Manuscript Details

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Title	Vastus intermedius muscle architecture predicts the late phase of the knee extension rate of force development in recreationally resistance-trained men
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Abstract

Objectives: The current study investigated the correlation between quadriceps muscle architecture and the knee extension rate of force development (RFD). Design: cross-sectional study. Methods: Muscle thickness, pennation angle and fascicle length normalized per the thigh-length were measured via ultrasound in vastus lateralis, rectus femoris, vastus intermedius and vastus medialis. The knee extension rate of force was assessed isometrically at 90° knee angle and calculated in different 50-ms epochs (0-50, 50-100, 100-150, 150-200 and 200-250 ms). The maximum voluntary contraction was also recorded. Results: Large correlations were observed between vastus intermedius muscle thickness and the 100-150 ms (r=0.694, p=0.004), 150-200 ms (r=0.597, p=0.019) and 200-250 ms (r=0.546, p=0.045) epochs. Large correlation was observed between vastus intermedius normalized fascicle length and 100-150 ms (r=0.570, p=0.043) and large correlations with 150-200 ms (r=0.643, p=0.010) and 200-250 ms (r=0.629, p=0.012) epochs. Additionally, large correlations were observed between vastus lateralis normalized fascicle length and the 100-150 ms (r=0.535, p=0.049), 150-200 ms (r=0.629, p=0.016) and 200-250 ms (r=0.563, p=0.046) epochs. Vastus intermedius muscle thickness predicted 59% (R2=0.581, p=0.002) of the RFD of the 100-150 ms epoch; vastus intermedius muscle thickness and fascicle length predicted 51% (R2=0.506, p=0.029) of the 150-200 ms epoch; vastus intermedius and vastus lateralis fascicle length predicted 48% (R2=0.483, p=0.037) of the 200-250 ms epoch. No further correlation was observed. Conclusions: Fascicle length and muscle thickness were observed as predictive of the late phase of the rate of force development. Vastus intermedius muscle architecture has a primary role in the knee extension RFD.

Keywords	muscle; ultrasound; quadriceps muscle; muscle strength; fascicle length; muscle thickness.
Taxonomy	Exercise Physiology, Biomechanics, Sports Medicine
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Suggested reviewers	David Rodríguez-Rosell, Martino Franchi, Nikolaos Zaras

Submission Files Included in this PDF

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Acknowledgements.docx [Acknowledgement]

Table 1 corr muscle thickness.docx [Table]

Table 2 corr penn angle.docx [Table]

Table 3 corr fascicle length.docx [Table]

Research Data Related to this Submission

There are no linked research data sets for this submission. The following reason is given:
Data will be made available on request

Dear Editor-in-Chief,

we recently submitted a manuscript entitled “*Vastus intermedius muscle architecture predicts the late phase of the knee extension rate of force development”* to the Journal of Science and Medicine in Sport.

We believe that the manuscript is in line with the Journal’s purposes. Given the interest in the factors affecting the rate of force development, we investigated whether or not muscle architecture could affect it. Considering separately the architecture of the quadriceps muscles and the knee extension rate of force development divided into early and late phase, we have observed that vastus intermedius muscle thickness and fascicle length play a major role in explaining the late phase of the knee extension rate of force development. Explanations and implications are consequently provided.

- Category of article: original research.
- Sub-discipline: sport science.
- Sources of outside support for research: none.
- Financial support for the project: no external financial support.
- The manuscript does not concern any financial product.
- The Ethical Guidelines has been followed. The study was approved by the Ethical Committee of the Università degli Studi di Milano (CE 27/17).
- The manuscript has not been published elsewhere nor it is considered for publication elsewhere nor it will be submitted elsewhere until a final decision for its acceptability of the JSAMS Editorial Board has been made.

Sincerely,

The Authors.

-Reviewer1

- The authors did a great job on improving the rationale of their study. I have only one minor suggestion (not mandatory).

We thank the reviewer.

- Do not elaborate on further research in your conclusion section, stick to the conclusion supported by your findings. You could move the discussion about future research up to your discussion (above or below your limitations).

As suggested, we have moved the "further research section" where more appropriate within the discussion. Please see line 239-241 and 276-279.

-Reviewer2

Thank you for addressing my comments. Please see below for my final comments.

We thank the reviewer.

