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# **Hamstring muscle elasticity differs in specialized high-performance athletes**

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**Running title:** Impact of sport on hamstring shear modulus

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1 **ABSTRACT (250 Words)**

2 The effect of training on hamstring flexibility has been widely assessed through the  
3 measurement of the maximal range of motion or passive torque. However, these global  
4 measures do not provide direct information on the passive muscle mechanical properties of  
5 individual muscle. This characterization is crucial to better understand the effect of  
6 interventions as selective adaptations may occur among synergist muscles.

7 Taking advantage of shear wave elastography, we aimed to determine whether elite sport  
8 athletes exhibit different passive shear modulus of hamstring heads compared to controls.

9 Passive shear modulus was measured on *semitendinosus* (ST), *semimembranosus* (SM) and  
10 *biceps femoris* (BF) using shear wave elastography with the knee flexed at 60° and 90°, and  
11 90° of hip flexion. A total of 97 elite athletes from various sports including running sprint,  
12 figure skating, fencing, field hockey, taekwondo, basket-ball and soccer, and 12 controls were  
13 evaluated.

14 The shear modulus measured at 60° of knee flexion was lower in SM for figure skating  
15 ( $P<0.001$ ;  $d=1.8$ ), taekwondo ( $P<0.001$ ;  $d=2.1$ ), fencing ( $P=0.024$ ;  $d=1.0$ ) and soccer  
16 ( $P=0.011$ ;  $d=0.9$ ) compared to controls, while no difference were found for athletic sprinters,  
17 field hockey and basket-ball players. Shear modulus of the BF and ST muscle was not  
18 significantly different between controls and elite athletes, regardless of the sport  
19 specialization (all  $P$  values=1).

20 We provide evidence that the shear modulus of the SM is altered in athletes involved in elite  
21 sport practice performed over large range of motion and/or including substantial stretching  
22 program in training content (taekwondo, figure skating, fencing and soccer).

23 **Keywords:** Stiffness - shear wave elastography - elite athletes

## 24 INTRODUCTION

25 Hamstring muscle complex consists of three main heads [*biceps femoris* long head  
26 (BF), *semimembranosus* (SM), and *semitendinosus* (ST)] acting on both hip and knee joint <sup>1,2</sup>.  
27 These bi-articular muscles are therefore significantly involved in numerous dynamic tasks  
28 (i.e., jumping, landing, running, kicking). The substantial loading applied on large range of  
29 motions during such movements expose hamstring muscles to a high risk of strain injury,  
30 particularly in high-velocity running during which they are actively stretched and withstand a  
31 maximum peak force at long muscle lengths <sup>3,4</sup>. Because flexibility may influence the ability  
32 of hamstring muscles to resist such stress, it has been proposed as a predisposing factor for  
33 developing muscle injury <sup>5,6</sup>.

34 Hamstring flexibility has been widely assessed through the maximal range of motion  
35 achieved during passive straight-leg-raise and sit-and-reach tests to determine the effects of  
36 training, to orient training contents, to determine the risk of injury or to evaluate the impact of  
37 previous injury <sup>7</sup>. Although reliable and easy-to-use, these evaluations are influenced by  
38 examiners' or subjects' subjectivity, lumbar and thoracic flexibility (for the sit-and-reach  
39 test), as well as stretch tolerance <sup>8,9</sup>. As a consequence, this global measure does not provide a  
40 direct estimation of the mechanical properties of each individual muscle <sup>8</sup>, and, in turn, do not  
41 inform about putative between-muscles differences due to intrinsic morphological properties  
42 (composition and architecture), various training contents (e.g., stretching <sup>10</sup>) or previous injury  
43 events <sup>11</sup>. It is therefore crucial to use appropriate methods allowing for reliable assessment of  
44 individual muscle mechanical properties in order to determine their specific training  
45 requirements.

