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

2   **EMG measurement?**

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4   Walaa M. Elsais, PhD[1], Stephen J. Preece, PhD[1], Richard K. Jones, PhD[1], Lee Herrington,

5   PhD[1]

6   [1]Centre for Health Sciences Research, University of Salford, Salford, Manchester, UK

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9   **Correspondence address:**

10   Stephen J. Preece,

11   Centre for Health Sciences Research

12   University of Salford

13   Salford, Manchester, UK.

14   Email: s.preece@salford.ac.uk

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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.

35

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

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39 **Word count**: 3030

Introduction

The adductor muscles of the hip make up 13.4% of the total muscle mass of the lower extremity[1] and have a large capacity for generating joint moments, both in the frontal and the sagittal plane[2]. However, despite their relative size, there have been only a small number of studies which have investigated their role during walking[3-5], running[6-9] and other functional tasks[10,11]. Importantly, although there are widely accepted guidelines, e.g. SENIAM[12], for many of the superficial lower limb muscles, there is minimal guidance for surface EMG measurement of the adductor muscles. This lack of guidance may be a barrier to future research aiming to understanding the role of the adductors during different functional tasks.

The individual hip adductor muscles are situated in close proximity on the medial aspect of the thigh[13]. Therefore, small movements between the muscle and skin could lead to a relative shift in the position of an adductor EMG electrode with respect to the underlying muscle and result in contamination of the EMG signal with electrical activity from an adjacent muscle. Such movement could arise from two separate mechanisms. Firstly, when a muscle contracts, the muscle is displaced[14] and so moves away from its uncontracted position directly under the EMG electrode. The second mechanism relates to the fact that when the hip moves through a large range of flexion-extension, there could be some associated movement of the muscle relative to the skin. Given these two mechanisms, there is a need to quantify the magnitude of the movement between the overlying skin and the adductor muscles in order to inform the development of protocols for surface EMG placement.

Ultrasonography has been shown to be an effective tool for non-invasively quantifying muscle architecture. For example, ultrasound has been used to measure muscle thickness[15] and elongation of muscle and soft tissue structures during maximal[16,17] and submaximal contraction[18]. Two previous studies have used ultrasound to identify the boundaries of the 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.

92

93 **Methods**

94   A cohort of 10 male subjects, with no history of lower limb injury or surgery, was

95 recruited for this study. The mean (SD) age of the subjects was 29 (8) years, height 1.74 (0.05)

96 m, mass 70.2 (7.3) kg, and body mass index 23.2 (1.4) $kg \cdot m^{-2}$. The study was approved by the

97 University of Salford Research and Ethics Committee and all participants gave written

98 informed consent prior to participation.

99   We carried out separate measurements for three adductor muscles: adductor longus,

100 gracilis, and adductor magnus. The other deep adductor muscles were excluded, as they are not

101 amenable to surface EMG measurement. For each subject, ultrasound imaging (A MyLab70,

102 Esaote, USA) with a probe (LA923) of 9.23 cm long, was used to map out the borders of the

103 three adductor muscles (Figure 1a), following the procedure described in Watanabe *et al.*[13].

104 The position of the centre of the EMG electrode was then marked on the skin in the middle of

105 the muscle belly at a predetermined point along the length of the muscle. This point was

106 referenced to thigh length (greater trochanter to lateral epicondyle) and was 60% of thigh length

107 for the gracilis and adductor magnus muscles and 80% of thigh length for the adductor longus

108 muscle (Figure 1b). These positions were determined via a pilot study on five people and

109 chosen as a compromise between being positioned at widest part of the muscle but not being

110 too close to the groin area, which sometimes led to discomfort during walking. As part of this

111 pilot study, we compared EMG amplitudes from signals collected at 60, 70 and 80% of thigh

112 length and selected the position which was associated with the largest signal. Placing EMG

113 electrodes over the innervation zone (IZ) leads to lower amplitudes[22], therefore this process

114 provided a degree of confidence that the placements were not over the IZ.

115

116

117   FIGURE 1 HERE

118

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 walking[25].