<u>Specific comments</u>

Ln 150

If the current study's principal aim was to investigate whether or not quadriceps muscle architecture was related to RFD, might the authors have considered an alternative method of data collection for RFD? For example, explosive muscle contractions, where the emphasis is purely on speed of force production, not maximal force also? This is an important point given the focus of the manuscript.

The reviewer proposed a valid and specific approach to detect and emphasize the RFD. However, as a secondary outcome, we also wanted to investigate the correlation between RFD and maximal force, since it was already proposed in the literature. At this purpose, we adopted the described protocol that gave us back the maximal force too. We hope we have justified our choice.

Comment**:** Please state this succinctly in the manuscript

As suggested, we have clearly stated it. Please see text.

Results.

I'd like to see the group mean Peak Force and RFD values. Likewise, it may be useful to present the data for the other variables.

Actually, the mean peak force and RFD values were already reported within the in-text results. We have highlighted it, please see text.

Comment**:** Thank you, although please remove the repetitious: mean(SD) and correct the units of RFD: N.s-1

As suggested, we have removed the repetitious "mean(SD)" throughout this section and corrected the unit of measures (N·s^{-1}). Please see text.

Nothing correlated with RFD 0-50 and 50-100, could this be due to typically greater variability of early phase RFD?

We agree that this could derive from the greater variability in 0-50 and 50-100 ms epochs. We have highlighted this following your next query. Please see text.

Comment: Please be explicit/ exemplify what you mean in the text, e.g. cite the V% values.

As suggested, we have inserted the coefficient of variation to support this. Please see text.

Ln 227 - This is slightly confusing, I think your data is in confirmation of previous findings of correlations between longer fascicle length and speed of force production..? Please re-order/rephrase for clarity

We apologize for having created confusion. We just wanted to highlight that the current data go against the hypothesis postulated by Maffiuletti et al (2016 Eur J Appl Physiol) and in favour of further experimental results found in the literature. We have rephrased it, please see text.

Comment: I don't understand this new statement: "Clinical and on-field implication was shown to derive from such physiological relationship." Please tidy up the sentence.

We agree that this sentence was not clear. Actually, we have preferred to delete it, since this was not so useful within the text.

Vastus intermedius muscle architecture predicts the late phase of the knee extension rate of force development in recreationally resistance-trained men

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ABSTRACT

Objectives: The current study investigated the correlation between quadriceps muscle architecture and the knee extension rate of force development (RFD).

Design: cross-sectional study.

Methods: Muscle thickness, pennation angle and fascicle length normalized per the thigh-length were measured via ultrasound in vastus lateralis, rectus femoris, vastus intermedius and vastus medialis. The knee extension rate of force was assessed isometrically at 90° knee angle and calculated in different 50-ms epochs (0-50, 50-100, 100-150, 150-200 and 200-250 ms). The maximum voluntary contraction was also recorded.

Results: *Large* correlations were observed between vastus intermedius muscle thickness and the 100-150 ms ($r=0.694$, $p=0.004$), 150-200 ms ($r=0.597$, $p=0.019$) and 200-250 ms ($r=0.546$, $p=0.045$) epochs. *Large* correlation was observed between vastus intermedius normalized fascicle length and 100-150 ms ($r=0.570$, $p=0.043$) and *large* correlations with 150-200 ms ($r=0.643$, $p=0.010$) and 200-250 ms ($r=0.629$, $p=0.012$) epochs. Additionally, large correlations were observed between vastus lateralis normalized fascicle length and the 100-150 ms ($r=0.535$, $p=0.049$), 150-200 ms ($r=0.629$, $p=0.016$) and 200-250 ms ($r=0.563$, $p=0.046$) epochs. Vastus intermedius muscle thickness predicted 59% ($R^2=0.581$, $p=0.002$) of the RFD of the 100-150 ms epoch; vastus intermedius muscle thickness and fascicle length predicted 51% ($R^2=0.506$, $p=0.029$) of the 150-200 ms epoch; vastus intermedius and vastus lateralis fascicle length predicted 48% ($R^2=0.483$, $p=0.037$) of the 200-250 ms epoch. No further correlation was observed.

Conclusions: Fascicle length and muscle thickness were observed as predictive of the late phase of the rate of force development. Vastus intermedius muscle architecture has a primary role in the knee extension RFD.

Keywords: muscle; ultrasound; quadriceps muscle; muscle strength; fascicle length; muscle thickness.

