



SURFACE EMG AMPLITUDE SPATIAL DISTRIBUTION OF MEDIAL  
GASTROCNEMIUS WITH CHANGES IN KNEE ANGLE

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Dissertação de Mestrado apresentada ao Programa de Pós-graduação em Engenharia Biomédica, COPPE, da Universidade Federal do Rio de Janeiro, como parte dos requisitos necessários à obtenção do título de Mestre em Engenharia Biomédica.

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Rio de Janeiro  
Novembro de 2014

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DISSERTAÇÃO SUBMETIDA AO CORPO DOCENTE DO INSTITUTO ALBERTO  
LUIZ COIMBRA DE PÓS-GRADUAÇÃO E PESQUISA DE ENGENHARIA  
(COPPE) DA UNIVERSIDADE FEDERAL DO RIO DE JANEIRO COMO PARTE  
DOS REQUISITOS NECESSÁRIOS PARA A OBTENÇÃO DO GRAU DE MESTRE  
EM ENGENHARIA BIOMÉDICA.

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RIO DE JANEIRO, RJ - BRASIL

NOVEMBRO DE 2014

Avancini, Carolina da Silva

Surface EMG amplitude spatial distribution of medial gastrocnemius with changes in knee angle / Carolina da Silva Avancini. – Rio de Janeiro: UFRJ/COPPE, 2014.

XI, 33 p.: il.; 29,7 cm.

Orientador: Luciano Luporini Menegaldo

Dissertação (mestrado) – UFRJ/ COPPE/ Programa de Engenharia Biomédica, 2014.

Referências Bibliográficas: p. 28-33.

1. Medial Gastrocnemius. 2. Surface EMG. 3. Muscle Architecture. 4. Knee Joint Angle I. Menegaldo, Luciano Luporini. II. Universidade Federal do Rio de Janeiro, COPPE, Programa de Engenharia Biomédica. III. Título.

# Dedicatória

Dedico este trabalho à meus pais, que sempre me ensinaram a importância dos estudos e estão sempre ao meu lado me apoiando e amando incondicionalmente. À meu irmão, me ensinou o que é perseverança. À professora Liliam, que acreditou em mim até quando eu mesma não acreditava mais.

# Agradecimentos

Por mais que eu escreva páginas e páginas, minhas palavras não seriam suficientes para expressar o quanto essa conquista é importante para mim. Só Deus sabe o quanto foi trabalhoso e árduo todo esse processo e que eu nunca conseguiria sozinha. Agradeço primeiramente à Deus porque Dele, por Ele e para Ele são todas as coisas, o meu melhor amigo e meu maior amor. Aos meus pais Jacqueline e Ruy que nunca mediram esforços, nunca negaram ajuda, nunca deixaram de apoiar e encorajar, e mesmo sem entender bem o que é engenharia biomédica nunca deixaram de se orgulhar de mim. Ao meu irmão Henrique, que é meu maior exemplo de que coisas incríveis acontecem quando você tem determinação, valeu chatim!

Agradeço à todos os professores do PEB, que de alguma forma me incentivaram e ensinaram, e até mesmo quando me desencorajavam estavam me ajudando a avançar mais. Aos funcionários do PEB que sempre foram muito gentis e solícitos. Ao meu orientador Luciano Menegaldo que soube sempre me direcionar pelos caminhos da engenharia com muito zelo e atenção. Ao meu co-orientador Taian Vieira, ao qual eu dei bastante trabalho, mas mesmo assim sempre me orientou com respeito e carinho apesar das mancadas ao longo do caminho. Obrigada por sua paciência comigo. À minha querida professora Liliam, que é mais que uma professora é uma amiga que sempre sabe o que dizer, e nunca me deixou pensar que eu não era capaz. Ela viu em mim o que eu mesma não sabia que tinha e acreditou em mim mesmo sem saber se iria dar certo, sem ela possivelmente não teria conseguido.

