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Effect of hip and knee joint angles on resting hamstring muscles rigidity in men and women

Jérémie Bouvier¹ · Cyril Martin¹ · Alexandre Fouré¹ 

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Abstract

Purpose Hamstring muscle strains are one of the most common injuries in sports practice, for both men and women. However, sex disparities in the rate of muscle injuries have been observed. As these muscular injuries usually occur at long muscle length, this study aimed to determine the effect of sex on hamstring muscles' resting rigidity under different stretching conditions.

Methods The shear wave speed (SWS) of resting hamstring muscles was measured in 12 men and 12 women in different hip and knee positions (hip extended with knee flexed, hip flexed with knee extended, both joints extended and both joints flexed).

Results Combining all the positions, the SWS of the *semitendinosus* was higher in men than in women (2.96 vs. 2.71 m.s⁻¹). Regardless of sex, a significant rise in SWS was systematically observed when the *semimembranosus* was stretched (1.86, 2.37, 2.76 and 4.39 m.s⁻¹) but it was neither the case for the *semitendinosus* ($p=0.82$) nor for the *biceps femoris* ($p=0.50$). Finally, differences in SWS among the hamstring muscles were only observed at the longest muscle length, with greater SWS values for the *semimembranosus* and *semitendinosus* in comparison with the *biceps femoris* (4.39 and 4.12 vs. 3.38 m.s⁻¹ respectively).

Conclusion In conclusion, a sex difference was only observed in the resting *semitendinosus* rigidity. Independently of sex, the increase in resting hamstring muscles SWS with stretch was muscle specific.

Keywords Elasticity · Hamstrings · Sex difference · Shear wave elastography · Ultrasound

Abbreviations

ANOVA	Analysis of Variance	ICC	Intraclass Correlation Coefficient
BF	Biceps Femoris long head	MDD	Minimal Detectable Difference
BMI	Body Mass Index	MRI	Magnetic Resonance Imaging
CV	Coefficient of Variation	ROI	Region of Interest
ECM	Extracellular Matrix	SEM	Standard Error of Measurement
H120 K180	Position with hip at 120° and knee at 180°	SM	Semimembranosus
H180 K180	Position with hip at 180° and knee at 180°	ST	Semitendinosus
H180 K90	Position with hip at 180° and knee at 90°	SWE	Shear Wave Elastography
H90 K90	Position with hip at 90° and knee at 90°	SWS	Shear Wave Speed

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Introduction

Hamstring muscle injuries are among the main reasons for stopping sports practice in both men and women (Ekstrand et al. 2011; Larruskain et al. 2017). Yet, from an epidemiologic perspective, men are 1.55–1.93 times more exposed to muscular injuries than women (0.59 vs. 0.38 injury per 100 athlete exposures and 1.52 vs. 0.79 injury per 1000 player hours, for men and women, respectively) (Cross et al. 2013; Larruskain et al. 2017). While the muscle injuries (or

exercise-induced muscle damage), mechanisms are clearly multifactorial and depend on numerous non-muscular structures, the involvement of intramuscular passive structures in these processes are increasingly discussed (Csapo et al. 2020). For example, while several recent studies reported a low resting hamstring muscles rigidity assessed from ultrasound shear wave elastography (SWE) in women compared to men, (Kumagai et al. 2019; McPherson et al. 2020; Wu et al. 2020), another did not (Avrillon et al. 2019). These discrepancies could be related to differences in experimental conditions and especially to the various hip and knee joint angles used in these studies.

Indeed, the passive behaviour of the hamstring muscles has been extensively studied during stretching on large ranges of motion with SWE measurements (Berrigan et al. 2020; Le Sant et al. 2015; Šarabon et al. 2019), mainly because many sport-related muscle injuries occur while the muscle is being stretched (Liu et al. 2017). Hip flexion and knee extension increase the hamstring muscles length (*i.e.*, *semimembranosus* [SM], *semitendinosus* [ST] and *biceps femoris long head* [BF]) and lead to a higher resting muscle rigidity, as attested by an increase in shear wave speed (SWS) or modulus (Dubois 2015; Le Sant et al. 2015; Miyamoto et al. 2020; Šarabon et al. 2019). However, the increase in SWS with muscle length can be different among the hamstring muscles, with greater SWS values reported at long muscle length for the SM (Miyamoto et al. 2017, 2020; Nakamura et al. 2016) or the BF (Avrillon et al. 2019; Le Sant et al. 2015) than for the ST. So far, it is still unknown whether sex-related differences may exist among resting hamstring muscles for different hip and knee joint angles.

The aim of this study was to determine the sex-related differences in resting hamstring muscles SWS at different hip and knee angles. A greater resting hamstring muscles SWS in men than in women, for all the hamstring muscles, was hypothesized. Moreover, the rise in resting hamstring muscles SWS with increasing hip flexion and knee extension was expected to be greater in both the BF and the SM than in the ST.