1. Introduction

Muscle architecture represents the muscle geometrical fascicle arrangement that can be assessed non-invasively by ultrasound and is associated with muscle function, whose changes could be used as index of hypertrophy/atrophy [1]. Indeed, longer fascicles were reported to favour more rapid strength exertion because of the greater amount of in-series sarcomeres [2–4]. Additionally, a greater amount of in-parallel sarcomeres configures greater pennation angle, promoting a greater physiological cross-sectional area and consequently increasing muscle strength [5]. Both the fascicle elongation and greater pennation angle contribute to increase the muscle thickness, a longitudinal-view estimation of the muscle size that was shown as representative of the changes in the anatomical cross-sectional area [6].

The rate of force development (RFD) is the ability to rapidly increase muscle force during a voluntary contraction [7]. RFD is crucial when performing explosive or ballistic tasks and daily activities (e.g. while balancing the body) and was proposed as more descriptive than maximum force of neuromuscular properties [8]. RFD can be assessed by measuring the difference in the exerted force divided by the difference in time within certain time-windows, usually starting from the onset of muscle contraction up to 250 ms [7,8]. The time-course of RFD has been divided in an early (up to 75-100 ms) and a late phase (between 100 and 250 ms) that can be respectively ascribed to neural and muscular factors [7,8]. While the neural factors encompass the motor units synchronization and the ability of rapidly activate the motor units [9,10], the muscular factors are associated with muscle morphology, muscle-tendon complex stiffness, muscle size and architecture [8]. Longer fascicles were correlated with greater RFD [11], even though the authors did not distinguish the early from the late phase. Further studies reported that longer fascicles were associated with explosive tasks like sprint running performance [4] or with a faster time-to-peak power in an all-out biking test [2]. Additionally, because RFD depends on the ability to generate force [7], larger muscles that are able to exert greater force also exhibit greater RFD [11], possibly suggesting a direct relationship.

The ability to rapidly generate force during a knee-extension depends on the intra- and inter-muscular synchronization and muscular characteristics of *vastus lateralis* (VL), *vastus intermedius* (VI), *vastus medialis* (VM) and *rectus femoris* (RF), that were shown to present different architectural characteristics [5], that should be considered separately during a knee extension force task. Interestingly, during an isometric contraction, VI muscle thickness was reported as the best predictor [12] and VI as the earlier contributor of the knee extension force exerted at 90° [13]. Hence, it would seem that the VI more than the other quadriceps muscles properties might play an important role during the onset of knee-extension force, i.e RFD. Therefore, the aim of the current study was to investigate the correlation between muscle architecture of VL, VI, VM and RF and the early and late phase of knee extension RFD. It was hypothesized that: i) greater muscle thickness and fascicle length would be associated with higher late phase of RFD; and ii) this correlation would be mostly visible in VI.

2. Material and Methods

The current investigation was designed as a cross-sectional study. The sample size was calculated using a statistical software (GPower 3.1, Stuttgart, Germany) based on previously reported results [11]. Given the study design, a two-tail possible correlation, a warranted power $1-\beta = 0.8$, $\alpha = 0.05$ and a *large* effect size ($\rho = 0.6$), a total of 17 participants was sufficient to ensure adequate statistical power.

The participants were involved in two different sessions. In the first session, the ultrasound data were collected, and the participants were familiarized with the knee-extension RFD protocol. In the second session, the RFD protocol was performed. To avoid any circadian variability, the second session took place from 11 am to 1 pm. The sessions were interspersed by two-to-four days, during which the participants were explained to refrain from any further form of strenuous physical activity.

Seventeen recreationally resistance trained men (age 22 ± 3 yrs, body mass 75.3 ± 5.6 kg, height 1.74 ± 0.08 m) volunteered for the present investigation. The participants were recruited among a University-based population, with a moderate experience in resistance training to be more familiar with the task. The participants used to train one or two times per week and had a resistance training experience ranging from 1 to 3 years. Any cardiorespiratory, lower-limb muscle and joint disease recorded in the previous year, smoking and a systematic use of any drug were listed as exclusion criteria. The participants received explanations of all procedures, signed an informed consent and were free to withdraw at any time. The Ethical Committee of the local University approved the procedures (CE 27/17), which were in line with the Declaration of Helsinki (1975 and further updates) concerning studies involving human subjects.

