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Effect of knee joint angle on *vastus medialis* and *vastus lateralis* rigidity during isometric submaximal voluntary knee extensions

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ABSTRACT

The use of shear wave elastography during voluntary contraction has enabled the non-invasive assessment of load sharing strategies between agonist muscles. However, the change in joint angle and voluntary contraction intensity can modify contribution between muscles. The aim of this study was to investigate the effect of knee joint angle on the local mechanical properties of the *vastus medialis* (VM) and the *vastus lateralis* (VL) during isometric submaximal voluntary contractions from shear wave elastography mapping. The VM and VL Young's modulus at rest and during constant isometric submaximal voluntary contractions (*i.e.*, 25%, 50% and 75% of maximal voluntary contraction [MVC]) were assessed for two knee angles (50° and 100° | knee fully extended = 0°) in twelve participants. No significant difference was found in the VM Young's modulus among all torque levels and knee angles ($p > 0.05$). VL Young's modulus was significantly higher at 25% MVC for a knee angle of 100° than at 75% MVC for the same knee angle and was greater at 25% MVC for a knee angle of 100° than for 50° ($p < 0.05$). In contrast to the VM, the contribution of the VL to the knee joint torque production during isometric voluntary contraction appears to depend on the muscle length and the relative knee extension torque level.

1. Introduction

The non-invasive estimation of individual muscle force remains difficult in humans. Surface electromyography (sEMG) has been considered as a potential powerful method to indirectly assess muscle force capacity. However, in many conditions such as eccentric contractions or fatiguing protocol, the individual muscle force capacity cannot be assessed from sEMG measurements (Dideriksen et al., 2010; Ghori et al., 1995). Ultrasound shear wave elastography (SWE) provides a local and accurate assessment of muscle rigidity (*i.e.*, an estimation of the Young's modulus calculated from shear wave velocity (Bercoff et al., 2004; Koo, 2015) leading to a closer estimation of individual muscle tension (Hug et al., 2015). Bouillard *et al.* demonstrated a close accordance between the change in measured torque and the one estimated from a SWE exploration during a fatiguing task, in which only one muscle was involved (*i.e.*, the *abductor digiti minimi* – sole abductor of the 5th finger) (Bouillard et al., 2012a). As a consequence, SWE has been used to estimate the load sharing change between three of the four *quadriceps* muscles during a prolonged constant isometric voluntary knee extension (Bouillard et al., 2014).

Considering the relatively low sample rate of the rigidity maps obtained from SWE explorations (*i.e.*, < 2 Hz), most of the previous studies assessed the load sharing of agonist muscles during isometric submaximal voluntary contractions (Bouillard et al., 2014; Mendes et al., 2018) to stabilize the signal inside the SWE maps (Mendes et al., 2018; Sasaki et al., 2014) and to avoid the potential confounding effect of length change during anisometric contractions (Fung, 1981). Few studies have reported an influence of joint angle on muscle rigidity during submaximal voluntary elbow, hip and plantar flexions (Deng et al., 2022; Kato et al., 2021; Lin et al., 2022; Zimmer et al., 2023). For instance, the *biceps brachii* rigidity has been reported to be greater at extended elbow angles in comparison to flexed ones for contraction intensities lower than 50% of maximal voluntary contraction, whereas it remained constant on the full range of motion for higher intensities (Zimmer et al., 2023). In addition, the relative involvement of the three *triceps surae* muscles during submaximal plantar flexion has been shown to change with knee angle (Lin et al., 2022). However, the combined effect of joint angle and contraction intensity on knee extensor muscles rigidity has never been investigated, while this effect has been proved to be dependent on muscle group (Lin et al., 2022; Zimmer et al., 2023). The

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aim of the present study was to assess the effect of change in knee joint angle on the local mechanical properties of the *vastus medialis* (VM) and the *vastus lateralis* (VL) during isometric submaximal voluntary contractions using SWE mapping.

