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1 **Could relative movement between the adductor muscles and the skin invalidate surface**

2 **EMG measurement?**

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16 **Running title:** Ultrasound of adductor muscles

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18

19 **Abstract**

20 The superficial hip adductor muscles are situated in close proximity to each other. Therefore,
21 relative movement between the overlying skin and the muscle belly could lead to a shift in
22 the position of surface EMG electrodes and contamination of EMG signals with activity from
23 neighbouring muscles. The aim of this study was to explore whether hip movements or
24 isometric contraction could lead to relative movement between the overlying skin and three
25 adductor muscles: adductor magnus, adductor longus and gracilis. We also sought to
26 investigate isometric torque-EMG relationships for the three adductor muscles. Ultrasound
27 measurement showed that EMG electrodes maintained a position which was at least 5 mm
28 within the muscle boundary across a range of hip flexion-extension angles and across
29 different contraction levels. We also observed a linear relationship between torque and EMG
30 amplitude. This is the first study to use ultrasound to track the relative motion between skin
31 and muscle and provides new insight into electrode positioning. The findings provide
32 confidence that ultrasound-based positioning of EMG electrodes can be used to derive
33 meaningful information on output from the adductor muscles and constitute a step towards
34 recognised guidelines for surface EMG measurement of the adductors.

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37 **Key words:** ultrasound, running, walking, medial thigh

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39 **Word count:** 3030

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Introduction

41 The adductor muscles of the hip make up 13.4% of the total muscle mass of the lower
42 extremity¹ and have a large capacity for generating joint moments, both in the frontal and the
43 sagittal plane². However, despite their relative size, there have been only a small number of
44 studies which have investigated their role during walking³⁻⁵, running⁶⁻⁹ and other functional
45 tasks^{10,11}. Importantly, although there are widely accepted guidelines, e.g. SENIAM¹², for
46 many of the superficial lower limb muscles, there is minimal guidance for surface EMG
47 measurement of the adductor muscles. This lack of guidance may be a barrier to future research
48 aiming to understanding the role of the adductors during different functional tasks.

49 The individual hip adductor muscles are situated in close proximity on the medial aspect
50 of the thigh¹³. Therefore, small movements between the muscle and skin could lead to a relative
51 shift in the position of an adductor EMG electrode with respect to the underlying muscle and
52 result in contamination of the EMG signal with electrical activity from an adjacent muscle.
53 Such movement could arise from two separate mechanisms. Firstly, when a muscle contracts,
54 the muscle is displaced¹⁴ and so moves away from its uncontracted position directly under the
55 EMG electrode. The second mechanism relates to the fact that when the hip moves through a
56 large range of flexion-extension, there could be some associated movement of the muscle
57 relative to the skin. Given these two mechanisms, there is a need to quantify the magnitude of
58 the movement between the overlying skin and the adductor muscles in order to inform the
59 development of protocols for surface EMG placement.

60 Ultrasonography has been shown to be an effective tool for non-invasively quantifying
61 muscle architecture. For example, ultrasound has been used to measure muscle thickness¹⁵ and
62 elongation of muscle and soft tissue structures during maximal^{16,17} and submaximal
63 contraction¹⁸. Two previous studies have used ultrasound to identify the boundaries of the
64 individual adductor muscles and guide placement of surface EMG electrodes^{13,19}. This

65 approach provides confidence that the EMG electrodes are positioned directly over the
66 adductor muscle in the position in which the electrodes are applied. However, it is not clear
67 whether there could be a shift in the relative position of the EMG electrode during muscle
68 contraction and/or movement of the lower limb. Therefore, further investigation is required to
69 understand relative movement between the skin and underlying muscle in order to inform
70 adductor muscle EMG measurement.