Não posso deixar de agradecer aos meus ilustres, queridos e lindos colegas de classe. Todos vocês contribuíram de forma especial para que eu concluísse esse trabalho. Ao Lucenildo por sempre me ajudar qualquer que fosse a dúvida. Ao Felipe Alvin pela paciência em me explicar coisas que eu não entendia. Ao Felipe Teixeira por

sempre me fazer rir quando eu estou nervosa. Ao Rhenan por se divertir 'debugando' minhas rotinas. Ao Paulo por me aguentar por quase dois anos reclamando. Ao Rogerio, Raoni, Vinicius, Lucas, Emanuel, e à todos que de alguma forma estiveram do meu lado nesse processo.

Em especial tenho que agradecer as mais lindas, as minhas amigas queridas que em toda essa caminhada são as que mais sabem o que passamos e como é terminar isso tudo. Agradeço á Lili por sempre me divertir com seu sotaque lindo e por elogiar incontáveis vezes meu brigadeiro. À Bia, por ter sempre palavras doces e um sorriso carinhoso. À Kelly que sempre tão elegante nos passa tranquilidade. À Raquel por falar as coisas mais inesperadas e acabar com qualquer tédio. À Lets que de alguma forma desperta meu lado mais comediante, principalmente em nossas longas e espremidas viagens no 485. À Aline que sempre tem bons conselhos e um sorriso que te impulsiona a sorrir, e faz com que os congressos sejam bem mais divertidos. À Vivi que nunca deixa que eu me sinta pra baixo e sabe sempre a melhor forma de me explicar coisas sem me apavorar, com sua prolixidade sem igual e sua gentileza sem reservas. Parte desse trabalho também é seu. À Natália, que inexplicavelmente já era minha 'best' antes mesmo de me conhecer e sempre soube que palavras usar e como me entender mesmo quando não concordava comigo, mas sempre me apoiando em tudo. À vocês meninas meu muito obrigada por todos as risadas, lágrimas, confusões, ajuda nos exercícios, histórias e memórias que fizeram mais do que me ajudar nesse mestrado, me ajudaram a crescer como pessoa.

Aos meus amigos que entenderam as minhas ausências e reclamações mas sempre me apoiaram e me deram força. Agradeço a todos que de alguma forma me ajudaram, acreditaram e sonharam comigo. O sonho se realizou.

Obrigada.

Resumo da Dissertação apresentada à COPPE/UFRJ como parte dos requisitos necessários para a obtenção do grau de Mestre em Ciências (M.Sc.)

## AMPLITUDE DA DISTRIBUIÇÃO ESPACIAL DO EMG DE SUPERFÍCIE DO GASTROCNÊMIO MEDIAL COM MUDANÇAS NO ÂNGULO DO JOELHO

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Novembro/2014

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Programa: Engenharia Biomédica

Investigar os efeitos da posição do joelho na distribuição da amplitude da eletromiografia (EMG) de superfície e quais efeitos estão associados com mudanças regionais do comprimento da fibra do Gastrocnêmio Medial (GM). Se a amplitude do EMG muda localmente com a flexão do joelho e o comprimento da fibra é o mecanismo que desencadeia e modula a ativação, maiores reduções na amplitude do EMG seriam esperadas em regiões do GM onde houvesse maior encurtamento da fibra. Foram detectados 15 EMGs de superfície proximo-distalmente no músculo GM enquanto os 22 participantes realizavam flexão plantar a 60% do contração máxima, com o joelho estendido e a 90 graus de flexão. Os canais que proveram EMGs com maior amplitude, sua relativa posição proximo-distal e média da amplitude do EMG foram considerados para caracterizar a atividade mioelétrica com a posição do joelho. Com imagens de ultrassom, foram computados o comprimento da fibra, ângulo de penetração e espessura do tecido subcutâneo para as regiões proximo-distais do GM. O EMG de superfície detectado com o joelho fletido foi em média 5 vezes menor do que com o joelho estendido. Entretanto, com a flexão de joelho, relativamente maiores EMGs foram detectados por um maior número de canais centrados na região mais proximal do GM. Variações na posição do joelho não afetaram os valores proximo-distais obtidos para as medidas de arquitetura muscular. Os principais achados revelaram que com o joelho fletido: i) há uma redistribuição da atividade em todo músculo GM; ii) EMGs detectado localmente não bastam para caracterizar mudanças no drive neural do GM; iii) fontes além do comprimento da fibra contribuem para determinar a rede de ativação do GM.