2. Materials and methods

2.1. Study population and design

Twelve healthy participants (6 females and 6 males | age: 29.8 ± 6.1 years, height: 168.8 ± 9.2 cm, mass: 65.3 ± 11.8 kg, BMI: 22.7 ± 2.6 kg. m^{-2}) with no known musculoskeletal, articular or cardiovascular abnormalities participated in this study. The study was conducted in conformity with the last version of the Declaration of Helsinki. All participants volunteered for this study and provided informed written consent. This study has been approved by the local ethics committee. Based on previously reported changes in *adductor longus* muscle rigidity with hip angle during submaximal voluntary contraction (Kato et al., 2021) and pilot SWE measurements, an *a priori* analysis to determine the sample size of the present study was conducted, showing that a group of twelve participants would allow the detection of a 35% difference in muscle Young's modulus between the two angles tested in the present study with sufficient power ($\alpha = 0.05$ and $1\text{-}\beta = 0.80$).

2.2. Experimental protocol

After a 5 to 10 min warm-up including a set of unilateral submaximal knee extensions under isometric conditions for the right leg, isometric maximal voluntary contraction (MVC) torque was assessed. SWE explorations were then performed during submaximal contractions (*i.e.*, 25%, 50% and 75% MVC). This protocol was randomly repeated at both 50° and 100° of knee angle (0°: knee fully extended).

2.3. Isometric maximal voluntary contraction torque measurements

The subject was seated on a chair with the hip flexed at 60° (0°: hip fully extended) and the knee at 50 or 100°. They were instructed to perform three unilateral MVC with the right leg while being strapped to the chair. The MVC trials were separated by a resting period of at least 1 min and quantified as the highest value of torque reached during the three trials for each knee position minus the baseline torque measured at rest before each contraction. Torque was calculated *a posteriori* from the force measured with a calibrated force sensor (Tedea-Huntleigh, United Kingdom) connected to a strain gauge conditioner (Meggitt Sensorex, Archamps, France) attached to the chair. Force signal was sampled at 2 kHz using a Powerlab system and Labchart software (ADinstruments, Colorado Springs, CO, USA) and was multiplied by the lever arm measured from the knee axis of rotation to the contact point on the tibia. *Quadriceps femoris* muscle group force was defined as the measured knee joint torque divided by the patellar tendon moment arm (Bakenecker et al., 2019) and the individual VL and VM muscle forces were then estimated from their respective physiological cross-sectional area (33.9 and 25.5% of the *quadriceps femoris* physiological cross-sectional area (Akima et al., 1995)).

2.4. Surface electromyography measurements

sEMG signal was recorded at 2 kHz from the *vastus lateralis* (VL) and *vastus medialis* (VM) of the right leg with pairs of surface electrodes (Delsys, Natick, Massachusetts, USA). After having shaved and cleaned the skin with alcohol, sEMG electrodes were placed on the *vastus lateralis* belly (at the vicinity of the ultrasound probe support – firstly placed on VL and VM muscles), according to SENIAM recommendations (Hermens et al., 2000).

The sEMG treatment process was computed with Matlab (MathWorks, Natick, Massachusetts, USA). Raw sEMG signals were run through a Butterworth bandpass filter between 20 Hz and 400 Hz. Thereafter, the root-mean-square (RMS) envelope of the signal was calculated on the middle 0.5 s of each maximal and submaximal contractions' plateau. For each knee angle, the sEMG RMS assessed during submaximal contractions was normalized for each participant with the sEMG RMS of the MVC.

2.5. Shear wave elastography measurements

Muscle Young's modulus was assessed from SWE explorations of the VL and VM during isometric submaximal voluntary contractions at two knee angles (Fig. 1) (Bernabei et al., 2020). SWE maps were obtained from ultrasound explorations performed with an *Aixplorer* ultrasound device (Mach30, v.2.1.0.3395, Supersonic Imagine, Aix-en-Provence, France), coupled with a linear transducer array (5–18 MHz, SuperLinear 18–5, Vermon, Tours, France). Assuming that the areas investigated were purely elastic, isotropic, incompressible and only composed of muscle tissue, the Young's modulus (E) is retrieved as follows:

$$E = 3\rho \times V^2.$$

with ρ the muscle density (1000 kg/m^3) and V the shear wave speed (Hug et al., 2015). Ultrasound device's persistence was set on "medium", smoothing level on "5" and optimization on "penetration". Ultrasound probe custom-made supports were placed on the VL and VM muscle bellies along the direction of the muscle fascicles, at 33% of the distance between the patella lateral side and the anterior superior iliac spine and at 20% of the distance between the femur medial epicondyle and the anterior superior iliac spine, respectively. These supports were placed at rest with the knee and hip joints fully extended and filled with acoustic gel.

