle structure was significantly correlated with IMTP peak force, with only trivial to small correlation coefficients of ≤ 0.20 ($p \geq 0.23$) observed.

Table 2 Descriptive and reliability statistics for muscle architecture data (n =15).

Variable	Image 1 Mean ± SD	Image 2 Mean ± SD	Image 3 Mean ± SD	Image Average Mean ± SD	ICC (90% CI)	%CV (90% CI)
Vastus Lateralis						
Muscle Thickness (cm)	3.13 ± 0.53	3.12 ± 0.55	3.12 ± 0.54	3.12 ± 0.52	0.99 (0.99-1.00)	1.60 (0.88-2.32)
Fascicle Length (cm)	7.98 ± 1.82	8.07 ± 1.95	8.08 ± 2.06	8.04 ± 1.86	0.98 (0.96-0.99)	2.38 (1.21-3.59)
Pennation Angle (deg)	24.14 ± 5.68	23.85 ± 5.79	23.94 ± 5.80	23.98 ± 5.54	1.00 (0.99-1.00)	1.45 (0.38-2.42)
Medial Gastrocnemius						
Muscle Thickness (cm)	2.35 ± 0.28	2.36 ± 0.24	2.38 ± 0.25	2.37 ± 0.24	0.95 (0.87-0.98)	2.43 (1.38-3.28)
Fascicle Length (cm)	6.10 ± 1.80	6.15 ± 1.69	6.23 ± 1.60	6.16 ± 1.63	0.99 (0.98-1.00)	2.54 (1.69-3.39)
Pennation Angle (deg)	23.84 ± 4.99	23.70 ± 5.06	23.54 ± 5.15	23.69 ± 4.88	1.00 (1.00-1.00)	1.26 (0.37-2.15)

SD = standard deviation, ICC = intraclass correlation coefficient, %CV = percentage coefficient of variation, and CI = confidence intervals

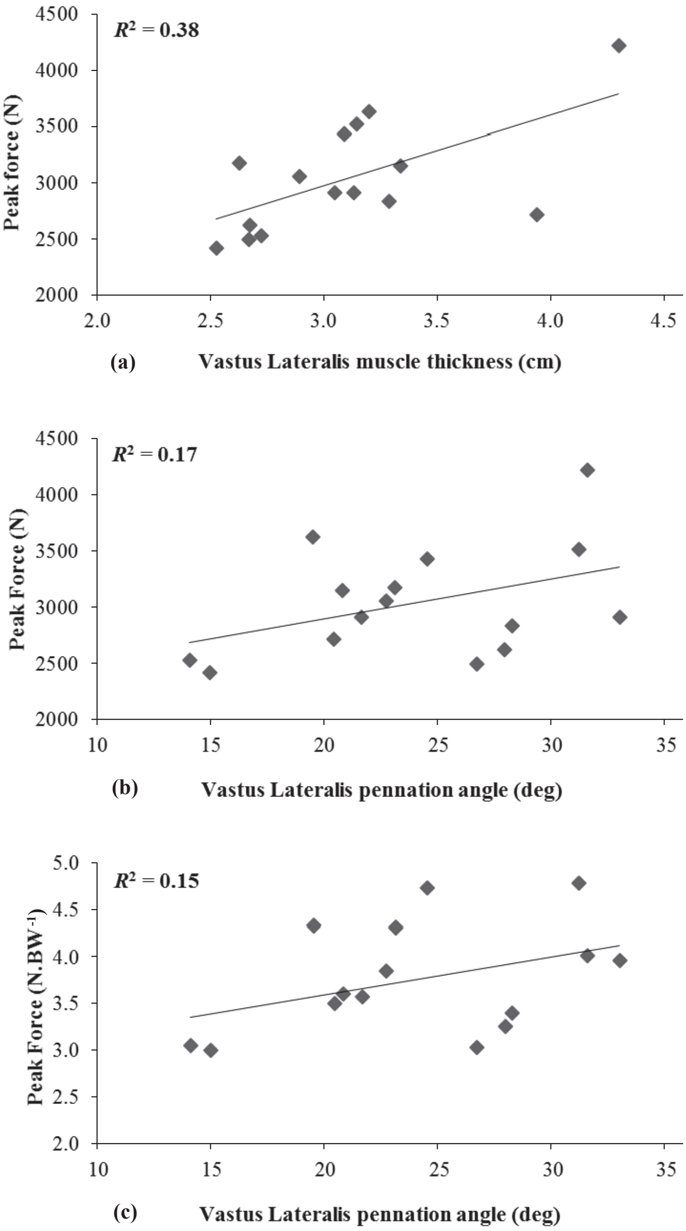

Figure 1 Relationships between (a) vastus lateralis muscle thickness and absolute isometric mid-thigh pull peak force; (b) vastus lateralis pennation angle and absolute isometric mid-thigh pull peak force; (c) vastus lateralis pennation angle and relative isometric mid-thigh pull peak force.