71 As well as understanding relative skin-muscle movement, confidence in EMG
72 measurements can be developed by investigating the relationship between joint torque and
73 EMG amplitude. Previous research has shown relationships between EMG amplitude and
74 isometric torque in different lower limb muscles, such as rectus femoris, vastus medialis, vastus
75 lateralis^{20,21}. A linear relationship between muscle output and torque, under isometric
76 conditions does not imply a simple relationship between torque and EMG amplitude during
77 dynamic tasks. Furthermore, interpretation of an observed relationship is complicated by the
78 fact that the load sharing among muscles can change, both for a constant joint torque and also
79 at different torque levels. Nevertheless, a strong monotonic relationship between an individual
80 muscle EMG and torque does provide a degree of confidence that dynamic EMG measurement
81 provide insight into differences in the level of muscle force production both within a task and
82 across different individuals. To date, there is no study exploring the relationship between hip
83 torque and EMG amplitude for the adductor muscles during isometric contraction.

84 At present, there is no widely accepted protocol for surface EMG measurement of the
85 adductor muscles. Therefore, building on a previously proposed technique which used
86 ultrasound to map muscle boundaries for EMG placement, we sought to quantify the movement
87 of the adductor muscles relative to overlying skin during hip flexion-extension movements and
88 during isometric contraction. We also sought to explore the torque-EMG relationship of the
89 adductor muscles during isometric contractions. It was felt that the insight gained from this

90 study would inform the development of subsequent guidelines for EMG measurement of the
91 adductor muscles.

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Methods

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A cohort of 10 male subjects, with no history of lower limb injury or surgery, was recruited for this study. The mean (SD) age of the subjects was 29 (8) years, height 1.74 (0.05) m, mass 70.2 (7.3) kg, and body mass index 23.2 (1.4) kg·m⁻². The study was approved by the University of Salford Research and Ethics Committee and all participants gave written informed consent prior to participation.

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We carried out separate measurements for three adductor muscles: adductor longus, gracilis, and adductor magnus. The other deep adductor muscles were excluded, as they are not amenable to surface EMG measurement. For each subject, ultrasound imaging (A MyLab70, Esaote, USA) with a probe (LA923) of 9.23 cm long, was used to map out the borders of the three adductor muscles (Figure 1a), following the procedure described in Watanabe *et al.*¹³. The position of the centre of the EMG electrode was then marked on the skin in the middle of the muscle belly at a predetermined point along the length of the muscle. This point was referenced to thigh length (greater trochanter to lateral epicondyle) and was 60% of thigh length for the gracilis and adductor magnus muscles and 80% of thigh length for the adductor longus muscle (Figure 1b). These positions were determined via a pilot study on five people and chosen as a compromise between being positioned at widest part of the muscle but not being too close to the groin area, which sometimes led to discomfort during walking. As part of this pilot study, we compared EMG amplitudes from signals collected at 60, 70 and 80% of thigh length and selected the position which was associated with the largest signal. Placing EMG electrodes over the innervation zone (IZ) leads to lower amplitudes²², therefore this process provided a degree of confidence that the placements were not over the IZ.

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FIGURE 1 HERE

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119 To address the first two aims, we used ultrasound measurement to quantify the
120 movement of the muscle relative to the mark on the skin representing electrode position
121 (described above). To collect each ultrasound image, the mark on the skin was aligned with a
122 specific point, marked on centre of the ultrasound probe which ensured a consistent positioning
123 of the ultrasound probe for each image. The ultrasound images were collected at different hip
124 flexion/extension angles (aim 1) and isometric contraction levels (aim 2). We chose four
125 different hip flexion-extension angles (0° , 20° , 40° of hip flexion, and 20° hip extension) which
126 correspond to a typical range of motion during running^{23,24}. Although abduction-adduction
127 movements of the hip are also likely be associated with muscle movement, these motions are
128 considerably smaller than sagittal motions during activities, such as running^{23,24} and walking²⁵.
129 Therefore, for this study, we chose to focus on hip flexion/extension. These angles were
130 measured between the thigh and the vertical using a transparent plastic goniometer with a 360°
131 head and 30 cm arms. For each angle, participants were instructed to maintain the specified hip
132 position, without external support, in each of the different hip angles while each of the adductor
133 muscles were imaged separately. The testing order of hip angles was randomised and a rest
134 period of three minutes was given between each hip test.