Abstract of Dissertation presented to COPPE/UFRJ as a partial fulfillment of the requirements for the degree of Master of Science (M.Sc.)

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This study investigates whether knee position affects the distribution of surface electromyogram (EMG) amplitude and whether such effect is associated with regional changes in medial gastrocnemius (MG) fibre length. If EMG amplitude changes locally with knee flexion, and if fibre length is the key mechanism shaping activation, greatest reductions in EMG amplitude are expected to manifest in MG regions showing greatest fibre shortening. Fifteen surface EMGs were detected proximo-distally from the MG muscle while 22 participants exerted isometric plantar flexion at 60% of their maximal effort, with knee fully extended and 90 deg flexed. The number of channels providing EMGs with greatest amplitude, their relative proximo-distal position and the EMG amplitude averaged over channels were considered to characterise changes in myoelectric activity with knee position. From ultrasound images, fibre length, pinnation angle and subcutaneous thickness were computed for MG proximo-distal regions. Surface EMGs detected with knee flexed were on average five times smaller than those collected during knee extended. However, during knee flexed, relatively larger EMGs were detected by greater number of channels, centred at the MG more proximal regions. Variation in knee position did not affect the proximo-distal values obtained for MG architectural features. Our main findings revealed that, with knee flexion: i) there is a redistribution of activity within the whole MG muscle; ii) EMGs detected locally unlikely suffice to characterise the changes in the neural drive to MG; iii) sources other than fibre length substantially contribute to determining the net, MG activation.



# Nota

O presente manuscrito foi submetido à publicação no formato de artigo científico com o título "Variations in the spatial distribution of the amplitude of surface EMGs are unlikely explained by changes in the length of medial gastrocnemius fibres with knee joint angle" na revista Plos One no dia 28 de novembro de 2014. Salvo o capítulo correspondente a revisão de literatura, as demais sessões estão presentes no artigo supracitado.

# Sumário

1 Introduction .....	1
2 Literature Review .....	4
3 Materials and Methods .....	7
3.1 Subjects.....	7
3.2 Experimental Protocol .....	7
3.3 Quantifying Gastrocnemius Architecture .....	8
3.4 Electrode Placement and EMG Recordings.....	10
3.5 Assessing the spatial distribution of EMG amplitude. ....	11
3.6 Statistical Analysis.....	13
4 Results .....	15
4.1 Amplitude and Spatial Distribution of MG Myoelectric Activity.....	15
4.2 MG Architectural Changes Revealed From US Images.....	18
5 Discussion.....	21
5.1 EMG Amplitude Distribution Rather Than EMG Amplitude Is Affected By Knee Position .....	21
5.2 Architectural Differences Within the Gastrocnemius Muscle Unlikely Explain the Changes in Activation With Knee Position .....	23
5.3 What is the origin for the redistribution of activity within the gastrocnemius muscle with knee flexion? .....	26
References .....	28

# Lista de Abreviações

EMG	Electromyogram
MG	Medial Gastrocnemius
MVC	Maximal Voluntary Contraction
RMS	Root Mean Square
ANOVA	Analysis of Variance
SOL	Soleus

# Chapter 1

## Introduction

The triceps surae muscle, composed by the two gastrocnemius heads and the soleus muscle, is the chief ankle plantar flexor. Approximately 70% of the plantar flexion torque applied at the ankle results exclusively from the triceps surae activation (Cresswell *et al.*, 1995). However, due to their anatomical differences, gastrocnemius and soleus muscles provide different relative contributions to the ankle plantar flexion torque. Differently from soleus, the gastrocnemius muscles span both the ankle and knee joints; their force vectors contribute to both ankle extension and knee flexion torque. As a consequence, the relative contribution of each head of the triceps surae to plantar flexion torque changes with the knee joint position.