Materials and methods

Study population

Twenty-four healthy participants [12 men (age: 25.0 ± 3.9 years, height: 180.3 ± 6.7 cm, mass: 76.3 ± 7.6 kg, BMI: 23.5 ± 2.2 kg.m⁻²) and 12 women (age: 24.2 ± 3.4 years, height: 163.8 ± 8.0 cm, mass: 56.8 ± 5.8 kg, BMI: 21.2 ± 1.4 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 our test–retest assessment and previous SWE studies (Kumagai et al. 2019; McPherson et al. 2020; Wu et al. 2020), groups of 12 participants allowed the detection of a 10% difference in SWS between the two groups, for each hamstring muscle ($\alpha=0.05$ and $1-\beta=0.80$).

Shear wave speed measurements

A single experimental session was performed to measure the resting SWS of the three hamstring muscles of the left thigh in four positions (Fig. 1). For two positions, the participants were lying prone with their hip fully extended (*i.e.*, 180°) and their knee flexed at 90° (H180 K90) or fully extended (H180 K180). For the two remaining positions, participants were lying on their back with both hip and knee flexed at 90° (H90 K90), and with the hip flexed at 120° while the knee was fully extended (H120 K180). The joint angles were controlled for each position with a goniometer (Baseline Absolute Axis Hi-Res 12'' Goniometer, Fabrication Enterprises Inc., USA).

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). Ultrasound device's persistence was set on "medium", smoothing level on "5" and optimization on "penetration". The boundaries of hamstring muscles were identified from B-mode transverse ultrasound images and marked on the skin. The proximal part of each muscle was directly localized with ultrasound and defined as the closest area to the muscle–tendon junction. The central part of each muscle was identified with a tape measurement at 50% of the distance between the greater trochanter and the medial epicondyle of the femur. Throughout the experiments, the probe has always been maintained perpendicular to the skin with the least pressure possible.

Throughout SWE experiments, subjects were instructed to relax completely and no movement occurred during measurements. The ultrasound probe was positioned along the direction of the muscle fascicles with acoustic gel applied between the probe and the skin. The order of the four positions was similar for all the participants, from the shortest to the longest hamstring muscles length (*i.e.*, from H180 K90 to H120 K180) based on numeric simulations (Gait2392 model, OpenSim version 4.3, SimTK). However, for each position, the investigation order of the three muscles (*i.e.*, BF, ST and SM) and the localization within these muscles (*i.e.*, proximal or muscle belly) were randomised. SWE maps were recorded without including any fascia, bone, intramuscular fat or skin to avoid saturated or unfilled parts.