Muscle architecture was assessed *in vivo* at rest in VL, RF, VI and VM (LOGIQS7, GE©, Fairfield, Connecticut, USA) with a 5-cm linear-array probe (mod. 9L, 3.1-10.0 MHz) in extended-field-of-view (EFOV) mode (LOGIQview). This technique was previously validated for fascicle length acquisition [14]. The participants lay supine on the examination bed with the hip joint extended and the knee joint almost fully extended (170° extension, with 180° full extension). The probe was held perpendicular to the skin surface by an expert operator, which ensured minimal pressure was applied to the muscle belly examined. No visually identifiable muscle compression was detected on the scan, as checked real time during the scan acquisition [15]. A transmission gel was applied to improve acoustic coupling. Images were obtained along the mid-sagittal plane of each muscle, which included both superficial and deep aponeuroses, and the probe was oriented so that a number of clearly visible fascicles were captured. Careful manipulation was provided to align the transducer to the muscle fascicle plane and optimize the echogenicity of muscle fascicles [1,2]. The 50% of muscle length and width were used as scanning sites for VL, RF, and VI [16]. For VM, the images were taken at the distal third of muscle belly [5]. All muscles were inspected before EFOV acquisition and a line was marked on the skin following the fascicular path, i.e. the line of orientation of the muscle fascicles, so to obtain a continuous fascicle visualization during EFOV [2,14]. To acquire the muscle image, a continuous single view was taken by moving the probe along the drawn line for about 15 cm in 3-4 s. For all EFOV para-sagittal images, the operator ensured that the probe was kept perpendicular to the skin. Each site was scanned twice. The images were analysed offline using an open source computer program (ImageJ 1.44b, National Institutes of Health, USA). Muscle fascicle length was measured by drawing a line along three clearly visible muscle fascicles between the deep and superficial aponeurosis. Any fascicle curvature was taken into account when present by drawing a curved line following the fascicle path. The average fascicle length was normalized for the thigh length [2,3] and used for the analysis. On the same highlighted fascicles, their insertion angle into the deep aponeurosis was measured as pennation angle. The three measured angles were averaged and used for the analysis. Muscle thickness was defined as the distance between the superficial and the deep aponeurosis [17].

Knee-extension RFD was assessed during a maximal voluntary isometric contraction using a customized chair equipped with a strain gauge (mod. SM-2000N, Interface, Crowthorne, UK). The participants sat on the chair at a hip angle of 80° (0°=full extension) and were secured by two seatbelts [18]. The belts secured the tested limb at 90° of knee flexion (0°=full extension) as used in previous relevant procedures [12] and the untested limb was immobilized by a fixed lever [17]. The upper limbs were crossed against the chest. A strap was placed below the knee to avoid side-to-side movement and limit any force dispersion. Before the maximal voluntary contraction assessment, the participants were familiarized with the procedures. Thereafter, they performed a warm-up protocol consisting of 20 1-s to 2-s isometric contractions, separated by 10 s each, starting from a self-selected force and progressively increasing until the maximal volitional force was exerted [18]. After five minutes, the participants were asked if they were ready to start and in case of negative response, more time to recover was provided. Following previous methodological recommendations [8], five separate maximal voluntary contraction trials were performed and the best three were averaged. Maximal force was required to check for possible correlation with RFD. If the difference between the trials exceeded 5%, further trials were performed. Each trial lasted 4 s and was separated by 3 min of passive recovery. The operators strongly encouraged the participants to "push" as fast and hard as they could to reach their maximal force on each trial. All force signals were recorded at 2 kHz using an AD conversion system (Mod UM150, Biopac, Biopac System Inc., Santa Barbara, CA, USA).

RFD was calculated for the following epochs: 0-50 ms, 50-100 ms, 100-150 ms, 150-200 ms and 200-250 ms [11] and calculated as the ratio between Δ force and Δ time ($N \cdot s^{-1}$) for each epoch. A threshold of three standard deviations above the baseline signal for three consecutive points obtained in a 100-ms interval of the resting condition immediately preceding the contraction was used to the onset of the force signal [19].