46 Ultrasound shear wave elastography (SWE) can be used as a reliable <sup>12</sup> and valid <sup>13</sup>  
47 method to assess regional shear modulus. This parameter reflects intrinsic muscle mechanical  
48 properties, regardless of its size. More precisely, it represents an index of tissue stiffness. For

49 a muscle of a given size, the higher the shear modulus, the higher the stiffness. Using SWE, it  
50 has been recently shown that passive muscle shear modulus increased after repeated eccentric  
51 contractions <sup>14</sup> or inversely decreased after a stretching protocol <sup>15</sup>. Interestingly, the  
52 magnitude of these changes may differ among the synergist muscles <sup>15</sup>. More precisely, a  
53 recent study has shown that a 4-week static stretching program induces a decrease in shear  
54 modulus in hamstring muscles (i.e., increase in hamstring shear modulus), with a higher effect  
55 on the SM compared to the BF and ST <sup>10</sup>. However, the impact of chronic sport practice on  
56 individual muscle shear modulus has not been described. It is well known that most of sports  
57 activities involve bouncing and jumping with high-intensity stretch-shortening cycles (e.g.,  
58 soccer, basketball, athletic sprinting). Such motor tasks stimulate muscle-tendon units of the  
59 lower limb to store and release high amounts of elastic energy and in turn amplify power <sup>16</sup>. In  
60 these sports and others, the hamstring muscles are also involved over moderate to large ranges  
61 of motion. For instance, Preuschl et al. <sup>17</sup> reported that specific movements regularly executed  
62 in taekwondo involved hip flexed angles about 65° (180° = full hip extension) and knee  
63 angles close to full extension (178°, 180° = full extension). Similarly, elite fencers regularly  
64 execute lunges with hip almost fully flexed (49°) combined with moderated knee extension  
65 angles (116°) <sup>18</sup>. A recent cross-sectional study reported that highly flexible ballet dancers  
66 display different morphological, mechanical, and functional properties of the triceps surae  
67 muscle-tendon unit, compared to control individuals with no history of stretching training <sup>19</sup>.  
68 Therefore, it is reasonable to assume that daily exposure to elite sport practice may lead to  
69 adaptations in hamstring muscle shear modulus. The description of the shear modulus of each  
70 individual hamstring head in elite athletes specialized in various activities (e.g., soccer,  
71 athletic sprinting, fencing, taekwondo) would provide the impetus to explore its putative  
72 importance in motor performance.

73 Taking advantage of shear wave elastography, we aimed to determine whether the  
74 shear modulus of hamstring heads (ST, SM, BF) differs between elite athletes (i.e., basketball,  
75 field-hockey, soccer, track and field, fencing, taekwondo, figure skating) and controls. We  
76 hypothesized that, compared to controls, elite athletes exhibit lower hamstring shear modulus  
77 due to high intensity stretch-shortening cycles <sup>16</sup> and/or moderate to large range of motion  
78 movements at the hip and knee (e.g., Preuschl et al. <sup>17</sup>), performed daily in their sport  
79 activities. We also hypothesized that sport specialization (i.e., taekwondo, figure skating,  
80 fencing, athletic sprinting, basketball, soccer, and field-hockey) would induce specific  
81 alterations of the shear modulus among hamstring muscle heads depending on the specific  
82 mechanical constraints associated with each sport activity.

83

## 84 **METHODS**

### 85 **Participants**

86 A total of 109 participants: 97 elite athletes (61 males) who trained once-to-twice a  
87 day on 25 to 40 h/wk regular basis, from soccer, track and field sprinting, fencing, taekwondo,  
88 figure skating, field hockey and basket-ball, and 12 healthy moderately active participants  
89 without sport specialization (6 males, 6 females) participated in this study (Table 1). Training  
90 programs of elite athletes included about  $\sim 150 \pm 110$  min of hamstring stretching routines per  
91 week. Note that this volume varied greatly between athletes, as some of them are doing  
92 additional individual specific stretching workout with physiotherapists. All of them had  
93 competed at the international level during the year of the experiment. 29 participants had an  
94 history of unilateral hamstring injury. Only the uninjured side of these athletes was included  
95 in the study to evaluate the effect of sport to avoid any putative effect of injury on shear  
96 modulus values. One participant who had a hamstring injury history for both sides was  
97 excluded from the analyses. All athletes did not perform any vigorous strength training of the