135 To quantify relative movement between the skin and the muscle during isometric
136 contraction, we used a ramped isometric protocol with contractions at 20, 40, 60, and 80% of
137 maximum hip adduction torque. These contraction were monitored using the Biodex System 3
138 isokinetic dynamometer (Biodex Medical Systems, Shirley, NY) and followed a protocol
139 described by Brent *et al.*²⁶, in which biofeedback is used to provide subjects with a visual target

140 at each contraction level. For each isometric test, the axis of rotation of the dynamometer was
141 aligned with the centre of hip rotation and the participant was instructed to push against the
142 dynamometer arm in the direction of adduction. For this test, the participant stood on the non-
143 tested leg while the tested leg hung freely in a vertical position. The test began with a
144 measurement of the maximum torque, after which the participant was provided with feedback
145 to enable them to contract at 20, 40, 60, and 80% of their maximum in a randomised order.
146 Similar to the previous test, the three adductor muscles were imaged separately at each
147 contraction level. The order of the isometric contraction tests, described above, was randomised
148 and a minimum rest of 30 seconds given between the images collected for each of the adductor
149 muscles.

150 To quantify the relationship between adductor EMG activity and torque produced by
151 the hip adductor muscles, the experiment described above was repeated. However, instead of
152 recording ultrasound images at each contraction level, EMG data was collected from gelled
153 electrodes, of 10 mm diameter and 20 mm separation, placed at the marked location (described
154 above) for each of the three adductor muscles. The EMG data was collected using a Telemetry
155 system (Noraxon USA) at 1500 Hz. The same protocol as the second experiment (described
156 above) was followed and the participant instructed to generate four different contraction levels
157 (20, 40, 60, and 80% of maximum) in a randomised order. For each condition, the participant
158 was instructed to maintain the contraction for a minimum of 5 seconds. A rest of at least 30
159 seconds was used between each test condition.

160 To quantify the movement of the skin relative to the underlying muscle (aim 1), the
161 ultrasound images for each subject (corresponding to each hip flexion/extension position) were
162 vertically aligned (Figure 2). Each ultrasound image captured a transverse plane cross section
163 of an adductor muscle, with the left side of each image corresponding to the anterior aspect and
164 the right side corresponding to the posterior aspect of the muscle. Vertical lines were then drawn

165 over each set of images to illustrate the projection of the edges of the EMG electrodes (Figure
166 3) onto the transverse plane cross section. As each image was collected with the ultrasound
167 probe located at the same position on the skin (see above), the aligned images provided a clear
168 measure of the movement of the muscle relative to the overlying skin (Figure 2). The distance
169 from the electrode boundary (vertical line) to the edge of the muscle (identified visually) was
170 then measured using the Image J software (available at:
171 <http://rsb.info.nih.gov/ij/docs/index.html>) for both the right and left sides. These distances
172 correspond to a measure, in the anterior-posterior direction, from the edge of the electrode to
173 the anterior/posterior border of the adductor muscle.

174

175 FIGURE 2 HERE

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177 Through the process described above, it was possible to obtain the distance (on both
178 the left and right side) between the edge of the electrode (vertical line) and the edge of the
179 muscle (shown as white dot) for each subject in each hip flexion/extension condition. For each
180 set of images, the edge of the muscle was identified visually as the point, furthest from the
181 vertical line, for which the muscle boundary was still clearly visible (Figure 2). The same
182 procedure was repeated for aim 2 and the corresponding ultrasound data collected at the five
183 different levels of isometric contraction. The primary aim of this investigation was to determine
184 whether the muscle remained within the EMG detection volume at different hip positions and
185 levels of contraction. Therefore, we calculated the minimum distance between the electrode
186 and muscle boundary across all 10 subjects. In addition, other descriptive data were derived to
187 characterise how the muscle moved relative the overlying skin.