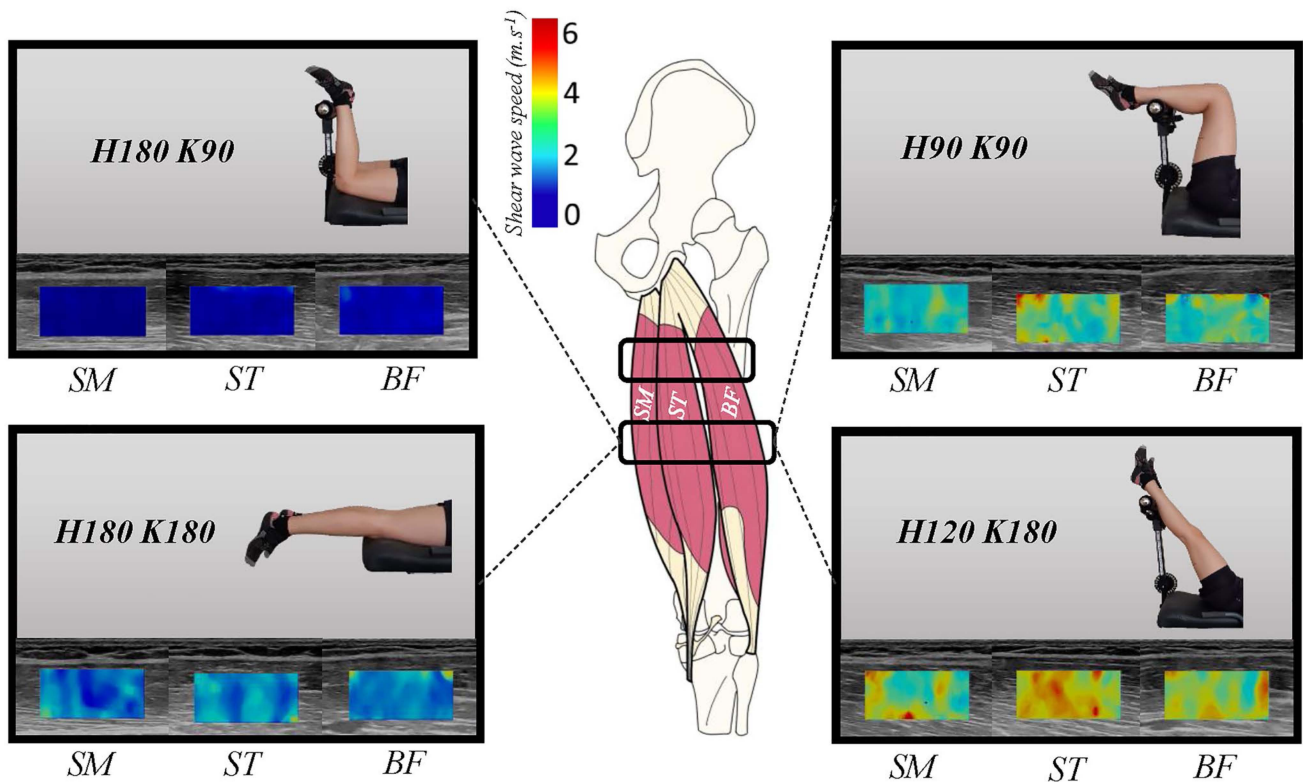


Fig.1 Schematic representation of the shear wave elastography explorations with typical examples of maps acquired for each position (H180 K90 hip extended and knee flexed at 90°, H180 K180 hip and knee extended, H90 K90 hip and knee flexed at 90°, H120 K180 hip flexed at 120° and knee extended | full extension = 180°) in the central

part of each hamstring muscle (*Semimembranosus* [SM], *Semitendinosus* [ST], *Biceps Femoris* long head [BF]). For all the participants, these measurements were repeated in the proximal part of each muscle for the four different positions

Data analysis

For each participant, 24 SWE maps were recorded (4 positions, 3 muscles, 2 localizations). All the SWE maps were acquired and analysed by the same experimenter (J.B.) using the ultrasound system's software (Qbox tool). On each map, an 8 mm diameter circular region of interest (ROI) was drawn and positioned where the standard deviation was the lowest. Potential over-saturated or unfilled areas in the SWE maps were not included for the ROI analyses. The quantification of the SWS was averaged over the proximal and the central parts for each muscle and each position.

Test–retest assessment

The test–retest assessment of the SWS measurements was assessed from two similar test sessions separated by 48 h in 10 participants [5 men (age: 23.2 ± 1.9 years, height: 180.6 ± 6.4 cm, mass: 69.8 ± 4.7 kg, BMI: 21.4 ± 0.8 kg·m⁻²) and 5 women (age: 23.4 ± 1.4 years, height: 161.4 ± 5.2 cm, mass: 54.2 ± 4.9 kg, BMI: 20.8 ± 1.1 kg·m⁻²)]. Intraclass correlation coefficients (ICC), standard

errors of measurement (SEM), coefficients of variation (CV) (Hopkins 2000), minimal detectable differences (MDD) and Bland–Altman plots were determined for measurements at each position and for each muscle.

Statistical analysis

All statistics were computed with *R* (version 4.1.1., The R Foundation for Statistical Computing). The normality of the data distribution was assessed with a Shapiro–Wilk test. A three-way ANOVA (sex \times position \times muscle) was used. Post hoc analysis was conducted using Tukey HSD test when appropriate. The effect size was calculated using partial eta squared (η^2_p) for the interactions between sex, positions and/or muscle, and using Cohen's *d* for the 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^2_p and 0.2, 0.5 and 0.8 for Cohen's *d* (Cohen, 1969). Data are presented as mean \pm standard deviation and the significance level was set at $p < 0.05$.

Results

Test–retest assessment

The ICC, SEM, CV and MDD of inter-day measurements ranged from 0.64 to 0.93, 0.08 to 0.27 m.s⁻¹, 3.6 to 7.0% and 0.2 to 0.75 m.s⁻¹, respectively (Table 1). Bland–Altman plots of the test–retest assessment are displayed in Online Resources 1, 2 and 3.

Effects of sex

While no significant sex × position × muscle interaction was found ($F_{6,0}=3.4$, $p=0.284$, $\eta^2_p=0.028$, small effect, Table 2), a significant sex × muscle interaction was observed ($F_{2,18}=3.4$, $p=0.036$, $\eta^2_p=0.025$, small effect). Indeed, when the SWS values were averaged over the four positions, the ST SWS was 9.0% higher in men than in women ($p=0.030$, $d=0.26$, small effect, Fig. 2). Conversely, BF and SM SWS did not differ between sexes ($p=1.00$). SM SWS was higher than BF SWS in men (+11.8%, $p=0.040$, $d=0.34$, small effect) but also in women (+9.7%, $p=0.029$, $d=0.28$, small effect). ST SWS was higher than BF SWS in men only (+16.1%, $p<0.001$, $d=0.47$, small effect, Fig. 2).