98 lower limb 48 hours before the experiment. They were informed regarding the nature, aims  
99 and risks associated with the experimental procedure before they gave their written consent to  
100 participate. This study was approved by the ethics committee of Île de France III (agreement  
101 no 3418) and conformed to the standards of the Declaration of Helsinki.

102

### 103 **Experimental set-up**

104 Participants laid supine on a bench positioned next to the motor of an isokinetic  
105 dynamometer (Con-trex, CMV AG, Dübendorf, Switzerland), with their hip flexed at 90° (0°  
106 = full extension; Fig. 1)<sup>20</sup>. The leg and the thigh were firmly fixed to the dynamometer arm  
107 with non-compliant straps to avoid any antero-posterior shift.

108

### 109 **Shear-wave elastography**

110 An ultrasound scanner (Aixplorer v6, Supersonic Imagine, Aix-en-Provence, France)  
111 coupled with a linear transducer (4-15 MHz, SuperLinear 15-4, Vermon, Tours, France) was  
112 used in SWE mode (custom musculoskeletal preset, penetration mode, smoothing level 5,  
113 persistence off). This technique provides a 2-dimensional map of the shear modulus (for  
114 review see Hug et al.<sup>21</sup>) of the targeted tissue at 1 Hz with a spatial resolution of 1×1 mm  
115 (Fig. 1).

116

117 The examiner was trained three months on the ultrasound scanner to adequately  
118 measure the shear modulus in hamstring muscles with minimal transducer pressure on the  
119 skin. Muscles were scanned using a handheld technique based on previous studies from our  
120 group that allowed reliable assessment of the shear modulus in hamstring muscles<sup>20</sup>. The  
121 probe was placed over the posterior face of the thigh, proximally to the tendinous inscription  
122 dividing this muscle into two portions to image ST. For SM and BF, the probe was placed

123 proximal to the musculotendinous junction, close to mid-thigh. Once the site of measurement  
124 was determined, the probe was orientated to measure the shear modulus along the fascicle's  
125 line of action. The probe location was considered appropriate when fascicles were clearly  
126 visible across the image and the obtained shear modulus map included no aponeurosis, and  
127 little amount of missing or non-physiological values. The locations were marked on the skin  
128 using a waterproof marker so that the transducer location remained constant throughout  
129 measurements.

130

### 131 **Protocol**

132 Participants first performed four slow ( $10^{\circ} \cdot s^{-1}$ ) passive loading/unloading cycles  
133 between  $90^{\circ}$  and  $30^{\circ}$  of knee flexion ( $0^{\circ}$  = full extension) to account for the possible effect of  
134 conditioning <sup>22</sup>. The resting shear modulus was then measured in each hamstring muscle  
135 during 10 s at two knee angles ( $90^{\circ}$  and  $60^{\circ}$ ). Before each acquisition, a 10-s period was kept  
136 between knee positioning and the onset of the elastography acquisition to further account for  
137 any potential stretch-relaxation effect <sup>23</sup>. The participants were instructed to remain as relaxed  
138 as possible throughout the measurements. The shear modulus was assessed in hamstring  
139 muscles of both legs to compare the dominant and non-dominant leg. These measures were  
140 performed in a randomized order on 79 participants with no injury in both lower limbs. The  
141 dominant leg was defined as the leg preferentially used to kick a ball.