Submaximal contractions were realised in sets of two for each intensity, in a randomised order. Submaximal torque was reached by the subject using visual real-time feedback, through a coloured area placed around the targeted torque (*i.e.*, ± 7%) for each submaximal contraction. SWE maps (13 × 23 mm^2) were recorded during each submaximal contraction synchronously with force and sEMG signals without including any fascia, bone, intramuscular fat or skin to avoid saturated or unfilled parts. As the saturation limit of the Aixplorer Mach30 was 1200 kPa, no saturated part was included in any of the SWE maps. SWE maps were also acquired at rest before and after each submaximal contraction. This procedure was repeated for each submaximal contraction (*i.e.*, 25%, 50% and 75% MVC) and knee angle (*i.e.*, 12 submaximal contractions).

All the SWE maps were analysed by the same experimenter (A.F.) using the ultrasound system's software (Qbox tool). On each map, two 11 mm diameter circular region of interest (ROI) were drawn on the left and right sides. The size of the ROI was slightly diminished in case of unfilled areas to avoid empty pixels during the quantification of the map. The Young's modulus was averaged over these two ROI for each map and over at least three images for each submaximal contraction, for each muscle and knee angle. The muscle Young's modulus was then defined as the difference between the SWE measurement realized during the submaximal contractions and at rest.

2.6. Statistical analysis

Statistical analyses were performed with Statistica software (Statsoft, Tulsa, USA). The normality of the data distribution was assessed using a Shapiro-Wilk test. A paired Student's *t*-test was performed to assess the effect of knee angle on MVC torque. A three-way ANOVA (knee angle × muscle × contraction intensity) was used for sEMG parameters and two-way ANOVA (knee angle × contraction intensity) were performed for the VL and the VM SWE measurements. Post-hoc analysis was conducted using Tukey HSD test when appropriate. Effects sizes were calculated using partial eta squared (η_p^2) for the significant results retrieved from