Table 2 Shear wave speed values measured in hamstring muscles for four positions in men and women

Position	Muscle	Men	Women
H180 K90	Hamstrings	1.80 ± 0.17	1.88 ± 0.21
	<i>Biceps femoris</i>	1.81 ± 0.17	1.93 ± 0.18
	<i>Semitendinosus</i>	1.75 ± 0.18	1.83 ± 0.23
	<i>Semimembranosus</i>	1.84 ± 0.17	1.88 ± 0.23
H180 K180	Hamstrings	2.43 ± 0.48	2.30 ± 0.33
	<i>Biceps femoris</i>	2.08 ± 0.24	2.15 ± 0.37
	<i>Semitendinosus</i>	2.75 ± 0.42	2.47 ± 0.22
	<i>Semimembranosus</i>	2.47 ± 0.50	2.28 ± 0.31
H90 K90	Hamstrings	2.87 ± 0.39	2.77 ± 0.43
	<i>Biceps femoris</i>	2.90 ± 0.40	2.87 ± 0.36
	<i>Semitendinosus</i>	2.92 ± 0.37	2.73 ± 0.47
	<i>Semimembranosus</i>	2.79 ± 0.39	2.72 ± 0.47
H120 K180	Hamstrings	4.04 ± 0.79	3.88 ± 0.75
	<i>Biceps femoris</i>	3.39 ± 0.56	3.36 ± 0.49
	<i>Semitendinosus</i>	4.42 ± 0.65	3.83 ± 0.62
	<i>Semimembranosus</i>	4.32 ± 0.72	4.45 ± 0.69

Data are expressed in m.s⁻¹

H180 K90 hip extended and knee flexed at 90°, *H180 K180* hip and knee extended, *H90 K90* hip and knee flexed at 90°, *H120 K180* hip flexed at 120° and knee extended (full extension = 180°)

Table 1 Test–retest assessment of the shear wave speed measurements

Position	Muscle	<i>n</i>	ICC	SEM (m.s ⁻¹)	CV (%)	MDD (m.s ⁻¹)
H180 K90	Hamstrings	10	0.90	0.06	3.6	0.17
	<i>Biceps Femoris</i>		0.87	0.13	6.6	0.36
	<i>Semitendinosus</i>		0.72	0.12	6.1	0.33
	<i>Semimembranosus</i>		0.70	0.08	4.4	0.22
H180 K180	Hamstrings	10	0.85	0.09	4.1	0.25
	<i>Biceps Femoris</i>		0.81	0.08	3.6	0.22
	<i>Semitendinosus</i>		0.89	0.12	5.2	0.33
	<i>Semimembranosus</i>		0.87	0.14	6.4	0.39
H90 K90	Hamstrings	10	0.83	0.12	4.2	0.33
	<i>Biceps Femoris</i>		0.79	0.15	4.9	0.42
	<i>Semitendinosus</i>		0.80	0.16	5.7	0.44
	<i>Semimembranosus</i>		0.90	0.12	4.6	0.33
H120 K180	Hamstrings	8	0.95	0.12	3.5	0.33
	<i>Biceps Femoris</i>		0.81	0.21	7.0	0.58
	<i>Semitendinosus</i>		0.88	0.22	5.9	0.61
	<i>Semimembranosus</i>		0.87	0.27	6.7	0.75
All positions	Hamstrings	8	0.97	0.17	5.8	0.46
	<i>Biceps Femoris</i>		0.96	0.15	5.2	0.41
	<i>Semitendinosus</i>		0.96	0.18	6.0	0.50
	<i>Semimembranosus</i>		0.97	0.17	5.8	0.47

ICC intraclass correlation coefficient, SEM standard error of measurement, CV coefficient of variation, MDD minimal detectable difference, *H180 K90* hip extended and knee flexed at 90°, *H180 K180* hip and knee extended; *H90 K90* hip and knee flexed at 90°, *H120 K180* hip flexed at 120° and knee extended (full extension = 180°)

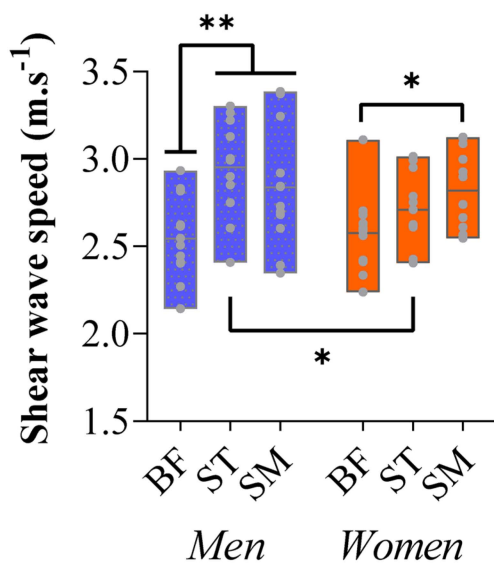


Fig. 2 Shear wave speed of *Biceps Femoris* long head (BF), *Semitendinosus* (ST) and *Semimembranosus* (SM) averaged over the four positions in men and women. Significant differences are represented as: * $p < 0.05$ and ** $p < 0.01$

Effects of articular positions among muscles

A significant interaction was found between position and muscle factors, independently of sex ($F_{6,12} = 12.6, p < 0.001, \eta^2_p = 0.223$, large effect). A significant difference in SWS between each position was observed for the SM ($p < 0.05$) but neither for the ST between the positions H180 K180 and H90 K90 ($p = 0.82$) nor for the BF between the positions H180 K90 and H180 K180 ($p = 0.50$, Fig. 3). However, the rise in SWS between the H180 K180 and H90 K90 positions was greater for the BF than for the ST and the SM (+361.3%, $d = 1.38, p < 0.001$ and +201.3%, $d = 0.84, p = 0.003$ respectively, large effects). Moreover, it appears