142

### 143 **Data analysis**

144 All data were processed using Matlab custom-written scripts (R2017a, The  
145 MathWorks Inc., Natick, USA) and Origin 2018 software (OriginLab Corporation,  
146 Northampton, USA). Mean shear modulus values were obtained over the largest possible  
147 region of interest. The unexpected presence of vein and intramuscular fascia may punctually

148 induce small-size artifacts <sup>24</sup>. Particular care was taken to not include artefacts and  
149 aponeurosis in the region of interest. Data were exported in ‘mp4’ format and transformed to  
150 a sequence of ‘jpeg’ images. Image processing then converted the resulting colored map into  
151 shear modulus values. The average Young’s modulus was divided by 3, to obtain the muscle  
152 shear modulus <sup>21</sup>. The five successive images that resulted in the lowest standard deviation  
153 were considered to calculate an average value of the shear modulus ( $\mu$ ).

154

## 155 **Statistics**

156 All statistical analyses were conducted using Statistica version 7.1 software (StatSoft,  
157 Tulsa, OK). Data were screened for normal distribution using the Shapiro–Wilk test. The  
158 inter-day reliability of shear modulus measurements was evaluated on control participants (n  
159 = 12) using the intraclass correlation coefficient (ICC), typical error (TE) and coefficient of  
160 variation (CV). Ages were compared between sports by using a one-way ANOVA (between  
161 subject factor: sport). The effect of laterality on muscle shear modulus was tested through a  
162 three-way ANOVA [side (dominant, non-dominant)  $\times$  muscle (BF, ST, SM)  $\times$  angle (90°,  
163 60°)] on participants with no injury on both lower limbs (n = 79). As the proportion of males  
164 and females differs between sports (cf. Table 1), the effect of sex was tested using a two-way  
165 ANOVA [within-subject variable: muscle (BF, ST, SM)  $\times$  angle (90°, 60°); categorical factor:  
166 sex (male, female)] on participants with no injury on both lower limbs (n = 79). For controls  
167 and uninjured athletes, the muscle shear modulus of the two limbs was averaged.

168 A three-way ANOVA was performed to determine whether elite athletes exhibit  
169 altered muscle shear modulus compared to controls [within-subject variable: muscle (BF, ST,  
170 SM), angle (90°, 60°), categorical factor: group (athlete (all sports pooled), control)]. Then,  
171 the effect of elite sport specialization on the shear modulus of each head of the hamstring was  
172 assessed using a three-way ANOVA [within-subject variable: muscle (BF, ST, SM), angle

173 (90°, 60°); categorical factor: group (soccer, track and field, fencing, taekwondo, figure  
174 skating, field hockey, basket-ball, control)]. When the sphericity assumption in repeated  
175 measures ANOVAs was violated (Mauchly's test), a Geisser-Greenhouse correction was  
176 used. Post-hoc analyses were performed using Bonferroni tests. The effect size was calculated  
177 using Cohen's d for between-sport comparisons considering <0.15, 0.15, 0.4, 0.75, 1.1, 1.45,  
178 >1.45 as *negligible*, *small*, *medium*, *large*, *very large*, and *huge* effect, respectively <sup>25</sup>. The  
179 mean difference was calculated for between-sport comparisons and presented with 95%  
180 confidence intervals. For all tests, the significance level was set at  $P < 0.05$ . Data are  
181 presented as mean  $\pm$  SD.