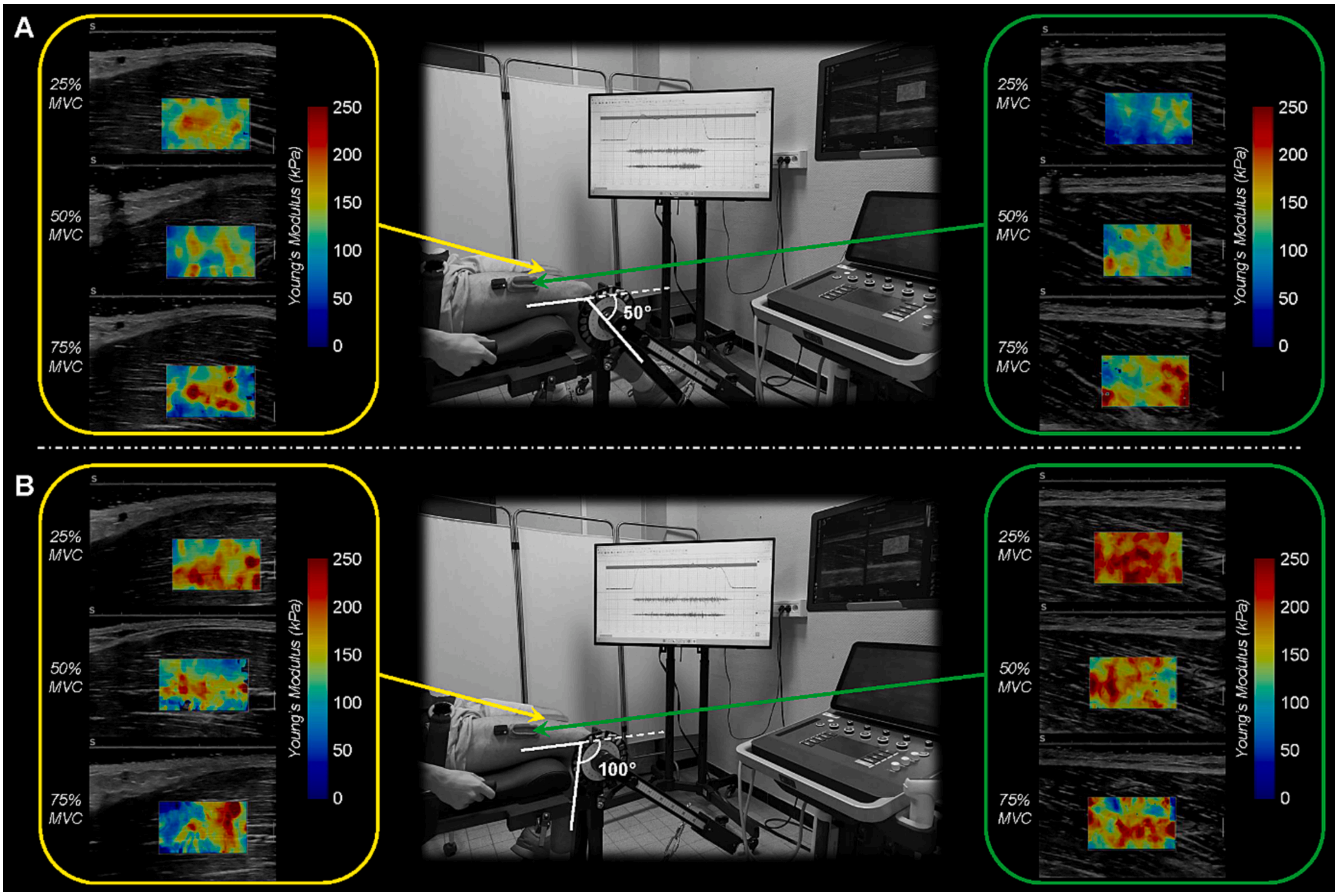

Fig. 1. Experimental setup used during shear wave elastography explorations and maps acquired in one subject for knee angle position at (**A**) 50° and (**B**) 100° [0°: knee fully extended] during isometric submaximal contractions (*i.e.*, 25%, 50% and 75% of maximal voluntary contraction [MVC] torque) on *vastus medialis* (left maps) and *vastus lateralis* (right maps).

ANOVA and using Cohen's *d* for post-hoc analysis. Small, medium and large effect sizes were reported at the threshold values of 0.01, 0.06 and 0.14 for η_p^2 and 0.2, 0.5 and 0.8 for Cohen's *d* (Cohen, 1969). Bravais-Pearson's correlation coefficients were calculated between muscle force and the Young's modulus measured during isometric submaximal voluntary contractions in VL and VM at each knee angle. Data are presented as mean ± standard deviation and the significance level was set at $P < 0.05$.

3 Results

3.1. Isometric maximal voluntary contraction torque measurements

No significant difference ($P > 0.05$) was found for the MVC torque between knee angles (Table 1) and similar submaximal torques were reached during the SWE explorations at 50° and 100° of knee angle.

3.2. Surface electromyography measurements

The sEMG RMS was similar between VL and VM during each submaximal voluntary contraction ($P > 0.05$) but a significant interaction was found between the intensity of the contraction and the knee angle ($P = 0.029$, $\eta_p^2 = 0.08$, Table 1). The sEMG RMS was higher at a knee angle of 100° than at 50° for 50% MVC ($P = 0.009$, $d = 0.9$) and 75% MVC ($P = 0.041$, $d = 0.7$).

Table 1
Maximal and submaximal voluntary contraction torque, mean relative electromyographic root mean square and Young's modulus obtained in both *vastus medialis* (VM) and *vastus lateralis* (VL) at 100° and 50° of knee angle (0°: knee fully extended).