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 Telemyo

155   system (Noraxon USA) at 1500 Hz. The same protocol as the second experiment (described

156   above) was followed and the participant instructed to generated 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 at least 30

159   seconds was used between each test condition.

160   To quantify the movement of the skin relative to the underling 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 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

176

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

190

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 clustering[27], 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.

199

200   **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).

208

209   TABLE 1 HERE

210

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

218

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 running[30]. 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 Bekey[32]; Lawrence and

273 De Luca[33], Woods and Bigland-Ritchie[34] 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 rates[37]. 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 adductors[22]. 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 techniques[22] 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 muscles[38] 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.

333

334   **References**

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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	0º	8	9	22	21	16 (5)	15 (5)	41 (11)
	20º flexion	10	11	31	23	18 (7)	16 (4)	44 (10)
	40º flexion	9	7	28	29	18 (8)	18 (6)	46 (13)
	20º extension	6	10	23	22	16 (6)	14 (4)	40 (9)
AM	0º	6	7	26	36	16 (7)	19 (9)	46 (14)
	20º flexion	6	6	36	36	18 (11)	18 (11)	46 (16)
	40º flexion	6	6	35	36	19 (10)	18 (9)	47 (15)
	20º extension	7	7	34	32	19 (11)	17 (9)	45 (13)
Gr	0º	6	7	24	25	18 (6)	18 (7)	46 (13)
	20º flexion	6	6	26	36	16 (7)	21 (9)	47 (15)
	40º flexion	6	6	34	30	17 (9)	19 (8)	45 (15)
	20º extension	6	6	33	28	18 (9)	19 (8)	47 (14)

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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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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.

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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

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Figures

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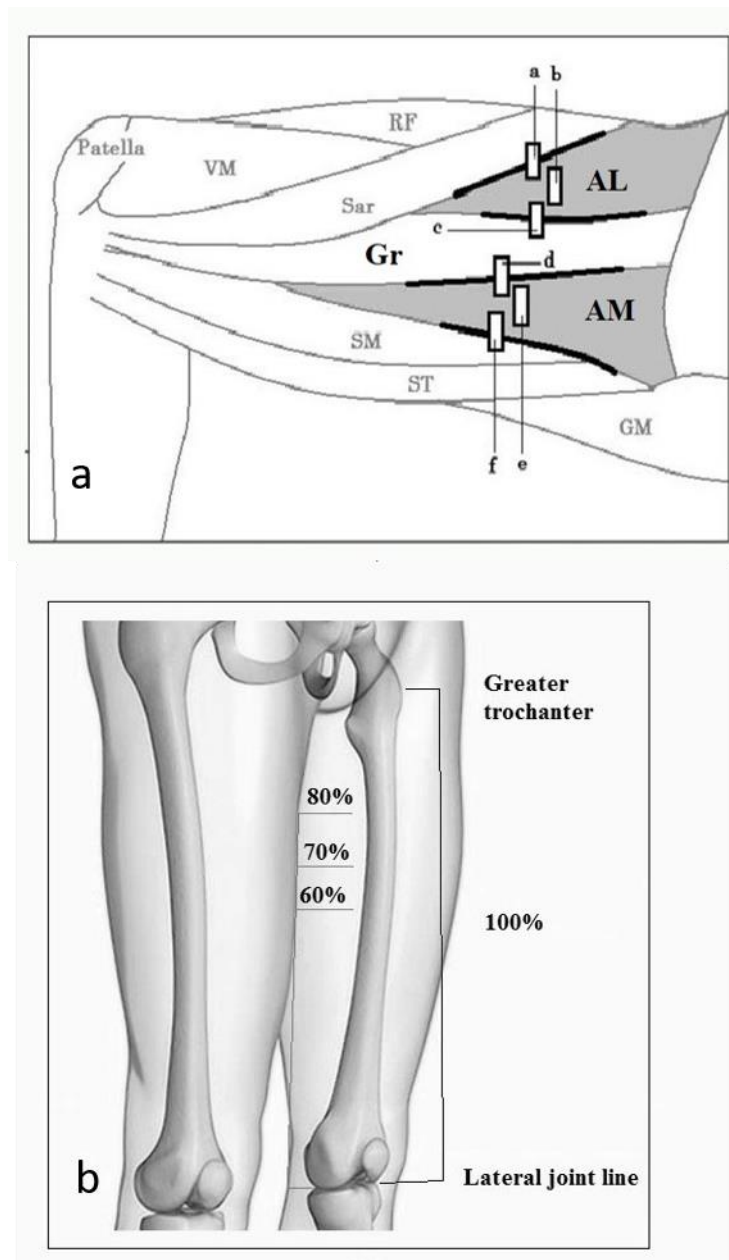
Figure 1: (a) Example ultrasound probe locations used to map out the boundaries of the three

