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Elsais, WM, Preece, SJ, Jones, R and Herrington, LC

http://dx.doi.org/10.1123/jab.2019-0299

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Could relative movement between the adductor muscles and the skin invalidate surface EMG measurement?

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Running title: Ultrasound of adductor muscles
Abstract

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

Key words: ultrasound, running, walking, medial thigh

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.

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

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

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

**Methods**

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.

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 amplitudes$^{22}$, therefore this process provided a degree of confidence that the placements were not over the IZ.
To address the first two aims, we used ultrasound measurement to quantify the movement of the muscle relative to the mark on the skin representing electrode position (described above). To collect each ultrasound image, the mark on the skin was aligned with a specific point, marked on centre of the ultrasound probe which ensured a consistent positioning of the ultrasound probe for each image. The ultrasound images were collected at different hip flexion/extension angles (aim 1) and isometric contraction levels (aim 2). We chose four different hip flexion-extension angles (0°, 20°, 40° of hip flexion, and 20° hip extension) which correspond to a typical range of motion during running. Although abduction-adduction movements of the hip are also likely be associated with muscle movement, these motions are considerably smaller than sagittal motions during activities, such as running and walking. Therefore, for this study, we chose to focus on hip flexion/extension. These angles were measured between the thigh and the vertical using a transparent plastic goniometer with a 360° head and 30 cm arms. For each angle, participants were instructed to maintain the specified hip position, without external support, in each of the different hip angles while each of the adductor muscles were imaged separately. The testing order of hip angles was randomised and a rest period of three minutes was given between each hip test.

To quantify relative movement between the skin and the muscle during isometric contraction, we used a ramped isometric protocol with contractions at 20, 40, 60, and 80% of maximum hip adduction torque. These contraction were monitored using the Biodex System 3 isokinetic dynamometer (Biodex Medical Systems, Shirley, NY) and followed a protocol described by Brent et al., in which biofeedback is used to provide subjects with a visual target.
at each contraction level. For each isometric test, the axis of rotation of the dynamometer was aligned with the centre of hip rotation and the participant was instructed to push against the dynamometer arm in the direction of adduction. For this test, the participant stood on the non-tested leg while the tested leg hung freely in a vertical position. The test began with a measurement of the maximum torque, after which the participant was provided with feedback to enable them to contract at 20, 40, 60, and 80% of their maximum in a randomised order. Similar to the previous test, the three adductor muscles were imaged separately at each contraction level. The order of the isometric contraction tests, described above, was randomised and a minimum rest of 30 seconds given between the images collected for each of the adductor muscles.

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

To quantify the movement of the skin relative to the underlying muscle (aim 1), the ultrasound images for each subject (corresponding to each hip flexion/extension position) were vertically aligned (Figure 2). Each ultrasound image captured a transverse plane cross section of an adductor muscle, with the left side of each image corresponding to the anterior aspect and the right side corresponding the posterior aspect of the muscle. Vertical lines were then drawn
over each set of images to illustrate the projection of the edges of the EMG electrodes (Figure 3) onto the transverse plane cross section. As each image was collected with the ultrasound probe located at the same position on the skin (see above), the aligned images provided a clear measure of the movement of the muscle relative to the overlying skin (Figure 2). The distance from the electrode boundary (vertical line) to the edge of the muscle (identified visually) was then measured using the Image J software (available at: http://rsb.info.nih.gov/ij/docs/index.html) for both the right and left sides. These distances correspond to a measure, in the anterior-posterior direction, from the edge of the electrode to the anterior/posterior border of the adductor muscle.

Through the process described above, it was possible to obtain the distance (on both the left and right side) between the edge of the electrode (vertical line) and the edge of the muscle (shown as white dot) for each subject in each hip flexion/extension condition. For each set of images, the edge of the muscle was identified visually as the point, furthest from the vertical line, for which the muscle boundary was still clearly visible (Figure 2). The same procedure was repeated for aim 2 and the corresponding ultrasound data collected at the five different levels of isometric contraction. The primary aim of this investigation was to determine whether the muscle remained within the EMG detection volume at different hip positions and levels of contraction. Therefore, we calculated the minimum distance between the electrode and muscle boundary across all 10 subjects. In addition, other descriptive data were derived to characterise how the muscle moved relative the overlying skin.
To address the third aim, EMG data was high pass filtered at 10 Hz and RMS EMG activity calculated across a 1 second window for each isometric contraction. For each participant, the RMS data for each contraction level was normalised by the RMS MVIC data. All EMG processing was performed using Matlab (Mathworks, USA). A linear regression approach, with standard errors adjusted for clustering\(^27\), was then used to investigate the relationship between EMG amplitude and isometric contraction level. This statistical technique was selected as it can deal with repeated measures from each participant and was performed separately for each of the three adductor muscles.

**Results**

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

The isometric contraction data also showed the electrode to remain inside the muscle boundary. Although the lowest distance was 3 mm for adductor magnus at high contraction levels (Table 2), at lower contraction levels (20-60%), the minimum distance was 5 mm across
all muscles. Furthermore, the mean distance (across the subjects) was between 12-20 mm, similar to the values reported in Table 1 for the different hip angles.