188

189 FIGURE 3 HERE

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191 To address the third aim, EMG data was high pass filtered at 10 Hz and RMS EMG
192 activity calculated across a 1 second window for each isometric contraction. For each
193 participant, the RMS data for each contraction level was normalised by the RMS MVIC data.
194 All EMG processing was performed using Matlab (Mathworks, USA). A linear regression
195 approach, with standard errors adjusted for clustering²⁷, was then used to investigate the
196 relationship between EMG amplitude and isometric contraction level. This statistical technique
197 was selected as it can deal with repeated measures from each participant and was performed
198 separately for each of the three adductor muscles.

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Results

201 As hip flexion/extension angle was varied (aim 1), the edge of electrode was observed
202 to remain within the boundary of the muscle for every subject. Specifically, the minimum
203 (across all subjects) distance between the muscle and electrode boundary was at least 6 mm for
204 each of the three adductor muscles (Table 1). However, the mean distance (across the 10
205 subjects) was between 14-19 mm (Table 1). Importantly, there were minimal side-to-side
206 differences in minimum, maximum or mean distance from the electrode to the muscle boundary
207 (Table 1).

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TABLE 1 HERE

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211 The isometric contraction data also showed the electrode to remain inside the muscle
212 boundary. Although the lowest distance was 3 mm for adductor magnus at high contraction
213 levels (Table 2), at lower contraction levels (20-60%), the minimum distance was 5 mm across

214 all muscles. Furthermore, the mean distance (across the subjects) was between 12-20 mm,
215 similar to the values reported in Table 1 for the different hip angles.

216

217 TABLE 2 HERE

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219 The regression models showed that there was a linear relationship between torque and
220 muscle activity ($p < 0.001$) for each of the three adductors, with r-squared values from 0.45-
221 0.61. These models showed that isometric torque significantly affected muscle activity, where
222 increasing isometric torque by 1% increased adductor activity by 3.3-4.0% (Table 3). Visual
223 inspection of the relationships between muscle activity and torque showed clear monotonic
224 relationships, for each separate participant across all three muscles.

225

226 TABLE 3 HERE

227

228 Discussion

229 This first two aims of this study were to quantify the magnitude of movement between
230 the adductor muscle and overlying skin that results from either hip flexion/extension or muscle
231 contraction. The data showed a minimum distance, across the ten subjects, of at least 5 mm
232 between the electrode and muscle boundary at different hip positions and low to moderate
233 contraction levels. In addition to the data on relative position, we demonstrated a linear
234 relationship between torque and muscle activity under isometric conditions. Taken together
235 these data provide confidence in the ability to derive useful information from EMG
236 measurements of the adductor muscles when ultrasound is used to guide muscle placement.

237 Validity of EMG measurement, during walking and running, is influenced by the
238 relative movement between the muscle and skin. Our data provide novel insight into whether

239 such relative motion could lead to movement of EMG electrodes away from the target muscle
240 and therefore contamination of the EMG signal by neighbouring muscles. The data showed
241 that, in almost all cases, there was a distance between the edge of the electrode and the muscle
242 boundary of at least 5 mm, which was equivalent to the radius of the EMG electrode. In many
243 cases, it is likely that the true boundary of the muscle was further from the electrode boundary
244 than our data suggest. This is because boundaries were identified conservatively as the furthest
245 point on the muscle border which was clearly visible in the ultrasound image, see the left side
246 of Figure 2d for an example. Given the nature of our measurements, distances are likely to be
247 underestimated and therefore likely to represent a lower bound. We propose that future studies
248 which use surface EMG to study adductor muscles should follow our protocol, using ultrasound
249 to position the EMG electrodes centrally over the individual adductor muscles at a distance of
250 60% of thigh length for the gracilis/adductor magnus muscles and 80% for the adductor longus
251 muscle.

252 It is important to acknowledge that relative movement between the skin and muscle
253 could also occur due to soft tissue vibration, which may result from the impacts associated with
254 foot contact. Interestingly, previous research has shown significant movement between skin
255 and underlying bone during walking^{28,29} and running³⁰. However, it is possible that the skin
256 and muscle may move together in response to impact loading. If this is the case, then there may
257 not be appreciable movement between the skin and muscle in which case EMG measurement
258 would not be affected. However, full investigation of this phenomenon would require dynamic
259 ultrasound, which was deemed beyond the scope of this investigation.