adductor muscles. AL: adductor longus; AM: adductor longus; Gr: gracilis; Sar: Sartorius;

SM: semimembranosus; ST: semitendinosus. Note that a-f denote the positions of the

ultrasound probe used to locate the muscle boundaries (adopted and amended from[13]). (b): the

protocol for determining the electrode location along the length of the muscle, measured from

the greater trochanter to the lateral joint line.

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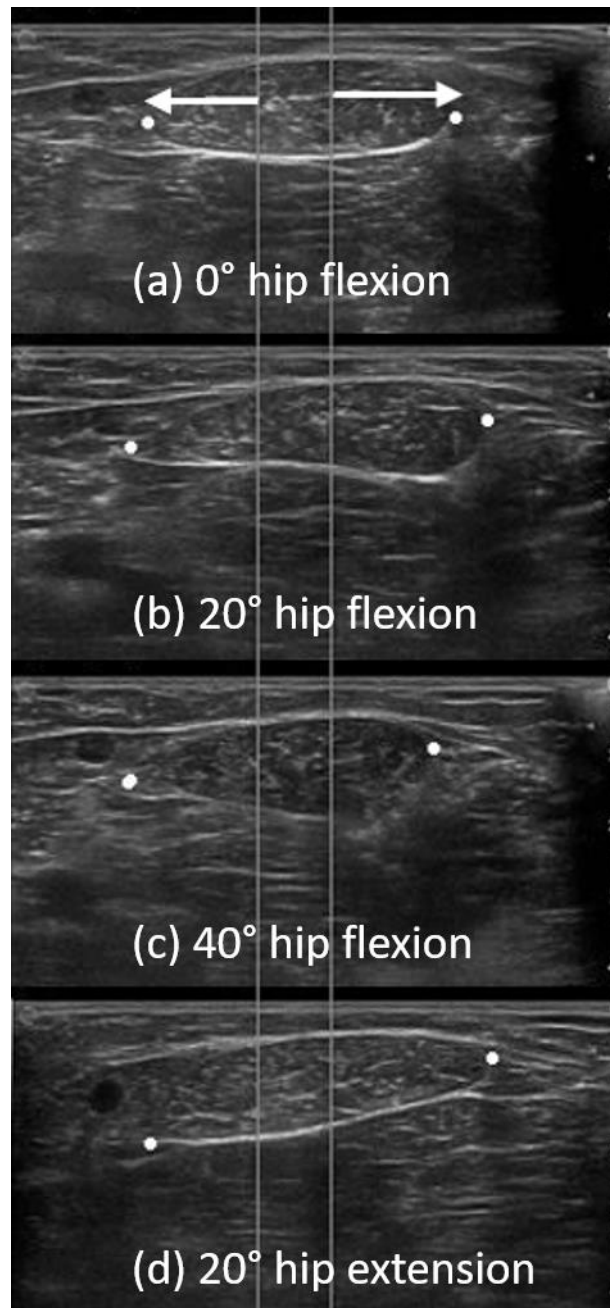
Figure 2: Example ultrasound images for gracilis at the four different hip joint angles (a-d).
The vertical lines represent the projection of the edge of the surface EMG electrodes and the
white dots show the (conservatively) identified boundary of the muscle. The arrows in image
a show the distances measured from the muscle boundaries to the edge of the EMG electrode
on the right and left sides.

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

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