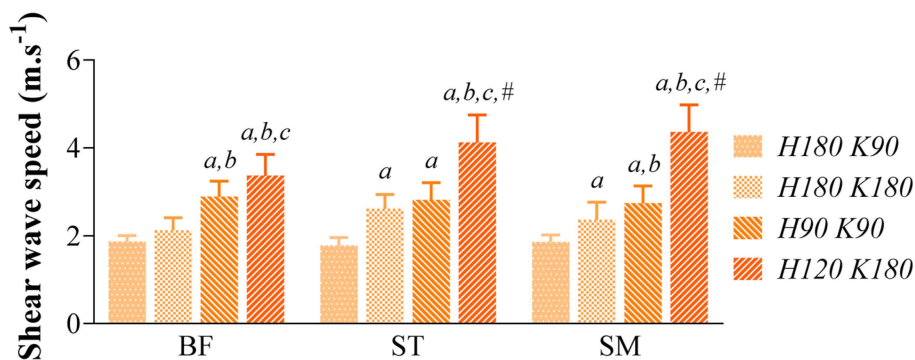


Fig. 3 Shear wave speed of *Biceps Femoris* long head (BF), *Semitendinosus* (ST) and *Semimembranosus* (SM) for each position (H180 K90 hip extended and knee flexed at 90°, H180 K180 hip and knee extended, H90 K90 hip and knee flexed at 90°, H120 K180 hip flexed

that only the position leading to the longest muscle length (*i.e.*, H120 K180) resulted in a difference in SWS between muscles, with greater SWS values for the SM and ST than for the BF (+29.8%, $d = 1.80$ and +22.0%, $d = 1.35$, respectively, large effects, $p < 0.001$, Fig. 3).

Discussion

The present study was designed to determine whether hamstring muscles SWS differed according to sex and stretch conditions. We hypothesized that the resting hamstring muscles rigidity would be greater in men than in women for all the hamstring muscles and that hip flexion and knee extension would result in a greater SWS in BF and SM than in ST. The main result of this study showed a higher resting ST SWS in men than in women and, independently of sex, a higher SWS in SM and ST than in BF at the longest hamstrings length. Interestingly, hip flexion and knee extension systematically increased the SWS in the SM, but neither in the ST nor in the BF.

SWS values and test–retest assessment

The SWS values measured in the present study ranged from 1.75 to 4.45 $m.s^{-1}$ and the test–retest of these measurements was assessed as moderate to very good, with ICC and CV ranging from 0.70 to 0.90 and from 3.6 to 7.0%, respectively. These results are consistent not only with previous studies reporting SWS values ranging from 1.71 to 5.45 $m.s^{-1}$ (Alfuraih et al. 2019; Kumagai et al. 2019; Wu et al. 2020) but also with those displaying ICC and CV values ranging, respectively, from 0.62 to 0.98 and from 2.1 to 13.4% for the hamstring muscles group (Avrillon et al. 2019; Ichihashi et al. 2016; Le Sant et al. 2015; Mendes et al. 2018; Nakao et al. 2018).

at 120° and knee extended | full extension = 180°) in the entire experimental population ($N = 24$). **a**: significant difference with H180 K90, **b**: significant difference with H180 K180, **c**: significant difference with H90 K90, **#**: significant difference with BF

Sex differences

Only a few studies have investigated the effects of sex on hamstring muscles SWS. Contrasting results have been reported, with a greater rigidity in men than in women (Kumagai et al. 2019; McPherson et al. 2020; Wu et al. 2020) or an absence of sex difference (Avrillon et al. 2019). A study presenting rigidity values for the different hamstring muscles reported a 10.8% higher ST SWS in men than in women (Wu et al. 2020), similar to the 9.0% difference observed in the present study. Another study reported a greater BF SWS in men than in women (McPherson et al. 2020) and a similar sex difference has been observed for the entire hamstrings muscle group (Kumagai et al. 2019). However, no difference has been found for the BF or the whole hamstrings muscle group in the present study. Differences in experimental positions between the present study and those of McPherson et al. (2020) and Kumagai et al. (2019) could explain the latter discrepancy. Another study reported similar hamstring muscles SWS values in men and women elite athletes (Avrillon et al. 2019). Since training affects muscle mechanical properties and as there is a huge gap in training status between both populations (25–40 h/week in the study of Avrillon et al. vs. 3 h/wk in the present study), their results are, however, hardly comparable to the ones from the present study.

When averaged over the four positions assessed in the present study, the ST SWS value was lower in women than in men. As the hamstrings originate from the ischial tuberosity, this difference in rigidity could result from the broader and larger shape in women pelvis (Fischer and Mitteroecker 2017), leading to a potential smaller ST length change with hip flexion and knee extension in women than in men.