## 182 RESULTS

183 The resting shear modulus values showed a good inter-day reliability for each  
184 hamstring head (ICC: 0.80-0.98, TE: 0.6-3.4 kPa, CV: 8.2-13.0%; Table 2). Considering this  
185 result, data were averaged between days for controls. We found a significant main effect of  
186 sport ( $P < 0.001$ ) on age. Specifically, control participants were significantly older than  
187 basketball players (+ 9.7 years;  $P < 0.001$ ), while no difference were found with other sports  
188 ( $P > 0.063$ ). The comparison between dominant and non-dominant limb in uninjured  
189 participants showed no main effect of laterality ( $P = 0.65$ ; Fig. 2). We found no main effect of  
190 sex ( $14.3 \pm 8.4$  vs.  $13.8 \pm 7.8$  kPa, for females and males, respectively;  $P = 0.46$ ) on shear  
191 modulus values. A significant effect of muscle ( $P < 0.0001$ ), angle ( $P < 0.0001$ ) and a  
192 significant muscle  $\times$  angle interaction was found ( $P < 0.0001$ ). Shear modulus was higher in  
193 BF ( $+41.8 \pm 28.8\%$ ) and SM ( $+38.3 \pm 37.8\%$ ) on average compared to ST ( $P$  values  $< 0.0001$ ),  
194 while no significant difference was observed between BF and SM ( $P = 1.00$ ).

195 The comparison between controls and athletes revealed a significant main effect of  
196 group ( $P = 0.005$ ), muscle ( $P < 0.0001$ ), angle ( $P < 0.0001$ ), muscle  $\times$  group interaction ( $P <$   
197  $0.0001$ ), muscle  $\times$  angle interaction ( $P < 0.0001$ ), group  $\times$  angle ( $P = 0.013$ ) and muscle  $\times$   
198 group  $\times$  angle interaction ( $P < 0.0001$ ) on shear modulus values of hamstring muscles. Post-  
199 hoc analysis showed that SM shear modulus measured at  $60^\circ$  was lower for athletes ( $21.9 \pm 6.5$   
200 kPa) than for control participants ( $32.1 \pm 11.9$  kPa) ( $P < 0.0001$ ). No significant between-group  
201 differences were found for ST and BF.

202 When comparing control and each sport specialization group, we found a significant  
203 main effect of group ( $P \leq 0.0001$ ), muscle ( $P < 0.0001$ ) and muscle  $\times$  group interaction ( $P <$   
204  $0.001$ ) and muscle  $\times$  group  $\times$  angle interaction ( $P < 0.03$ ) on shear modulus values of  
205 hamstring muscles (Fig. 3). Muscle  $\times$  group  $\times$  angle interaction showed that, compared to  
206 control, shear modulus at  $60^\circ$  was lower in SM for figure skating ( $-17.2$  kPa [ $-26.0$ ;  $-8.5$ ];  $P <$

207 0.001;  $d = 1.8$ ), taekwondo (-18.0 kPa [-26.0;-10.1];  $P < 0.001$ ;  $d = 2.1$ ), soccer (-9.0 kPa [-  
208 17.3;-0.8];  $P = 0.011$ ;  $d = 0.9$ ), and fencing (-10.3 kPa [-19.7;-0.9];  $P = 0.024$ ;  $d = 1.0$ ) (Fig.  
209 3). No significant differences were found between controls and basketball, athletics, and field  
210 hockey (all  $P$  values  $> 0.14$ ). Shear modulus of the BF and ST muscle was not significantly  
211 different between controls and elite athletes, regardless of the sport specialization (all  $P$  values  
212 = 1; Fig. 3).

213 **DISCUSSION**

214 To our knowledge, this the first study to report a variable distribution of shear  
215 modulus among hamstring muscle heads between sports in a large cohort of elite athletes.  
216 Two major findings can be highlighted from this investigation: (i) the shear modulus of the  
217 SM is lower in athletes involved in taekwondo, figure skating, soccer and fencing compared  
218 to controls while no significant difference were found for basketball, athletics and field  
219 hockey, (ii) the shear modulus of the BF and ST is not different from controls in elite athletes,  
220 regardless of the sport specialization. Prospective work is needed to determine whether the  
221 selective lower SM shear modulus relates to the mechanical constraints imposed by sport  
222 activities and its putative role in motor performance.