Mechanically, the gastrocnemius muscles may produce substantially greater plantar flexion torque when the knee is at progressively more extended positions. When the knee is fully extended, previous estimates suggest the plantar flexion torque produced by the gastrocnemius muscle amounts to ~45% of the total, plantar flexion torque (Cresswell *et al.*, 1995). These figures decrease to ~30% for knee flexed positions (Fukunaga *et al.*, 1992). The smaller values of plantar flexion torque observed for the more flexed knee positions are typically attributable to the gastrocnemius force-length curve (Hahn *et al.*, 2011). Specifically, for knee joint angles smaller than that corresponding to full extension, the gastrocnemius fibres are on average shorter than their optimal length for force production (Kawakami *et al.*, 1998). Presuming the

neural drive to gastrocnemius motor neurons remains constant for different knee joint positions, the muscle mechanical output is therefore expected to decrease with knee flexion.

Through the recording of surface electromyograms (EMG), previous studies have consistently reported a differentiated degree of activation of the gastrocnemius muscle for different, knee joint positions (Miaki *et al.*, 1999; Nourbakhsh *et al.*, 2004; Cronin *et al.*, 2010). These differences in activation seem to manifest equally during both dynamic and isometric contractions. Tamaki and co-workers (1997), for example, recorded surface EMGs from the gastrocnemius muscle while subjects moved their ankle into plantar flexion, at three different speeds and at three knee joint angles. Regardless of the contraction speed, these authors observed significantly smaller peak values of integrated EMGs for the more flexed knee positions. Smaller values of EMG amplitude have been similarly documented for the gastrocnemius muscle during isometric plantar flexion contractions performed with knee flexed rather than extended (Miaki *et al.*, 1999). Such decrease in EMG amplitude with knee flexion has been conceived as a strategy of the nervous system to more efficiently distribute the neural drive across plantar flexors (Kennedy and Cresswell 2001). In virtue of the suboptimal length of gastrocnemius fibres at knee-flexed positions, the relative active contribution of this muscle to the production of plantar flexion torque likely decreases with knee flexion.

Previous studies reporting the effect of fibre length on the gastrocnemius mechanical efficiency and activation have conceived the muscle as a homogeneous medium. On the other hand, for a number of circumstances, anatomical and electrophysiological evidence suggests the changes in architecture and activation may distribute unevenly within the gastrocnemius muscle. For example, spatial changes in

fibre length within the MG muscle were observed during walking and running (Lichtwark *et al.*, 2007) and with multi-joint leg extension (Hahn *et al.*, 2011). Similarly, imaging techniques and electromyography have consistently revealed a significant differential pattern of activation between proximal and distal gastrocnemius regions. These regional variations in activation have been reported following dynamic plantar flexion contractions at different intensities (Kinugasa *et al.*, 2011), during quiet standing (Vieira *et al.*, 2010a), during electrically elicited contractions (Hodson-Tole *et al.*, 2013), with changes in ankle force direction (Staudenmann *et al.*, 2009) and with fatigue (Gallina *et al.*, 2011; McLean and Goudy, 2004). Whether the nervous system accounts for anatomical inhomogeneities within the gastrocnemius muscle to shape activation with the changes in knee position remains however an open issue. If fibre length is the key parameter shaping activation, then, the gastrocnemius regions showing smallest reductions in fibre length with knee flexion may be activated most strongly.

In this study we therefore use ultrasound and a large array of surface electrodes to investigate how knee joint angle affects the distribution of activity and of fibres' length within the medial gastrocnemius (MG) muscle. Specifically, our main research question is: does the distribution of EMG amplitude on skin regions covering the MG muscle change with knee position? If it does, then we further investigate whether these spatial inhomogeneities in activity are associated with changes in fibre length within the MG muscle. If the nervous system redistributes the neural drive to the MG muscle predominantly according to the length of its fibres, in agreement with previous accounts on changes in EMG amplitude with knee position (Kennedy and Cresswell 2001; Cronin *et al.*, 2010), we expect to observe greatest reductions in EMG amplitude where reductions in fibre length are greatest.