Statistical analysis was performed using a statistical software (SPSS 22.0, IBM, Armonk NY, USA). The normality of data was checked using test Shapiro-Wilk's test. The test-retest reliability for the ultrasound parameters was calculated using an intra-class coefficient and interpreted as follows: $\alpha \geq 0.9$ = *excellent*; $0.9 > \alpha \geq 0.8$ = *good*; $0.8 > \alpha \geq 0.7$ = *acceptable*; $0.7 > \alpha \geq 0.6$ = *questionable;* $0.6 > \alpha \geq 0.5$ = *poor* [20]. Standard error of the measurement (SEM) was also calculated and reported. Descriptive statistics are reported as mean(SD). The correlation between VL, RF, VI and VM muscle thickness, pennation angle and fascicle length and maximum force with the RFD calculated during the 0-50 ms, 50-100 ms, 100-150 ms, 150-200 ms and 200-250 ms epochs were calculated using Pearson's product-moment correlation coefficient and interpreted as follows: 0.00 to 0.09 = *trivial*; 0.10 to 0.29 = *small*; 0.30 to 0.49 = *moderate*; 0.50 to 0.69 = *large*; 0.70 to 0.89 = *very large*; 0.90 to 0.99 = *nearly perfect*; 1.00 = *perfect* [21]. When a correlation was significant, the independent parameter was inserted into a stepwise multiple linear regression. Predictors were included in the model if a significant R^2 change ($p < 0.05$) was reported. Results are reported if assumptions for multiple regression analysis were met, demonstrating independent errors (indicated by a Durbin- Watson score between 1 and 3), no multicollinearity between predictors (reflected by a variance inflation factor < 10 and tolerance > 0.2), and homoscedasticity of residuals (normal distribution of standardized residuals). The figures show the regressions with the 95% confidence interval bands. The linear regression equations and R^2 are also shown.

3. Results

For muscle thickness, ICC ranged from 0.935 to α = 0.967 and SEM from 1.5% to 2.3%. For pennation angle, ICC ranged from α = 0.923 to α = 0.947 and SEM from 1.6% to 2.5%. For fascicle length, ICC ranged from α = 0.903 to α = 0.939 and SEM from 2.1% to 4.0%. The mean(SD) of muscle thickness was 24.5(5.2) mm for VL, 22.0(3.2) mm for RF, 18.2(3.7) mm for VI and 20.4(3.8) mm for VM. Pennation angle was 19.3(3.5)° for VL, 17.5(3.5)° for RF, 14.8(4.0)° for VI and 17.5(4.2)° for VM. Normalized fascicle length was 0.16(0.04) for VL, 0.16(0.05) for RF, 0.16(0.20) for VI and 0.11(0.05) for VM.

The values of the 0-50 ms, 50-100 ms, 100-150 ms, 150-200 ms and 200-250 ms RFD epochs were 2290(1879) $N \cdot s^{-1}$, 2655(1992) $N \cdot s^{-1}$, 1798(1059) $N \cdot s^{-1}$, 1266(699) $N \cdot s^{-1}$ and 969(642) $N \cdot s^{-1}$ respectively. Maximum force was 1074(423) N.

Table 1 shows the correlation between muscle thickness of each muscle and the RFD epochs. VI muscle thickness showed *large* correlations with the RFD late phase epochs. As reported in table 2, pennation angle did not show any correlation with the RFD epochs. Table 3 shows the correlation between normalized fascicle length of each muscle and the RFD epochs. VI and VL fascicle length was *largely* correlated with the 100 to 250 ms epochs. VI muscle thickness predicted 59% (R^2=0.581, p=0.002, β=0.762) of the RFD in the 100-150 ms epoch; VI muscle thickness and fascicle length 51% (R^2=0.506, p=0.029, β=0.443 and β=0.549

respectively) of the 150-200 ms epoch and VI and VL fascicle length predicted 48% (R^2=0.483, p=0.037, β=0.857 and β=0.465 respectively) of the 200-250 ms epoch.

Table 1 here

Table 2 here.

Table 3 here

Maximum force was correlated with the 100-150 ms (r=0.608, p=0.021), 150-200 ms (r=0.819, p<0.001) and 200-250 ms (r=0.667, p=0.009) but not with the 0-50 ms (r=0.339, p=0.260) and 50-100 ms (r=443, p=0.113) epochs. Together, the epochs from 100 to 250 ms predicted 69% (R^2=0.693, p=0.006) of the maximum voluntary contraction variance.