In addition to the sex difference in pelvis geometry, muscle composition can account for the discrepancy in ST SWS observed between men and women. A recent study reported a higher number of fast-type muscle fibres and relative area inside the ST in men than in women (Fournier et al. 2022). This difference could be due to the effects of estrogens on muscle fibres. Animal studies have shown that estrogen insufficiency shifts muscle composition towards faster fibre-types, while estrogen replacement can counteract this effect (Kitajima and Ono 2016; Liu et al. 2009). The continuous exposure to estrogen experienced by women all along their reproductive life could, therefore, explain the high proportion of slow-type muscle fibres observed in their ST compared to men's one. Given that Young's modulus has been shown to be higher in type II muscle fibres than in type I (Malisoux et al. 2006), the sex difference in muscle typology may account for the greater ST muscle rigidity observed in men in the present study. Further studies are, however, still needed to ensure that the ST is the only hamstring muscle to present this sex-related difference in muscle typology.

The effects of sex hormones on the components of the muscle extracellular matrix (ECM) could, however, explain this muscle-specific discrepancy in rigidity between men and women. Indeed, the administration of estradiol has been reported to diminish the amount of type-I collagen in human tissues (Fede et al. 2019). In women, estradiol could therefore alter the muscle mechanical response to its lengthening through a regulation of the composition of the ECM, which may explain the sex discrepancies observed in the current study in terms of ST rigidity. As BF and SM SWS did not differ according to sex, this hypothesis implies that those muscles may be less sensitive to estrogens than the ST. However, to date this question has never been studied. Similarly, no information is available on a potential sex-related difference in the distribution of connective tissue among the hamstring muscles. Considering the other components of muscle, no sex difference in the proportion of intramuscular fat of the three hamstring muscles was found from MRI explorations (Hogrel et al. 2015).

Effects of position

Regardless of sex, increasing hamstring muscles length usually results in a muscle-specific rise in SWS values (Le Sant et al. 2015; Miyamoto et al. 2020). In the present study, the ST SWS was similar between the positions H180 K180 and H90 K90, akin with a previous observation (Berrigan et al. 2020). The latter result can be explained by the small changes in ST muscle length between these two positions compared to the other hamstring muscles (Kellis et al. 2021).

An unchanged SWS was similarly observed for the BF between the positions H180 K90 and H180 K180. However, this result contrasts with a previous study displaying an 80% rise in BF SWS between these two positions (Dubois 2015). These differences could be related to the measurement localizations, with single distal measurements in Dubois et al. (Dubois 2015) study against averages of central and proximal explorations in the present study. The potential influence of the *biceps femoris* short head on the passive tension generated by its long head during knee extension could also be involved and still cannot be ruled out.

Thus, extending the knee when the hip was in full extension did not affect the BF SWS, whereas the ST and SM SWS increased. However, the hamstrings lengthening caused by the flexion of the hip joint between the position H180 K180 and H90 K90 induced a greater rise in the BF length than in the ST and SM ones. As muscle damage and injuries appear when the muscle is highly stretched (Lieber and Friden 1993; Liu et al. 2017) and that the BF is being subject to a great lengthening under this range of motion (*i.e.*, between H180 K180 and H90 K90), it could explain that the hamstring injuries appear preferentially in the BF (Koulouris and Connell 2003). One must, however, be aware

that our SWS analyses only rely on intra-muscle measurements and that the tendons of these muscles must play a non-negligible role in the kind of injury processes described above, role that we cannot estimate based on the present study's results.

In line with the findings of previous SWE studies, between-muscles differences in hamstring muscles SWS have only been observed at long muscle length (Avrillon et al. 2019; Le Sant et al. 2015; Miyamoto et al. 2020). However, the hamstring muscle presenting the greatest SWS at long muscle length is still debated. In the most stretched position (including hip and knee joint angle changes), prior works reported a higher rigidity for the SM (Miyamoto et al. 2020), the BF (Le Sant et al. 2015), or both (Avrillon et al. 2019), whereas greater SWS were found for the SM and the ST in the present study. Although the positions in which these results were obtained were different in terms of hip and knee angles, they all led to comparable SWS values. Differences in probe positioning could, however, explain that, in the studies of Le Sant et al. and Avrillon et al., the ST was constantly the less rigid hamstring muscle while the opposite was observed in the present study (Avrillon et al. 2019; Le Sant et al. 2015). Indeed, their measurements were only made close to mid-thigh for the BF and SM and near its proximal origin for the ST. Although the SWS has been reported to be homogeneous within the hamstring muscles at long muscle length (Miyamoto et al. 2020), this intramuscular variability of SWS measurement has only been investigated in one study, whose outcomes differed from the ones observed in the present study (Online resource 4). Therefore, the assessment of intramuscular variability in hamstring muscles SWS still requires additional experimentations, at least to confirm that differences in probe positioning could not prevent between-studies comparisons. Moreover, further investigations are needed to determine whether the functional involvement of these muscles (ST and SM) in the medial knee rotation could have an influence on their resting mechanical properties (in comparison to the BF involved in lateral rotation).