223

224 The shear modulus values obtained for control participants in relaxed condition were  
225 close to those previously obtained from hamstring heads during passive stretching cycle at the  
226 same hip (90°) and knee configuration (90°) [ST = 9.7 vs. 6.8 kPa, SM = 10.4 vs. 10.9 kPa,  
227 BF = 13.2 vs. 11.8 kPa for <sup>20</sup> and the current study, respectively]. In agreement with most of  
228 the studies dealing with the effect of sex on muscle shear modulus <sup>26,27</sup>, no significant  
229 differences in hamstring muscles shear modulus were found between male and female  
230 athletes. This allowed us to compare muscle shear modulus between sports, regardless of the  
231 distribution between males and females. In addition, laterality did not affect muscle shear  
232 modulus (Fig. 2), even when only considering asymmetric sport activities (i.e. field hockey,  
233 taekwondo, fencing; leg effect:  $P = 0.53$ ). In line with the current body of literature using  
234 shear wave elastography <sup>15,28</sup>, we observed a high variability of hamstring shear modulus  
235 between individuals among both healthy controls and elite athletes, especially in extended  
236 knee position (i.e. 60°) with SD comprised between 4.3 kPa (27% of the mean value) and 10.0  
237 kPa (44%) (cf. Fig. 2). The hip and knee joint angles used in the current study placed the

238 participants at a different percentage of their maximal range of motion which may partly  
239 explain the variability in muscle shear modulus observed between individuals. However, both  
240 passive tension developed by muscle-tendon units and the sensation of this tension (i.e.,  
241 discomfort) limit the maximal tolerable range of motion (for review, see Weppeler &  
242 Magnusson <sup>9</sup>). Therefore, a similar relative joint angle (i.e., normalized to the maximal range  
243 of motion) would have not necessarily reduced the inter-individual variability in muscle shear  
244 modulus. This could also reflect the effect of innate properties and/or functionally driven  
245 adaptations elicited by elite sport practice.

246

247         Of note, our findings showed that SM and BF muscles were 38% and 42% stiffer than  
248 ST, respectively. This finding is similar to previous reports, which demonstrated that ST  
249 muscle exhibits the lowest resting shear modulus values among hamstring heads <sup>20,29</sup>.  
250 Hamstring muscles present distinct architecture, SM and BF being pennate muscles while ST  
251 is fusiform or with a small pennation angle depending on the studies <sup>2</sup>. Due to this muscle  
252 architecture, the assessment of shear modulus in hamstring remains limited to some specific  
253 regions <sup>20</sup>. Hence, the regions of interest were chosen to ensure reliable measurements as  
254 reflected by the high to very-high inter-day reliability reported in the results section. One  
255 could note that the alignment between the ultrasound probe and the fascicle's path may  
256 increase the shear modulus values <sup>21</sup>. Importantly, this methodological issue does not explain  
257 the higher shear modulus values obtained for BF and SM compared to ST, as the maximal  
258 shear wave velocity is reached when the probe is along the fibres <sup>30</sup>. Therefore, this influence  
259 is likely marginal between SM and BF which present close pennation angle <sup>31</sup>. Thus, the  
260 lower shear modulus values for ST compared to SM and BF could result from the variance in  
261 biomechanical loads for each hamstring muscle. During running, Schache et al. <sup>32</sup> showed that  
262 BF exhibits the largest peak strain while SM produced the highest peak force and performed



263 the largest amount of work. When repeated, these actions elicited by sport activity may induce  
264 specific mechanical adaptations on each head. This could in turn contribute to the lower  
265 passive muscle shear modulus observed in BF and SM comparatively to ST<sup>33</sup>.