DISCUSSION

The main finding of this study was that a large positive relationship ($r = 0.62$, $p < 0.01$) was observed between VL muscle thickness and absolute IMTP peak force, resulting in VL muscle thickness accounting for 38% of the variance in absolute IMTP peak force capacity (Figure 1a). The direction and magnitude of this correlation is very similar to values reported by Secomb et al. in elite male surfers ($r = 0.53$-0.60, $p \leq 0.04$)[3] and in junior competitive male and female surfers ($r = 0.67$, $p < 0.01$),[12] which adds credence to the present results and highlights the importance of developing the VL muscle thickness of collegiate athletes in order to induce increases in lower limb peak force capacity. As mentioned earlier, increasing the force generating capacity of an athlete's lower limb(s) positively influences their ability to sprint, jump and change direction[3, 14-19] and the present results suggest that this may be facilitated by developing hypertrophy of the VL musculature.

Moderate relationships were observed between VL pennation angle and both absolute ($r = 0.41$, $p = 0.06$, power = 0.60) and relative ($r = 0.39$, $p = 0.08$, power = 0.46) IMTP peak force (Figures 1b and 1c, respectively), but these correlations were not statistically significant. Nevertheless, the trends reported here may reflect previous observations that VL muscle thickness is positively related to VL pennation angle[34] and thus both a greater thickness and pennation angle of the VL muscle will augment its capacity to produce high forces.[35] A strength training program which included exercises such as the back squat was shown to increase VL muscle thickness and pennation angle in concurrently training athletes in as little as five weeks.[36] Strength and conditioning coaches should, therefore, encourage their athletes to perform exercises such as the back squat as part of their strength training programs in order induce such structural adaptations to the VL muscle. This type of training should also help athletes to increase IMTP peak force capacity, given the previously reported high association with 1-RM back squat performance ($r = 0.97$, $p < 0.05$).[24]

Although Secomb et al.[3] observed large correlations between the LG pennation angle of elite surfers' left leg and both absolute and relative IMTP peak force ($r = 0.63$-0.70, $p = 0.01$), the present study did not replicate these findings with the MG. The reason for this difference may be due to the differential contributions of the LG and MG to isometric peak force production.[26] However, the MG was found to be the greatest contributor to triceps surae activation during maximal voluntary isometrics contractions[26] and so one might have expected MG architecture to have demonstrated a higher association to IMTP peak force capacity in the present study. The fact that MG muscle thickness and pennation angle was recently reported to be correlated with 1-RM power clean performance ($\rho = 0.48$-0.54, $p < 0.05$),[6] a task which is highly related to IMTP peak force ($r = 0.74$, $p \leq 0.05$),[16] emphasises this notion. Based on this previous work, it may be reasonable to assume that the correlation coefficients between left LG pennation angle and IMTP peak force reported by Secomb et al.[3] represented a distinct quality of elite male surfers who, in this case, relied more heavily on left leg (i.e. dominant leg) force production as part of their sport. Although MG muscle architecture of the subjects' dominant leg was assessed in the present study, the types of sports performed by the subjects tested (Table 1) are unlikely to induce the same degree of asymmetry when compared to elite surfers who habitually adopt a stance in training and competition which places more force through one leg.

A limitation of this study is that muscle structure was imaged for one leg only, although a recent similar study also tested the dominant limb only[8] and there were no significant bilateral differences in the VL muscle structure of recreationally trained males reported in an earlier study[7]. Nevertheless, it may be prudent for future research to assess relationships between unilateral IMTP kinetics and unilateral muscle structural properties given the possibility for bilateral differences between these relationships.[3] A further limitation of this study and, indeed, the study conducted by Secomb et al.[3] is the relatively small sample size tested (n = 15 in both). The relationships between VL pennation angle and both absolute and relative IMTP peak force would have reached statistical significance if a larger sample of subjects were tested in the present study. Indeed, this was observed in the more recent study conducted by Secomb et al.[12] whereby significant moderate relationships were found between VL pennation angle and IMTP peak force ($r = 0.46$, $p < 0.01$) for a sample of 30 junior surf athletes. To that end, future research should consider exploring relationships between IMTP kinetics and aspects of lower body muscle structure with a larger cohort in to order expand upon the key trends presented in this study. Finally, it should be noted that the results of this study apply to male collegiate athletes only, thus it would be prudent to avoid the assumption that the relationships reported here apply to female athletes too, given that previous research reported gender differences in lower body muscle structure.[37] Further research into the associations between IMTP kinetics and the lower body muscle structure of female athletes is, therefore, warranted.

CONCLUSION

The VL muscle thickness of male collegiate athletes' dominant leg is largely correlated to their bilateral absolute IMTP peak force capacity (demonstrating 38% shared variance). Furthermore, the VL pennation angle of this group's dominant leg is moderately, but non-significantly, correlated to their bilateral absolute and relative IMTP peak force capacity. The MG muscle structure of the dominant leg on the other hand is not related to bilateral IMTP peak force capacity in male collegiate athletes.

Based on these results, practitioners should seek to develop the thickness and pennation angles of male collegiate athletes' VL musculature in order to augment their bilateral IMTP peak force capacity. This can be achieved by incorporating fundamental exercises that appropriately train the knee extensors, such as the back squat,[9, 36] into athletes' strength training programs. Developing these distinct aspects of VL muscle structure, and thus IMTP peak force capacity, should transfer to improvements in the ability of male collegiate athletes to sprint, jump and change direction for their respective sports.[3, 14-19]

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