260 No previous studies have used ultrasound to investigate relative movements between
261 the skin and the muscle in the context of EMG measurements. However, it is interesting to
262 compare our data with research that has used ultrasound measurement to determine changes in
263 muscle morphology that occur with muscle contraction. For example, during isometric

264 contraction, Delaney *et al.*³¹ examined the rectus femoris and found a decrease in muscle width
265 of 8 mm to be associated with an increase in contraction to 30% of MVIC. Similarly, at
266 different knee angles, Delaney *et al.*³¹ also observed a change in the width of rectus femoris of
267 3 mm. These data on rectus femoris are similar to those observed in the current study for
268 adductor longus with different hip flexion extension angles (Table 1) and gracilis during
269 isometric contraction (Table 2).

270 Although there has been no previous research investigating torque-EMG relationships
271 for the adductor muscles, it is interesting to compare our findings with studies investigating
272 such relationships in other muscles. Our data match that of Perry and Bekey³²; Lawrence and
273 De Luca³³, Woods and Bigland-Ritchie³⁴ and Alkner *et al.*³⁵ who reported a close relationship
274 between torque and EMG activity for the biceps brachii, deltoid, soleus and quadriceps femoris
275 muscles respectively under isometric conditions. In addition, our data is consistent with those
276 of Bilodeau *et al.*³⁶ who also reported a positive correlation between the RMS EMG for rectus
277 femoris (RF), vastus medialis (VM), and vastus lateralis (VL) muscles and the torque in both
278 men and women. This consistency with research into other muscles provides further confidence
279 in our ability to measure the degree of activation of the superficial adductor muscles using the
280 proposed protocol.

281 Our data show a linear relationship between torque and EMG under isometric
282 conditions. However, we acknowledge we were not able to quantify this relationship under
283 dynamic conditions. With a dynamic contraction, there will be a change in the specific motor
284 units that lie within the EMG detection volume and this, along with the muscle
285 lengthening/shortening velocity will affect the magnitude of the EMG signal and therefore the
286 torque-EMG relationship. Although the effect of these changes has not been precisely
287 quantified, it is likely that there will still be some degree of relationship between torque and
288 EMG as the primary determinant of muscle force is the number of active motor units and their

289 firing rates³⁷. Therefore, we suggest that our proposed protocol should be appropriate for
290 characterising the coordination patterns of the superficial adductor muscles during dynamic
291 activities.

292 There some limitations to this study which should be acknowledged. Firstly, the
293 investigation was restricted to a cohort of lean male subjects in order to minimise the effect of
294 subcutaneous fat, which will attenuate the EMG signal. Although we would not expect this
295 subcutaneous layer to change the fundamental nature of the torque-EMG relationships,
296 further research is required to understand if increased subcutaneous fat would lead to more
297 relative displacement of the skin and underlying muscle with hip flexion/extension. Another
298 limitation is that we did not attempt to characterise the relative movement between the skin
299 and the thigh, which might be associated with impact accelerations. However, we suggest
300 that, although such impacts are likely to lead to muscle motions, they may not lead to
301 significant movement of the skin relative to the underlying muscles. Nevertheless, further
302 research using dynamic ultrasound would be required to confirm this idea.

303 Another limitation that warrants consideration is that the electrode locations were not
304 selected from a knowledge of the position of the innervation zones, as such data are not
305 readily available for the adductors²². However, we did identify a position which, in a pilot
306 study, was associated with maximal EMG amplitudes. Nevertheless, further work is required,
307 using array EMG techniques²² to fully map the position of the innervation zones for the
308 adductor muscles and inform EMG placement. Finally, it is important to acknowledge that
309 only a small portion of adductor longus and adductor magnus are amenable to surface EMG
310 measurement. Therefore, the validity of this work, particularly the investigation of torque-
311 EMG relationships, is dependent on the degree to which the part of the muscle, from which
312 EMG was measured, is representative of force generation throughout the entire muscle.