266

267 In line with our hypothesis, the present study reports that the shear modulus of the SM  
268 is lower in athletes than in controls. Specifically, taekwondo practitioners, figure skaters,  
269 fencers and soccer players had a lower shear modulus than controls when considering SM  
270 (Fig. 3). Even though we cannot rule out that muscle shear modulus is related to initial  
271 (innate) properties, we assume that the resting shear modulus may reflect localized  
272 mechanical adaptations resulting from joints movements and repeated solicitations  
273 encountered during elite sport practice. Indeed, these activities demand high flexibility of the  
274 lower limbs to execute complex movements over large joint amplitude<sup>17,34</sup>. For instance,  
275 Preuschl et al.<sup>17</sup> reported that specific movements regularly executed in taekwondo involved  
276 hip flexed angles (65°, 180° = full hip extension) and knee angles close to full extension  
277 (178°, 180° = full extension). Similarly, elite fencers regularly execute lunge with hip flexed  
278 (49°) combined with moderated knee extension angles (116°). Interestingly, during these  
279 fencing and taekwondo movements, the activation of the stretched hamstrings remains low  
280 (10% of the EMG max) towards the ending phase of the motion<sup>18,35,36</sup>. The selective lower  
281 shear modulus of the SM in sports that elicit stretching of the hamstrings over large range of  
282 motion activities (taekwondo, figure skating and fencing) is in accordance with the greater  
283 association between maximal hip flexion angle (straight-leg-raises test) and SM shear  
284 modulus ( $r = -0.75$ ) compared to ST ( $r = -0.67$ ) and BF ( $r = -0.61$ )<sup>37</sup>. The inclusion of  
285 substantial stretching routines in the training volume may also explain this result as two recent  
286 studies showing a larger decrease in shear modulus of the SM compared to ST and BF after an  
287 acute<sup>36</sup> and chronic<sup>10</sup> stretching program. It is likely that stretching usually performed to

288 increase flexibility in taekwondo and figure skating contributes to the selective lower stiffness  
289 in the SM (large effect for both sports;  $d > 1.8$ ). Although the volume of the stretching  
290 routines has not been quantified in the current study, it is also reasonable to assume that the  
291 lower shear modulus in SM (large effect;  $d = 0.9$ ) exhibited by soccer players compared to  
292 controls relates to their high amount of stretch training, as it represents one of the main  
293 strategy used to prevent muscle strain injury<sup>37</sup>. Contrarily to our hypothesis, we did not find  
294 any difference in hamstring shear modulus (SM, ST, and BF) in basketball, athletics, and field  
295 hockey compared to controls while these activities elicit movement over moderate amplitudes  
296 (e.g. drag flick in field hockey) and stretch shortening cycles. This result is strengthened by  
297 the *negligible to moderate* differences observed with controls, depending on the muscle and  
298 the sport activity. Note that we found that basketball players were younger than control  
299 participants. However, it is unlikely that this difference in age between basketball players and  
300 controls (9.7 years) explain the absence of difference in shear modulus, as previous works  
301 reported a negligible impact of age on muscle shear modulus below 60 years old<sup>27</sup>. Both the  
302 duration and intensity of the stretching play an important role on muscle mechanical and  
303 architectural adaptations (e.g., Freitas et al.<sup>38</sup>). Therefore, we can speculate that the absence  
304 of differences in shear modulus in these activities may be related to the relative small time  
305 spent at moderate amplitudes compared to other actions performed at short muscle length  
306 (e.g., jogging, walking, strength and conditioning;<sup>39,40</sup>). More importantly, these sports elicit  
307 high intensity eccentric contractions of the hamstring muscles<sup>41,42</sup> which may lead to  
308 potential adaptations in muscle shear modulus. A recent study has shown a prolonged increase  
309 in muscle shear modulus (i.e. 21 days) after a protocol including a high amount of high  
310 intensity negative work (i.e., maximal eccentric actions)<sup>14</sup>. In contrast, taekwondo, figure  
311 skating and fencing result in lower hamstring activation during stretching-oriented

312 movements. Further investigations are required to determine how muscle state (high or low  
313 eccentric force) modulates long-term muscle mechanical adaptations.