	Knee Angle	
	100°	50°
MVC torque (N.m)	**152 ± 57**	**158 ± 42**
75% MVC	$115 \pm 68^{\#,\dagger}$	$118 \pm 31^{\#,\dagger}$
50% MVC	$81 \pm 47^{\#}$	$80 \pm 21^{\#}$
25% MVC	$40 \pm 23^{\dagger}$	$44 \pm 17^{\dagger}$
EMG RMS (%max)		
75% MVC	$58.6 \pm 19.0^{\#,\dagger}$	$48.4 \pm 8.4^{*,\#,\dagger}$
50% MVC	$39.5 \pm 15.6^{\#}$	$27.6 \pm 8.3^{*,\#}$
25% MVC	$19.7 \pm 6.5^{\dagger}$	$15.6 \pm 7.4^{\dagger}$
Resting Young's Modulus (kPa)	***28 ± 5***	***18 ± 4*****
Pre-contraction	26 ± 5	18 ± 5
VL	26 ± 5	18 ± 5
VM	26 ± 4	17 ± 2
Post-contraction	$29 \pm 5^{\ddagger}$	19 ± 4
VL	29 ± 6	18 ± 4
VM	29 ± 4	19 ± 3

MVC: Maximal voluntary contraction, EMG RMS: Electromyographic root mean square. Young's modulus at rest in bold is the mean value of the pre- and post-contraction measurements.
*Angle effect: * $p < 0.05$ and ** $p < 0.01$, #: different from 25% MVC, †: different from 50% MVC, ‡: different from pre-contraction.*

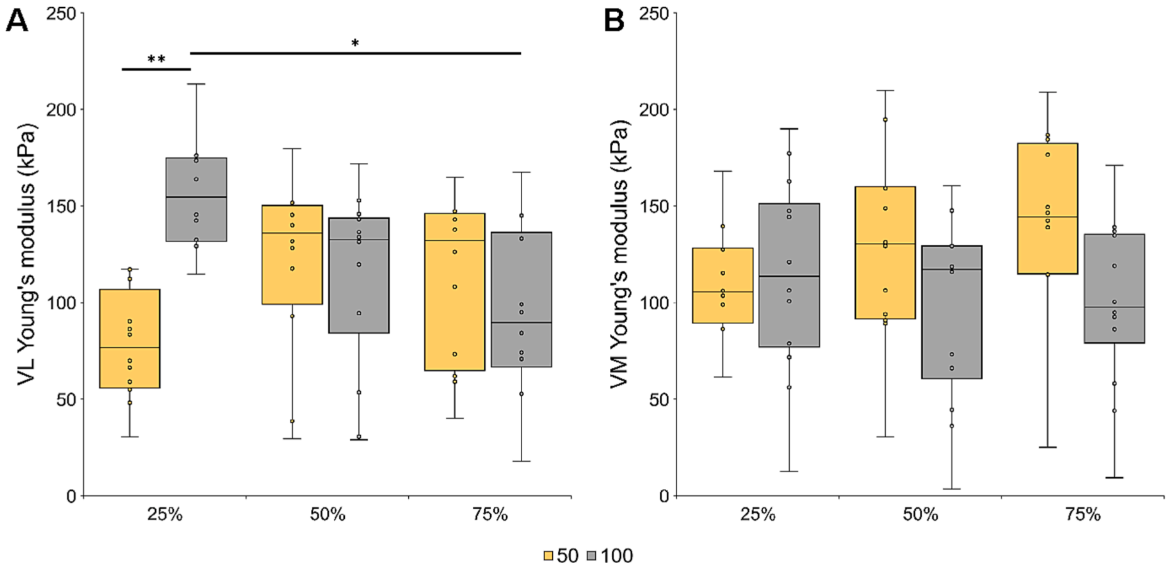

Fig. 2. Muscle Young's modulus of (**A**) *vastus lateralis* (VL) and (**B**) *vastus medialis* (VM) during the isometric submaximal voluntary contractions (*i.e.*, 25%, 50% and 75% of maximal voluntary contraction torque) at 50° and 100° of knee angle. *: $p < 0.05$ and **: $p < 0.01$.