313 This is the first study to use ultrasound to track relative motion between the muscle
314 and overlying skin and provides new insight into electrode positioning. We chose to focus on
315 the superficial adductors as these muscles are situated in close proximity and there are no
316 obvious bony landmarks to guide EMG placement. However, our approach has the potential
317 to be applied to other muscles which are amenable to surface EMG measurement. Recent
318 developments allow for the acquisition of concurrent EMG and ultrasound data from
319 superficial muscles³⁸ and could facilitate this approach. We suggest that data on innervation
320 zone position could be combined with data on relative skin-muscle motion to develop
321 guidelines which could improve the validity of surface EMG measurement. If performed on a
322 large scale, such work could be used to publish an atlas for different muscles, similar to the
323 work of Barbero *et al.*²². This would be invaluable for the training of both physiotherapists
324 and movement scientists.

325 In conclusion, our data show that when EMG placements over the adductor muscles are
326 guided by ultrasound imaging, the electrodes will remain within the boundaries of the muscle
327 during different hip flexion/extension and different levels of muscle contraction. In addition, a
328 linear relationship was observed between torque and EMG amplitude under isometric
329 conditions. Taken together these data provided confidence that proposed protocol for
330 positioning surface EMG electrodes can be used to derive meaningful information on muscle
331 output. We therefore suggest that our proposed protocol be used for future measurement of the
332 adductor muscles during both static and dynamic tasks.

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444 **Tables**

445

446 **Table 1.** Distances between the right and left edge of the electrode and the muscle boundary
 447 at the different hip joint angles. The minimum/maximum distances (across all participants)
 448 are shown along with the mean (SD) distance and the mean (SD) muscle width. All values
 449 are presented in millimetres. AL: Adductor longus; AM: Adductor magnus; Gr: Gracilis.

	Hip angle	Min distance		Max distance		Mean distance		Mean muscle width
		Right	Left	Right	Left	Right	Left	
AL	0°	8	9	22	21	16 (5)	15 (5)	41 (11)
	20° flexion	10	11	31	23	18 (7)	16 (4)	44 (10)
	40° flexion	9	7	28	29	18 (8)	18 (6)	46 (13)
	20° extension	6	10	23	22	16 (6)	14 (4)	40 (9)
AM	0°	6	7	26	36	16 (7)	19 (9)	46 (14)
	20° flexion	6	6	36	36	18 (11)	18 (11)	46 (16)
	40° flexion	6	6	35	36	19 (10)	18 (9)	47 (15)
	20° extension	7	7	34	32	19 (11)	17 (9)	45 (13)
Gr	0°	6	7	24	25	18 (6)	18 (7)	46 (13)
	20° flexion	6	6	26	36	16 (7)	21 (9)	47 (15)
	40° flexion	6	6	34	30	17 (9)	19 (8)	45 (15)
	20° extension	6	6	33	28	18 (9)	19 (8)	47 (14)

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453

454 **Table 2.** Distances between the right and left edge of the electrode and the muscle boundary
 455 at the different isometric torque levels. The minimum/maximum distances (across all
 456 participants) are shown along with the mean (SD) distance and the mean (SD) muscle width.
 457 All values are presented in millimetres. AL: Adductor longus; AM: Adductor magnus; Gr:
 458 Gracilis.