314

## 315 **PERSPECTIVES**

316 Askling et al. <sup>3</sup> reported the existence of two specific type of acute hamstring injury.  
317 The first occurring in extreme positions during stretching exercise affects the SM, while the  
318 second, occurring during maximal speed running affects the BF. Despite the preventive  
319 strategies adopted by elite sports stakeholders involved in sprinting activities (e.g., eccentric  
320 strengthening of the hamstring), their shear modulus values were similar to that of moderately  
321 active individuals. The absence of difference in BF is surprising as this muscle exhibits the  
322 greater muscle-tendon unit strain among the hamstrings during sprinting <sup>32</sup>. Taken together  
323 with the high injury rate of the BF among hamstring muscle <sup>11</sup>, findings suggest further  
324 research to determine whether selective stretching exercises (e.g., foot external rotation during  
325 prone leg curl; Beuchat & Maffiuletti <sup>43</sup>) is an effective strategy to reduce the occurrence of  
326 BF muscle injury <sup>44</sup>. One should note that the way muscle shear modulus interacts with force-  
327 generating potential (activation, force-length relationship) is still unclear (for review see Holt  
328 & Williams <sup>45</sup>), especially during dynamic tasks. Therefore, an increase in muscle shear  
329 modulus may not be relevant when muscles have to produce a substantial amount of negative  
330 work at long muscle length. The recent advances in musculo-skeletal models implementing  
331 individual muscle geometry and mechanical properties (e.g., Martin & Nichols <sup>46</sup>) may  
332 provide new insights of the optimal biomechanical muscle properties for human performance  
333 while minimizing injury risk

334

## 335 **CONCLUSION**

336 Hamstring shear modulus varied between individuals, muscles and sports, reflective of  
337 mechanical adaptations elicited by high-level sport practice. We provide evidence that the  
338 shear modulus of the SM is increased in athletes involved in elite sport practice performed  
339 over large range of motion (taekwondo, figure skating and fencing). Despite the execution of  
340 movement over moderate to large range of motion and/or preventive strategies adopted by  
341 elite sports stakeholders, they exhibit similar BF and ST shear modulus than moderately  
342 active individuals. Prospective work is needed to determine whether the selective lower SM  
343 shear modulus relates to the mechanical constraints of the sport activities and its putative role  
344 in motor performance

345

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359

360 **CONFLICT OF INTEREST**

361 No conflicts of interest, financial or otherwise, are declared by the authors.

362

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- 480



481 **FIGURES**

482 **Figure 1.** Typical example of shear modulus measurements in *semitendinosus* (A),  
483 *semimembranosus* (B) and *biceps femoris* (C) muscle. Participants were lying supine with the  
484 hip angle fixed at 90° (0° = hip fully extended), and knee at 90° and 60° using an isokinetic  
485 dynamometer (0° = full knee extension). Shear modulus was measured over the region of  
486 interest outlined by white dashed lines (the images display shear modulus maps obtained at  
487 60° of knee angle). The ultrasound probe was held manually by the investigator over the  
488 posterior face of the thigh.

489

490 **Figure 2.** Individual (dots) and mean (black lines) shear modulus values measured at 90° (A,  
491 left panel) and 60° (B, right panel; 0° = full leg extension) in *semitendinosus* (ST, black),  
492 *semimembranosus* (SM, dark grey) and *biceps femoris* long head (BF, light grey) for  
493 dominant and non-dominant limb of uninjured participants. n = 79 (67 athletes + 12 controls).  
494 \*, significant difference with ST muscle ( $P < 0.05$ ).

495

496 **Figure 3.** Individual (colored dots) and mean (vertical solid line) shear modulus values in  
497 *semitendinosus* (A, top panel), *semimembranosus* (B, middle panel) and *biceps femoris* long  
498 head (C, bottom panel) of elite athletes in each sport and control participants, grey dots and  
499 dashed line, respectively. Data correspond to values of the measurements performed at 60° of  
500 knee angle and are pooled between limbs for non-injured participants ( $n = 79$ ; no effect of  
501 laterality), for the sake of clarity.