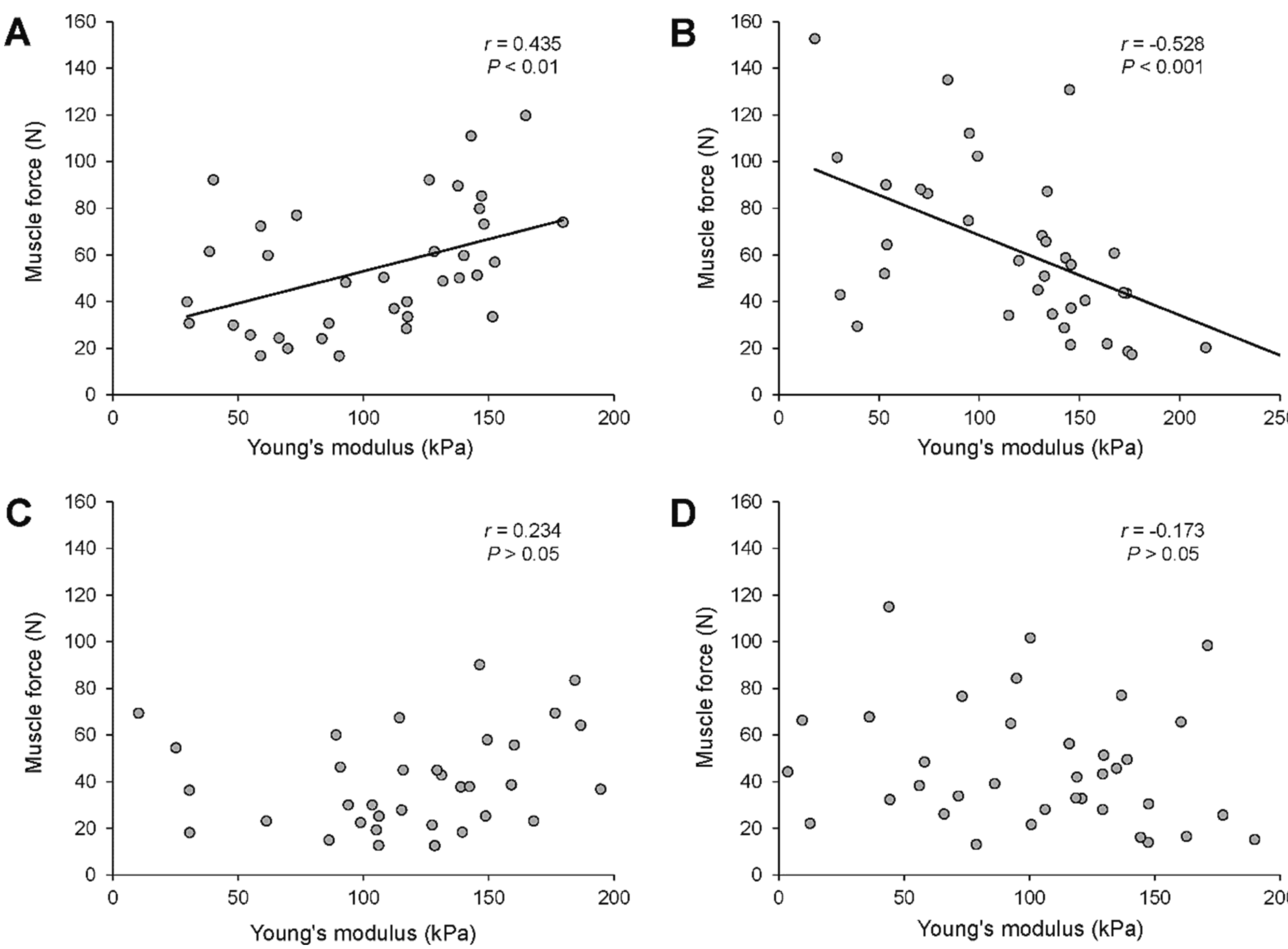

Fig. 3. Correlations between muscle force and Young's modulus measured during isometric submaximal voluntary contractions in (**A**) the *vastus lateralis* (VL) at 50° of knee angle, (**B**) the VL at 100°, (**C**) the *vastus medialis* (VM) at 50° and (**D**) the VM at 100°.