# Chapter 2

## Literature Review

The triceps surae muscle group is considered the lead synergist for the plantar flexion contraction (Murray *et al.*, 1976). This muscle group is constituted by the two-joint muscles crossing the knee and ankle joint: the lateral and medial gastrocnemius and the soleus, which crosses only the ankle joint. Each portion has different architectural properties, as muscle and fiber length and pinnation angle (De Ruyter *et al.*, 1995). The medial and lateral heads of the gastrocnemius, for instance, originates at the medial and lateral femoral condyles, respectively, and inserts through a single tendon on the calcaneus bone. Consequently, the net amount of force that may be produced by the gastrocnemius muscle is influenced by the position of both joints. In addition to the muscle force, the neural drive to gastrocnemius fibres seem to change with the muscle length (Cresswell *et al.*, 1995); the neural drive seems to reduce as the fibres are shortened due to knee flexion. However, the modulation of neural activation could be not only due to the decrease in muscle length, as suggest by Arampatzis *et al.*, (2006). During maximal voluntary plantar flexion contraction, they observed that the EMG activity of the MG decreases with knee flexed, despite of no differences in the fascicle length.

Knee flexion changes the fiber arrangement features, increasing pinnation angle and decreasing MG fiber length (Wakahara *et al.*, 2007). Kawakami and co-workers (1998) measured the muscle length and the torque production of all muscles that

composes the triceps surae varying the knee and ankle joint angle. Those measures were made in a passive and an active condition. They reported that changes in the ankle and knee joint angle were related to changes in muscle length also the knee and ankle joint position affected the torque with a decrease in plantar flexion torque. Moreover, Cresswell *et al.*, (1995) notice that the normalised EMG RMS value with the knee flexed with different contraction levels was smaller than fully extended, showing 60% of torque reduction, with a smaller signal amplitude with knee flexed although for the soleos muscle the amplitude remained unchanged. Changes in architectural features can lead to modifications in the neural drive to the target muscle. Such mechanical dependence of the gastrocnemius neural drive is presumably related to minimization of the metabolic cost (Ferguson *et al.*, 2001). As the shortened fibers produce less force, other synergist muscles which fibres are less affected by changes in joint angle, are preferentially recruited (Lauber *et al.*, 2014). Indeed, the soleus activity seems to increase during contractions with flexed knee (Miaki *et al.*, 1999; Nourbakhsh *et al.*, 2004).

Medial gastrocnemius fibres present different pinnation angles and length within the muscle, as revealed by imaging techniques (Shin *et al.*, 2009; Lichtwark *et al.*, 2007). These regional differences in architecture could account for the regional distribution of activation. For example, simulation studies revealed that the obliquity of muscle fiber affect the amplitude and the shape of surface potentials, where the inclination of the muscle fibers lead to a concentration of the amplitude distribution more toward the superficial tendon (Mesin *et al.*, 2011). EMG is the usual technique to identify regional variations of activation during different tasks. Kinugasa *et al.*, (2011) showed that an increase of plantar flexion contraction intensity with the knee fully lead to an increase of the activated volume within the whole MG muscle. The regional



variation of gastrocnemius activity was also reported, with changes in ankle force direction (Staudenmann *et al.*, 2009) and during a fatigue protocol, suggesting that myoelectric manifestations of fatigue were distributed regionally (Gallina *et al.*, 2011). However, the effects of knee joint position on the regional activation of the MG muscle, as well as its relationship with architectural parameters variations, are still unclear.

# Chapter 3

## Materials and Methods

### 3.1 Subjects

Twenty-two healthy (13 male) volunteers participated in the study (range values; age: 23 – 47 years; height: 150 – 195 cm; body mass: 44 – 90 Kg). Participants were instructed about the experimental procedures and provided written, informed consent prior to participation. Experimental procedures conformed to the standards set by the latest revision of the Declaration of Helsinki and were approved by the institutional ethics committee (HUCFF/UFRJ - 127/2013).