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

Discussion

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

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

It is important to acknowledge that relative movement between the skin and muscle could also occur due to soft tissue vibration, which may result from the impacts associated with foot contact. Interestingly, previous research has shown significant movement between skin and underlying bone during walking\textsuperscript{28,29} and running\textsuperscript{30}. However, it is possible that the skin and muscle may move together in response to impact loading. If this is the case, then there may not be appreciable movement between the skin and muscle in which case EMG measurement would not be affected. However, full investigation of this phenomenon would require dynamic ultrasound, which was deemed beyond the scope of this investigation.

No previous studies have used ultrasound to investigate relative movements between the skin and the muscle in the context of EMG measurements. However, it is interesting to compare our data with research that has used ultrasound measurement to determine changes in muscle morphology that occur with muscle contraction. For example, during isometric
contraction, Delaney et al.\textsuperscript{31} examined the rectus femoris and found a decrease in muscle width of 8 mm to be associated with an increase in contraction to 30\% of MVIC. Similarly, at different knee angles, Delaney et al.\textsuperscript{31} also observed a change in the width of rectus femoris of 3 mm. These data on rectus femoris are similar to those observed in the current study for adductor longus with different hip flexion extension angles (Table 1) and gracilis during isometric contraction (Table 2).

Although there has been no previous research investigating torque-EMG relationships for the adductor muscles, it is interesting to compare our findings with studies investigating such relationships in other muscles. Our data match that of Perry and Bekey\textsuperscript{32}; Lawrence and De Luca\textsuperscript{33}, Woods and Bigland-Ritchie\textsuperscript{34} and Alkner et al.\textsuperscript{35} who reported a close relationship between torque and EMG activity for the biceps brachii, deltoid, soleus and quadriceps femoris muscles respectively under isometric conditions. In addition, our data is consistent with those of Bilodeau et al.\textsuperscript{36} who also reported a positive correlation between the RMS EMG for rectus femoris (RF), vastus medialis (VM), and vastus lateralis (VL) muscles and the torque in both men and women. This consistency with research into other muscles provides further confidence in our ability to measure the degree of activation of the superficial adductor muscles using the proposed protocol.

Our data show a linear relationship between torque and EMG under isometric conditions. However, we acknowledge we were not able to quantify this relationship under dynamic conditions. With a dynamic contraction, there will be a change in the specific motor units that lie within the EMG detection volume and this, along with the muscle lengthening/shortening velocity will affect the magnitude of the EMG signal and therefore the torque-EMG relationship. Although the effect of these changes has not been precisely quantified, it is likely that there will still be some degree of relationship between torque and EMG as the primary determinant of muscle force is the number of active motor units and their
firing rates\textsuperscript{37}. Therefore, we suggest that our proposed protocol should be appropriate for characterising the coordination patterns of the superficial adductor muscles during dynamic activities.

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

Another limitation that warrants consideration is that the electrode locations were not selected from a knowledge of the position of the innervation zones, as such data are not readily available for the adductors\textsuperscript{22}. However, we did identify a position which, in a pilot study, was associated with maximal EMG amplitudes. Nevertheless, further work is required, using array EMG techniques\textsuperscript{22} to fully map the position of the innervation zones for the adductor muscles and inform EMG placement. Finally, it is important to acknowledge that only a small portion of adductor longus and adductor magnus are amenable to surface EMG measurement. Therefore, the validity of this work, particularly the investigation of torque-EMG relationships, is dependent on the degree to which the part of the muscle, from which EMG was measured, is representative of force generation throughout the entire muscle.
This is the first study to use ultrasound to track relative motion between the muscle and overlying skin and provides new insight into electrode positioning. We chose to focus on the superficial adductors as these muscles are situated in close proximity and there are no obvious bony landmarks to guide EMG placement. However, our approach has the potential to be applied to other muscles which are amenable to surface EMG measurement. Recent developments allow for the acquisition of concurrent EMG and ultrasound data from superficial muscles\(^{38}\) and could facilitate this approach. We suggest that data on innervation zone position could be combined with data on relative skin-muscle motion to develop guidelines which could improve the validity of surface EMG measurement. If performed on a large scale, such work could be used to publish an atlas for different muscles, similar to the work of Barbero et al.\(^{22}\). This would be invaluable for the training of both physiotherapists and movement scientists.

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

References


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

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

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<th>Mean muscle width</th>
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Table 3. Fit of the linear mixed model, r-squared and percentage increase in muscle activity for every 1% increase in torque for adductor longus, adductor magnus and gracilis muscles.

<table>
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<th>Muscle</th>
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<th>R-squared</th>
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<tr>
<td>Adductor magnus</td>
<td>3.3 (2.8-3.8)%</td>
<td>&lt;0.001</td>
<td>0.45</td>
</tr>
<tr>
<td>Gracilis</td>
<td>3.8 (3.2-4.4)%</td>
<td>&lt;0.001</td>
<td>0.61</td>
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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\textsuperscript{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.
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.
**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.