3.3. Shear wave elastography measurements

At rest, a significant effect of knee angle ($P < 0.001$, $n_p^2 = 0.59$) was found with a higher Young's modulus for a knee angle of 100° than for a knee angle of 50° (Table 1). In addition, the resting Young's modulus was also high post-contraction as compared to the pre-contraction time point (significant time effect with $P < 0.001$, $n_p^2 = 0.54$).

During the submaximal contractions, significant changes in Young's modulus between knee angles and contraction intensity were reported for the VL ($P < 0.001$, $n_p^2 = 0.20$) but not for the VM ($P = 0.254$, $n_p^2 = 0.04$, Fig. 2). The VL Young's modulus determined at 50° of knee angle and for a contraction intensity of 25% MVC was found to be lower than the modulus determined at 100° and 25% MVC ($P < 0.01$, $d = 1.8$, Fig. 2). The VL Young's modulus determined at 100° and 25% MVC was found to be higher than the one measured at 75% MVC at the same knee angle ($P < 0.05$, $d = 1.2$, Fig. 2). Significant correlations were observed between the VL muscle force and Young's modulus at 50 and 100° of knee angle ($r = 0.435$, $P < 0.01$ and $r = -0.528$, $P < 0.001$, respectively) but not between the VM muscle force and its active rigidity ($r = 0.234$, $P = 0.059$ and $r = -0.173$, $P = 0.183$, respectively, Fig. 3). Correlations between the VL and VM muscle force normalized to body mass and Young's modulus are available for both knee angles in supplementary materials (Fig. S1).

4. Discussion

The aim of the present study was to assess the effect of two knee joint angles on the local mechanical properties of the VL and VM muscles at rest and during isometric submaximal voluntary contractions from SWE and sEMG measurements. The main results showed a higher VL Young's modulus at 25% MVC for a knee angle of 100° than 50°. Moreover, the VM Young's modulus was not influenced by knee angle and intensity of muscle contraction, whereas the VL one was higher at 25 than at 75% MVC for a knee angle of 100°.

The Young's modulus values measured in the present study ranging from 37 to 268 kPa for the VL and from 27 to 229 kPa for the VM are consistent with previous studies reporting Young's modulus values ranging from 125 to 250 kPa for the VL and from 85 to 195 kPa for the VM (Bouillard et al., 2014; Deng et al., 2022; Otsuka et al., 2019). The effect of joint angle on muscle rigidity assessed during submaximal voluntary contraction has only been reported in a few recent studies (Deng et al., 2022; Kato et al., 2021; Lin et al., 2022; Zimmer et al., 2023). However, none has investigated the combined effect of knee angle and contraction intensity on *quadriceps femoris* muscles SWE measurements. In the present study, the VL Young's modulus increased between 50° and 100° of knee angle at 25% MVC. To support the latter result, a recent study reported low muscle Young's moduli at flexed elbow angles (*i.e.*, short muscle lengths) compared to more extended positions - especially at low contraction intensity, even if no significant interaction between elbow angle and contraction intensity was found (Zimmer et al., 2023). Regarding the VM, no effect of knee angle on Young's modulus has been found. Moreover, contraction intensity had no significant effect on VM Young's modulus. A similar result has been reported before with no change in *brachialis* shear elastic modulus during a ramp of isometric elbow flexion from 7% to 35% MVC (Bouillard et al., 2012b). A higher proportion of type I fibre has been reported in the VM than in the VL (Johnson et al., 1973). This difference in fibre type distribution could explain that no change in VM rigidity was observed with contraction intensity in the present study for both knee angles. However, even though the *vastii* present similar architectures (Blazevich et al., 2006) and theoretical force–length relationships (Herzog et al., 1990), a potential intramuscular heterogeneity in muscle tension could also interfere with the SWE measurements during voluntary submaximal contraction. The latter assumption is supported by the relative heterogeneity in muscle rigidity reported at rest in other thigh's muscles (Kodesho et al., 2021). Although the validity of this hypothesis has never been confirmed during muscle contraction, an intramuscular heterogeneous behaviour has also been hypothesized during electrically induced submaximal contractions of the VL and the VM (Fouré et al., 2020). Therefore, the probe positioning in the present study could have impacted differently the rise in Young's modulus with contraction intensity.