	% MVIC	Min distance		Max distance		Mean distance		Mean muscle width
		Right	Left	Right	Left	Right	Left	
AL	20%	6	6	22	24	12 (5)	15 (6)	37 (9)
	40%	7	5	25	20	14 (6)	12 (4)	36 (9)
	60%	10	6	19	26	14 (4)	13 (5)	37 (8)
	80%	9	5	17	21	12 (3)	14 (5)	36 (6)
	100%	9	6	18	25	13 (3)	14 (6)	37 (7)
AM	20%	6	7	27	28	18 (7)	17 (7)	45 (13)
	40%	5	5	29	28	17 (9)	15 (8)	43 (13)
	60%	6	5	28	29	16 (9)	16 (9)	43 (15)
	80%	5	3	29	33	16 (8)	17 (11)	43 (15)
	100%	6	3	29	30	17 (9)	16 (8)	43 (15)
Gr	20%	8	9	27	28	18 (6)	20 (7)	47 (12)
	40%	6	8	29	28	19 (7)	18 (7)	48 (13)
	60%	9	6	31	25	19 (7)	17 (6)	46 (12)
	80%	6	6	34	28	20 (9)	18 (8)	48 (14)
	100%	8	4	27	25	15 (7)	17 (7)	42 (12)

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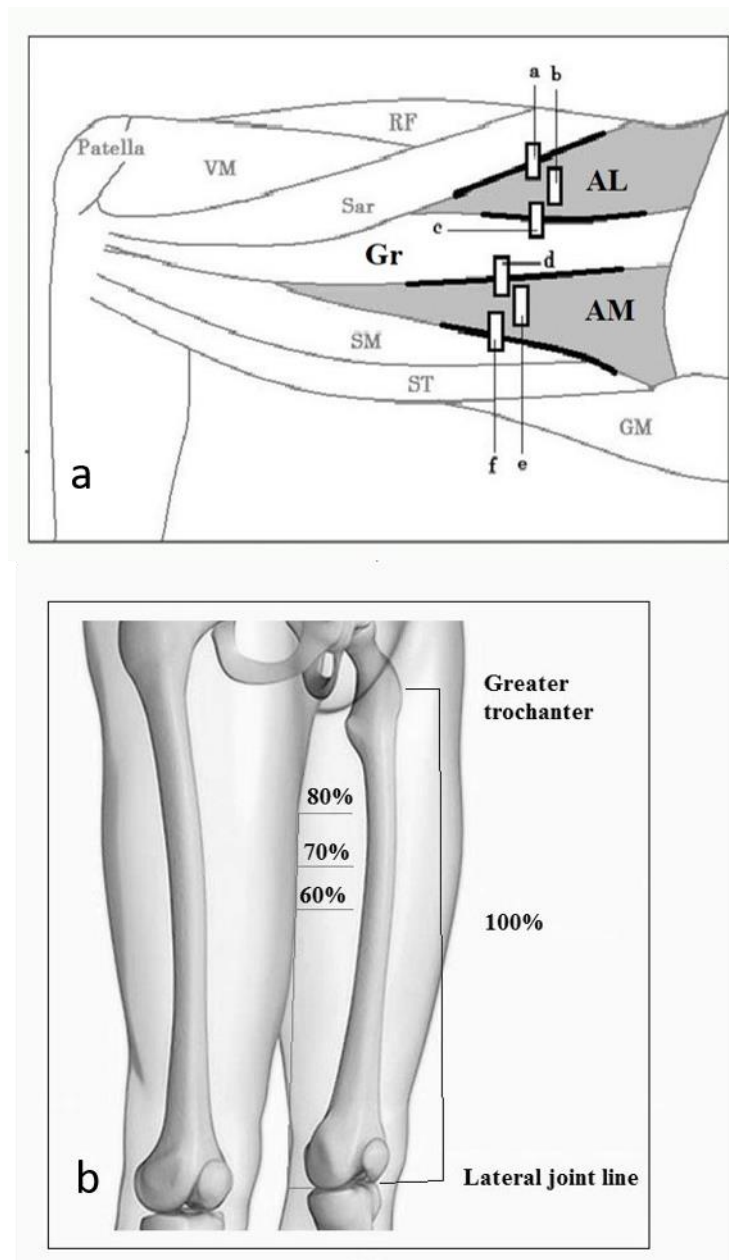
460

461 **Table 3.** Fit of the linear mixed model, r-squared and percentage increase in muscle activity
462 for every 1% increase in torque for adductor longus, adductor magnus and gracilis muscles.