4. Discussion

The present cross-sectional study was designed to investigate whether or not quadriceps muscle architecture was related to RFD. The current results highlighted that the RFD epochs from 100 to 250 ms were correlated with VI muscle thickness and fascicle length and VL fascicle length. VI muscle thickness predicted 59% of the variance of the 100-150 ms and VI muscle thickness and fascicle length 51% of the150-200 ms epoch, while VI and VL fascicle length predicted 48% of the 200-250 ms epoch variance. No correlation was found between pennation angle whatever the muscle and any of the RFD epochs. No correlation was found between muscle architecture and the RFD epochs from 0 to 100 ms. Lastly, the RFD calculated in the epochs from 100 to 250 ms explained 69% of the maximum force variance. The present data confirm the initial hypothesis that thicker muscles and longer fascicles contribute to the late phase of RFD, without any influence of the early phase.

RFD depends on both neural and structural determinants that are mainly associated with its early and late phase [8], respectively. The fact that muscle architecture seems to play a role in the RFD late but not early phase reinforces what was previously described [7,8,22]. Particularly, the relationship between larger muscles and greater RFD was already proposed [7,8]. Indeed, quadriceps cross-sectional area was positively correlated with the knee extensors RFD [23], and the increase in muscle size was shown as concurrent with the increment in

RFD [24]. Although these results refer to the cross-sectional area, muscle thickness can be used as a muscle size index, given its correlation with the cross-sectional area [6]. The current results highlight that such a relationship occurs after 100 ms, when the structural determinants become prevalent [8]. Additionally, this may be also due to the lower variability observed in the >100 ms RFD epochs (coefficient of variation: 55% to 66%) compared to the 0-50 ms (82%) and 50-100 ms (74%) epochs. Longer fascicles have greater amount of in-series sarcomeres, potentially increasing the muscle contraction speed [5]. Indeed, VL fascicle length was positively correlated with RFD while performing an isometric leg press [11]. Additionally, several studies showed a relationship between VL fascicle length and the ability to perform explosive actions such as the power exerted during squat and countermovement jump [25], sprinting ability in running [4], swimming [26] or time-to-peak power in cycling [2]. Moreover, longer VL and gastrocnemii fascicles were found in running sprinters compared to both endurance runners and a control population [3]. Additionally, VL fascicle length was correlated with high-velocity but not low-velocity dynamic force exertion [27]. Interestingly, these studies did assess muscle architecture only in VL as representative of the whole quadriceps and did not investigated systematically the role of each quadriceps muscles. Although these consistent results, it was argued that greater fascicle length might impair the rapid force transmission because of the greater in-series compliance that would cause slackening in the force transmission [8]. Nevertheless, the present results seem to contradict this last hypothesis and to be in line with the experimental data reported in the literature. It could be prospectively argued that the possible training-induced changes in muscle size or fascicle length may be related to the possible changes in RFD. Further longitudinal studies are needed to confirm this hypothesis.

Maximum strength was shown to be correlated to RFD, and such a correlation was higher with the late epochs [28]. This is also what was shown here, given the *large* correlations between the 100 to 250 ms RFD epochs and the maximum force. Therefore, one may expect that a factor that contributes to the maximum force, also contributes to RFD, as previously proposed [7,8]. Greater pennation angle depends on greater amount of in-parallel sarcomeres [5], which increases the physiological cross-sectional area, and, in turn, the ability of developing more strength. Nevertheless, no correlation was found between pennation angle and any of the RFD epochs. Two possible considerations can be made. Firstly, pennation angle favours the force exertion through an increase in the muscle physiological cross-sectional area, whose increase is shown to favour greater maximum force production [2]. Secondly, pennation angle is not equivalent to the physiological cross-sectional area, and the latter's role was not investigated here and should be investigated further.

Considering the whole quadriceps, the four muscles have a unique own architecture [5], that leads to unique function during the knee extension. The current results highlight the prevalent role of VI in the knee extension late phase RFD prediction. Importantly, VI was shown as the earliest contributor in the development of the knee extension isometric force, so that its role in the initial phase of the force production was shown as primary [13]. Consequently, VI muscle architecture was reported as the best predictor of the knee extension isometric force [12]. Remarkably, the knee extension force was assessed at 90° and it was shown that the VI electromyographic activity decreased if assessed at longer muscle length [29,30], so the current results should be interpreted with caution. From the current findings, VL plays a secondary role, and this may derive from the high recruitment during an isometric knee extension performed at 90° [30]. The remaining muscles (RF and VM) seem not to play a decisive part in the early knee extension force development. Interestingly, the role of VI was shown to decrease and the role of VL, RF and VM to simultaneously increase with the increment of force production [13]. Therefore, it is possible that the force produced during the time-windows examined here for RFD may be relatively low, so that VI may be the main contributor in this phase compared to the other muscles. From a sport and rehabilitation perspective, the role of each quadriceps muscle depends on the force exerted during the knee extension, so increasing/decreasing the load may reflect the single quadriceps muscles contribution and possibly stimulus.