Limitations

One of the limitations of the current study is related to the lack of menstrual cycle control in women. The sex-related difference in ST SWS observed in the present study may be the result of the effects of sex hormones on the muscle mechanical properties (Eiling et al. 2007; Fede et al. 2019; LeMoine et al. 2009; Miller et al. 2007). As the concentrations of these hormones are modulated by the menstrual cycle, it could, therefore, have impacted the SWS values obtained in the current study. Second, the BF short head could have affected the passive properties of the BF long head, especially for the positions with the

knee fully extended. In addition, resting muscle SWS measurements were performed at absolute joint angles, which can represent different relative angles according to the various maximal joint ranges of motion among the participants. Even if an a priori statistical power analysis has been performed to ensure that the sample size was sufficient to detect group differences, it should be acknowledged that the sample size of the present study is small and can represent a potential limitation to the interpretation of the results. Even though it did not affect the test–retest repeatability of our SWS measurements, the viscoelastic behaviour of the musculo-tendinous tissues investigated in this study has not been considered. Finally, the results of the present study are limited by the lack of muscle activity control. However, prior to the main experiments, it was checked that the positions tested would not induce any muscle activation superior to 2% of the maximal EMG activation (Le Sant et al. 2019). Moreover, the instructions repeated to ensure that the participants were as relaxed as possible and the good test–retest results suggest that all the muscles investigated were in a passive state during the main experiments.

Perspective

Although sex hormones seem to exert diverse effects on the muscle tissue, further studies are warranted to evaluate the potential muscle mechanical properties adaptations to these hormones. Interestingly, a difference in ST rigidity has been observed between men and women, which could be linked to long-term effects of sex hormones on women's muscles. Additional investigations on the SWS of the three hamstring muscles in conjunction with hormonal assessments could thus be of utmost interest. Further investigations are also warranted to better understand the interaction between skeletal muscle and tendinous tissues in the processes of exercise-induced muscle injuries and damage.

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Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interests The authors declare no conflict of interest, financial or otherwise.

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.