463

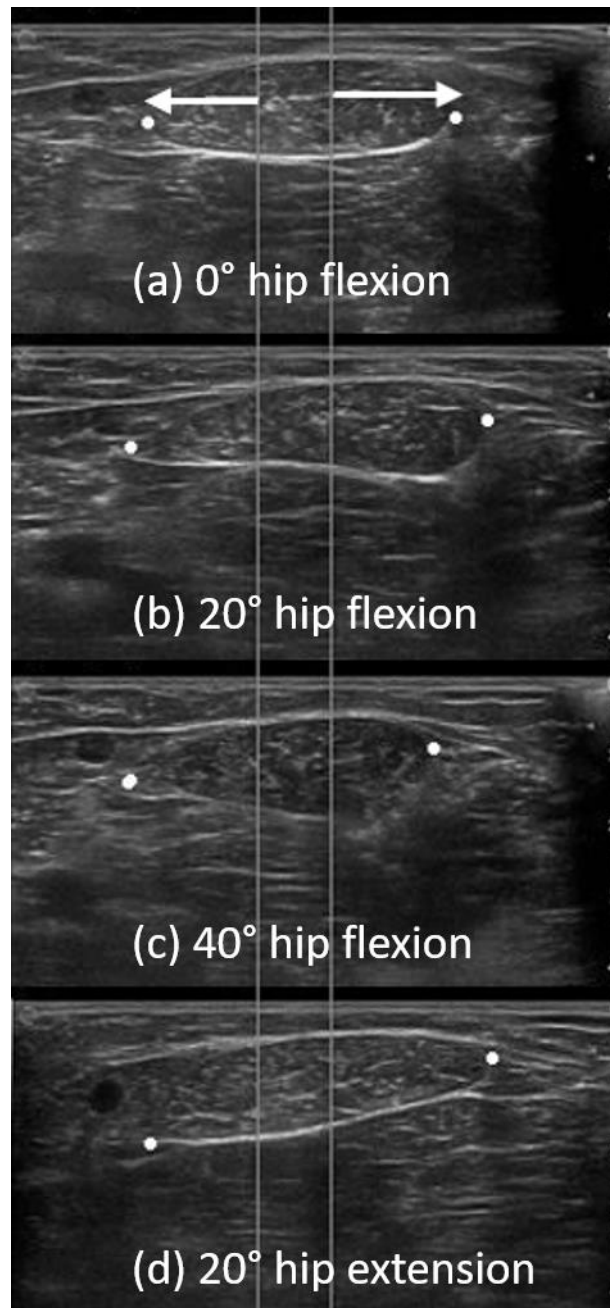
Muscle	Percentage increase in muscle activity for 1% increase in torque (95% Confidence interval)	P-value for fit of the linear model	R-squared
Adductor longus	4.0 (3.0-5.1)%	<0.001	0.54
Adductor magnus	3.3 (2.8-3.8)%	<0.001	0.45
Gracilis	3.8 (3.2-4.4)%	<0.001	0.61

464



466

467 **Figure 1:** (a) Example ultrasound probe locations used to map out the boundaries of the three
 468 adductor muscles. AL: adductor longus; AM: adductor longus; Gr: gracilis; Sar: Sartorius;
 469 SM: semimembranosus; ST: semitendinosus. Note that a-f denote the positions of the
 470 ultrasound probe used to locate the muscle boundaries (adopted and amended from¹³). (b): the
 471 protocol for determining the electrode location along the length of the muscle, measured from
 472 the greater trochanter to the lateral joint line.



473

474 **Figure 2:** Example ultrasound images for gracilis at the four different hip joint angles (a-d).

475 The vertical lines represent the projection of the edge of the surface EMG electrodes and the

476 white dots show the (conservatively) identified boundary of the muscle. The arrows in image

477 a show the distances measured from the muscle boundaries to the edge of the EMG electrode

478 on the right and left sides.

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484 **Figure 3:** EMG electrodes which comprise two 1 cm diameter metal contacts, with a centre-
485 to-centre separation of 2 cm. Vertical lines show electrode boundaries depicted on Figure 2.

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