Some limitations accompany this investigation. Firstly, different knee angles at which the knee extension RFD could be assessed may result in different RFD values, so that the association between muscle architecture and RFD could be different. Secondly, the relationship between muscle architecture and RFD is specific for the muscle and task selected, so different muscle/task pairs could result in different findings. Thirdly, the results presented here are specific for the population involved and should not be extended to other populations. Lastly, correlation does not mean causation, so the results should be interpreted with caution. Future researches are needed to confirm these outcomes, examining different angles to possibly accounting this relationship for muscle length, different muscles (e.g. hamstrings or triceps) or different populations (e.g. elderly, women or sport-specific trained people).

5. Conclusions

In conclusion, VI muscle thickness and fascicle length seem to play a key-role in the late phase of the knee extension RFD at 90° in recreationally resistance-trained men. VL fascicle length seems to be a secondary factor. Pennation angle does not seem to play any role. The early phase does not appear to be correlated with any of the structural factors measured here.

Practical implications:

- Muscle architecture can be assessed to examine the role of structural factors in RFD.
- Quadriceps muscles architecture does not equally predict the knee-extension RFD.
- Knee-extension maximum force accounts for RFD late but not early phase.

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Table 1: The correlation values (above r-value; below p-value) between muscle thickness and the RFD epochs are shown. Significant correlations, reported in *italics,* were observed between VI muscle thickness and the RFD late-phase epochs.

		0-50 ms	**50-100 ms**	**100-150 ms**	**150-200 ms**	**200-250 ms**
VL	r-value	0.307	0.050	0.005	0.181	0.214
	p-value	0.266	0.859	0.987	0.519	0.444
RF	r-value	0.050	0.157	0.049	0.166	0.211
	p-value	0.858	0.577	0.864	0.553	0.450
VI	r-value	0.455	0.271	*0.694*	*0.597*	*0.546*
	p-value	0.089	0.328	*0.004*	*0.019*	*0.045*
VM	r-value	0.173	0.075	0.090	0.108	0.145
	p-value	0.537	0.790	0.750	0.700	0.606

VL: vastus lateralis; RF: rectus femoris; VI: vastus intermedius; VM: vastus medialis.

Table 2: The correlation values (above r-value; below p-value) between pennation angle and the RFD epochs are shown. No significant correlation was observed.

		0-50 ms	**50-100 ms**	**100-150 ms**	**150-200 ms**	**200-250 ms**
VL	r-value	0.181	0.188	0.150	-0.089	-0.232
	p-value	0.519	0.502	0.594	0.752	0.405
RF	r-value	-0.097	-0.101	-0.223	-0.393	-0.336
	p-value	0.730	0.721	0.425	0.148	0.221
VI	r-value	0.218	0.394	0.395	0.241	0.057
	p-value	0.435	0.146	0.146	0.386	0.840
VM	r-value	-0.172	0.023	0.156	0.300	0.412
	p-value	0.540	0.934	0.580	0.278	0.127

VL: vastus lateralis; RF: rectus femoris; VI: vastus intermedius; VM: vastus medialis.

Table 3: The correlation values (above r-value; below p-value) between normalized fascicle length and the RFD epochs are shown. Significant correlations, reported in *italics,* were observed between VI muscle thickness and the RFD late-phase epochs.

		0-50 ms	**50-100 ms**	**100-150 ms**	**150-200 ms**	**200-250 ms**
VL	r-value	0.368	0.378	*0.535*	*0.629*	*0.563*
	p-value	0.177	0.133	*0.049*	*0.016*	*0.046*
RF	r-value	0.259	0.295	0.278	0.165	0.437
	p-value	0.350	0.286	0.316	0.556	0.103
VI	r-value	0.335	0.363	*0.570*	*0.643*	*0.629*
	p-value	0.242	0.184	*0.043*	*0.010*	*0.012*
VM	r-value	-0.097	-0.010	-0.018	0.121	0.203
	p-value	0.742	0.973	0.952	0.681	0.487

VL: vastus lateralis; RF: rectus femoris; VI: vastus intermedius; VM: vastus medialis.