References

- Alfuraih AM, Tan AL, O'Connor P, Emery P, Wakefield RJ (2019) The effect of ageing on shear wave elastography muscle stiffness in adults. *Aging Clin Exp Res* 31(12):1755–1763. <https://doi.org/10.1007/s40520-019-01139-0>
- Avrillon S, Lacourpaille L, Hug F, Le Sant G, Frey A, Nordez A, Guilhem G (2019) Hamstring muscle elasticity differs in specialized high-performance athletes. *Scand J Med Sci Sports* 30(1):83–91. <https://doi.org/10.1111/sms.13564>
- Berrigan WA, Wickstrom J, Farrell M, Alter K (2020) Hip position influences shear wave elastography measurements of the hamstring muscles in healthy subjects. *J Biomech* 109:109930. <https://doi.org/10.1016/j.jbiomech.2020.109930>
- Cohen J (1969) *Statistical power analysis for the behavioral sciences*. Academic Press, New York
- Cross KM, Gurka KK, Saliba S, Conaway M, Hertel J (2013) Comparison of hamstring strain injury rates between male and female intercollegiate soccer athletes. *Am J Sports Med* 41(4):742–748. <https://doi.org/10.1177/0363546513475342>
- Csapo R, Gumpenberger M, Wessner B (2020) Skeletal muscle extracellular matrix: what do we know about its composition, regulation, and physiological roles? *A Narrat Rev Front Physiol* 11(253):15
- Dubois G (2015) Reliable protocol for shear wave elastography of lower limb muscles at rest and during passive stretching. *Ultrasound Med Biol* 41(9):2284–2291
- Eiling E, Bryant AL, Petersen W, Murphy A, Hohmann E (2007) Effects of menstrual-cycle hormone fluctuations on musculotendinous stiffness and knee joint laxity. *Knee Surg Sports Traumatol Arthrosc* 15(2):126–132. <https://doi.org/10.1007/s00167-006-0143-5>
- Ekstrand J, Hägglund M, Waldén M (2011) Epidemiology of muscle injuries in professional football (soccer). *Am J Sports Med* 39(6):1226–1232. <https://doi.org/10.1177/0363546510395879>
- Fede C, Pirri C, Fan C, Albertin G, Porzionato A, Macchi V, De Caro R, Stecco C (2019) Sensitivity of the fasciae to sex hormone levels: modulation of collagen-I, collagen-III and fibrillin production. *PLoS ONE* 14(9):e0223195. <https://doi.org/10.1371/journal.pone.0223195>
- Fischer B, Mitteroecker P (2017) Allometry and sexual dimorphism in the human pelvis. *Anat Rec* 300(4):698–705. <https://doi.org/10.1002/ar.23549>
- Fournier G, Bernard C, Cieviet-Bonfils M, Kenney R, Pingon M, Sappey-Marinié E, Chazaud B, Gondin J, Servien E (2022) Sex differences in semitendinosus muscle fiber-type composition. *Scand J Med Sci Sports Sms*. <https://doi.org/10.1111/sms.14127>
- Hogrel J-Y, Barnouin Y, Azzabou N, Butler-Browne G, Voit T, Moraux A, Leroux G, Behin A, McPhee JS, Carlier PG (2015) NMR imaging estimates of muscle volume and intramuscular fat infiltration in the thigh: variations with muscle, gender, and age. *Age* 37(3):60–71. <https://doi.org/10.1007/s11357-015-9798-5>
- Hopkins WG (2000) Measures of reliability in sports medicine and science. *Sports Med* 30(1): 1–15. <https://doi.org/10.2165/00007256-200030010-00001>
- Ichihashi N, Umegaki H, Ikezoe T, Nakamura M, Nishishita S, Fujita K, Umehara J, Nakao S, Ibuki S (2016) The effects of a 4-week static stretching programme on the individual muscles comprising the hamstrings. *J Sports Sci* 34(23):2155–2159. <https://doi.org/10.1080/02640414.2016.1172725>
- Kellis E, Konstantinidou A, Ellinoudis A (2021) Muscle length of the hamstrings using ultrasonography versus musculoskeletal modelling. *J Funct Morphol Kinesiol* 6(1):26–39. <https://doi.org/10.3390/jfmk6010026>
- Kitajima Y, Ono Y (2016) Estrogens maintain skeletal muscle and satellite cell functions. *J Endocrinol* 229(3):267–275
- Koulouris G, Connell D (2003) Imaging of hamstring injuries: therapeutic implications. *Skeletal Radiol* 32:582–589
- Kumagai H, Miyamoto-Mikami E, Hirata K, Kikuchi N, Kamiya N, Hoshikawa S, Zempo H, Naito H, Miyamoto N, Fuku N (2019) ESR1 rs2234693 polymorphism is associated with muscle injury and muscle stiffness. *Med Sci Sports Exerc* 51(1):19–26. <https://doi.org/10.1249/MSS.0000000000001750>
- Larruskain J, Lekue JA, Diaz N, Odriozola A, Gil SM (2017) A comparison of injuries in elite male and female football players: a five-season prospective study. *Scand J Med Sci Sports* 28(1):237–245. <https://doi.org/10.1111/sms.12860>
- Le Sant G, Ates F, Brasseur J-L, Nordez A (2015) Elastography study of hamstring behaviors during passive stretching. *PLoS ONE* 10(9):1–13. <https://doi.org/10.1371/journal.pone.0139272>
- Le Sant G, Gross R, Hug F, Nordez A (2019) Influence of low muscle activation levels on the ankle torque and muscle shear modulus during plantar flexor stretching. *J Biomech* 93:111–117. <https://doi.org/10.1016/j.jbiomech.2019.06.018>
- LeMoine JK, Lee JD, Trappe TA (2009) Impact of sex and chronic resistance training on human patellar tendon dry mass, collagen content, and collagen cross-linking. *Am J Physiol-Regul Integr Comp Physiol* 296(1):R119–R124. <https://doi.org/10.1152/ajpregu.90607.2008>
- Lieber RL, Friden J (1993) Muscle damage is not a function of muscle force but active muscle strain. *J Appl Physiol* 74(2):520–526
- Liu Y-H, Huang Y, Shao X (2009) Effects of estrogen on genioglossal muscle contractile properties and fiber-type distribution in chronic intermittent hypoxia rats. *Eur J Oral Sci* 117:685–690
- Liu Y, Sun Y, Zhu W, Yu J (2017) The late swing and early stance of sprinting are most hazardous for hamstring injuries. *J Sport Health Sci* 6(2):133–136. <https://doi.org/10.1016/j.jshs.2017.01.011>
- Malisoux L, Francaux M, Nielens H, Theisen D (2006) Stretch-shortening cycle exercises: an effective training paradigm to enhance power output of human single muscle fibers. *J Appl Physiol* 100(3):771–779. <https://doi.org/10.1152/jappphysiol.01027.2005>
- McPherson AL, Nagai T, Schilaty ND, Hale R, Hewett TE, Bates NA (2020) High school male basketball athletes exhibit greater hamstring muscle stiffness than females as assessed with shear wave elastography. *Skeletal Radiol* 49(8):1231–1237. <https://doi.org/10.1007/s00256-020-03397-w>
- Mendes B, Firmino T, Oliveira R, Neto T, Infante J, Vaz JR, Freitas SR (2018) Hamstring stiffness pattern during contraction in healthy individuals: analysis by ultrasound-based shear wave elastography. *Eur J Appl Physiol* 118(11):2403–2415. <https://doi.org/10.1007/s00421-018-3967-z>
- Miller BF, Hansen M, Olesen JL, Schwarz P, Babraj JA, Smith K, Rennie MJ, Kjaer M (2007) Tendon collagen synthesis at rest and after exercise in women. *J Appl Physiol* 102(2):541–546. <https://doi.org/10.1152/jappphysiol.00797.2006>