The unexpected result of the present study was the high VL Young's modulus observed with the knee flexed at 100° for 25% MVC in comparison to the one assessed at 75% MVC. The latter result could be related to a change in load sharing between agonist muscles with increasing contraction intensity (Bouillard et al., 2012b) - the greater the contraction intensity, the less the VL contributes to the knee joint torque as supported by the negative correlation displayed in the Fig. 3B. This correlation represented the variation in muscle rigidity in relation to the knee joint torque adjusted by the VL PCSA measured at rest. The muscle PCSA is commonly used to represent the relative contribution of a muscle to the overall torque produced by the muscle group it belongs to (*e.g.*, Avrillon et al., 2020). This is based on the assumption that the percentage of muscle PCSA measured at rest within a muscle group represents the percentage of the overall muscle group torque produced during contraction. While this assumption has been validated for maximal voluntary torque measurements (Fouré et al., 2018), it could be too simplistic when dealing with submaximal torque levels. Indeed, previous studies suggest that there might be changes in relative contribution between agonist muscles as torque increases at submaximal levels (Bouillard et al., 2012b), which cannot be identified using the relative muscle PCSA. This could account for the opposite dynamics observed in the present study between the VL relative contribution estimated using the knee joint torque adjusted by PCSA and the one estimated by SWE. However, a decrease in a muscle active rigidity with the increase in torque has never been reported. As both VL and VM muscles present larger relative amounts of type I fibres (less rigid than type II ones) in their deep parts (Johnson et al., 1973), a potential effect of the SWE measurements' depth which changes with contraction could have influenced the results reported in the present study.

The ANOVA conducted in the present study revealed that sEMG RMS increased in the same way for both muscles with the increase in knee joint torque, dependently on muscle length. On the opposite, the Young's modulus was either positively, negatively (for the VL), or not correlated (for the VM) to knee joint torque depending on knee angle, reflecting a different relationship than between torque and sEMG. These two methods proposed to evaluate inter-muscle coordination during contraction thus yielded contrasting results, questioning the interchangeable use of these technics as proxies for individual muscle force (Hug et al., 2015).

From a methodological point of view, the VL and VM were the only knee extensors investigated in the present study even though the assessment of their agonists could have provided new insights into their respective behaviour. Indeed, an increase in the *rectus femoris* rigidity with knee extension contraction intensity, that could have influenced the behaviour of the *vastii,* has been reported from 20 to 60% MVC (Otsuka et al., 2019). Moreover, the high variability in the Young's modulus values recorded within each SWE maps during submaximal contractions could have limited the sensitivity to detect potential changes in VM rigidity with knee angle or contraction intensity in the present study. Finally, although SWE measures performed during voluntary contractions have already been shown to be repeatable in previous studies (*e.g.*, Mendes et al., 2018), no reliability measurement has been performed in the present study. Nevertheless, the high *a posteriori* statistical power (1-β > 0.95) for the main result strongly supports the truthfulness of the observed effect in the VL at 100°.

The SWE explorations realised in the present study reveal that the local mechanical state of the *vastii* muscles investigated during isometric submaximal voluntary contractions is different from the one of muscles located in other joints. The VL contribution to the submaximal knee joint torque production appears to be dependent on muscle length and relative knee extension torque, in contrast to the VM which was neither influenced by the knee joint angle nor by the torque produced at the knee joint. This rather complex torque-modulus relationship compared to the torque-sEMG one questions the interchangeable use of these methods to estimate individual muscles contribution during contraction.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors thank all the subjects who participated in the present study.

Ethics approval.

The study was conducted in conformity with the last version of the Declaration of Helsinki and has been approved by the local ethics committee.

Consent to participate.

Informed consent was obtained from all individual participants included in the study.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jelekin.2023.102826.

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