### 3.2 Experimental protocol

Isometric plantar flexions were applied with participants carefully positioned on a dynamometer chair (Biodex System 4, New York, USA). The axis of rotation of the dynamometer was aligned as coaxially as possible with the axis of rotation of the right ankle, defined as the line connecting the tips of medial and lateral malleolus (Wu *et al.*, 2002). This alignment was approximated with the assistance of a laser pen, pointing from the centre of the dynamometer's axis of rotation to the most prominent region of each malleolus. After aligning and securing the right foot to the dynamometer footplate, volunteers were instructed to exert two maximal voluntary contractions (MVCs) for the knee fully extended and two for the knee flexed at 90 deg, lasting 5 s each. The highest peak torque value was retained as representative of the individuals'

maximal effort in each knee position. A rest period of at least 1 min was provided between MVCs. Verbal encouragement assisted participants in reaching their highest plantar flexion torque. At least 2 minutes after the maximal attempts, participants were asked to exert isometric plantar flexions at 60% MVC, with their knee in extended and flexed positions. Contractions lasted 10 s each, with a rest period of 1 min in-between. Visual feedback of ankle torque was provided to ensure participants kept their plantar flexion effort within 10% of the target level.

### **3.3 Quantifying gastrocnemius architecture**

Gastrocnemius architecture was carefully analysed to investigate whether anatomical factors affected the degree and the distribution of MG activity. Of particular interest was the effect of pinnation angle (Mesin *et al.*, 2011), of fibre length (Chow *et al.*, 2000) and of fat thickness (Farina *et al.*, 2002) on the amplitude distribution of surface EMGs. These variables were therefore estimated for knee flexed and extended positions from ultrasound images (10 MHz B mode linear probe with 70% gain and 7 cm depth view; MYLab25 Gold; ESAOTE S.p.A., Italy). All images were taken during rest and with the feet free from the litter and with the ankle joint held in neutral position. The specific experimental procedures considered to estimate MG architecture are detailed below.

Anatomical MG sites were first identified with ultrasound imaging and marked on the skin. Initially, the insertion of the Achilles tendon to the calcaneous bone was identified with the probe oriented longitudinally to the leg. After that, with the probe at the same orientation, the femur-tibia medial interface was identified. The distance between the medial condyle and Achilles tendon insertion was considered to quantify the muscle-tendon length. From the medial condyle location, the probe was moved

distally until the most proximal MG fibres could be visualised; their location was marked on the skin. At 30% of the muscle-tendon length, the lateral and medial boundaries of MG were identified with the probe oriented transversally to the leg. A line was then drawn from the Achilles tendon insertion to the medial condyle, passing through halfway the distance between MG boundaries. With the probe oriented longitudinally along this line, the MG-Achilles tendon junction was located and marked on skin. Finally, the region defined from the femoral condyle to the myotendinous junction was considered for the acquisition of panoramic image from the MG muscle. Two panoramic images were collected for each of the two knee positions, flexed and extended.

Key architectural MG parameters were quantified from the panoramic images. These images were analysed with the *Image J* software (National Institute of Health, version 1.42, Bethesda, Maryland, USA). First, the length of the MG muscle sampled from surface electrodes was quantified as the distance between skin regions located in correspondence of the distal extremity of the MG superficial aponeurosis and of the most proximal electrode (see next subsection). Then, based on this length, the MG muscle was divided into two portions; proximal and distal portions (Figure 1). MG pinnation angle and fat thickness were quantified at the first and second thirds of each portion and then averaged, resulting into a single value for each muscle portion. The pinnation angle was estimated as the angle between MG fascicles and the deep aponeurosis. The thickness of the fat tissue was measured as the distance between the skin/fat and the fat/superficial aponeurosis interfaces (Chow *et al.*, 2000) [19]. Fibre length was estimated as the average length of lines drawn along fascicles located nearby the midpoint of ultrasound images, extending from the superficial to the deep aponeurosis.

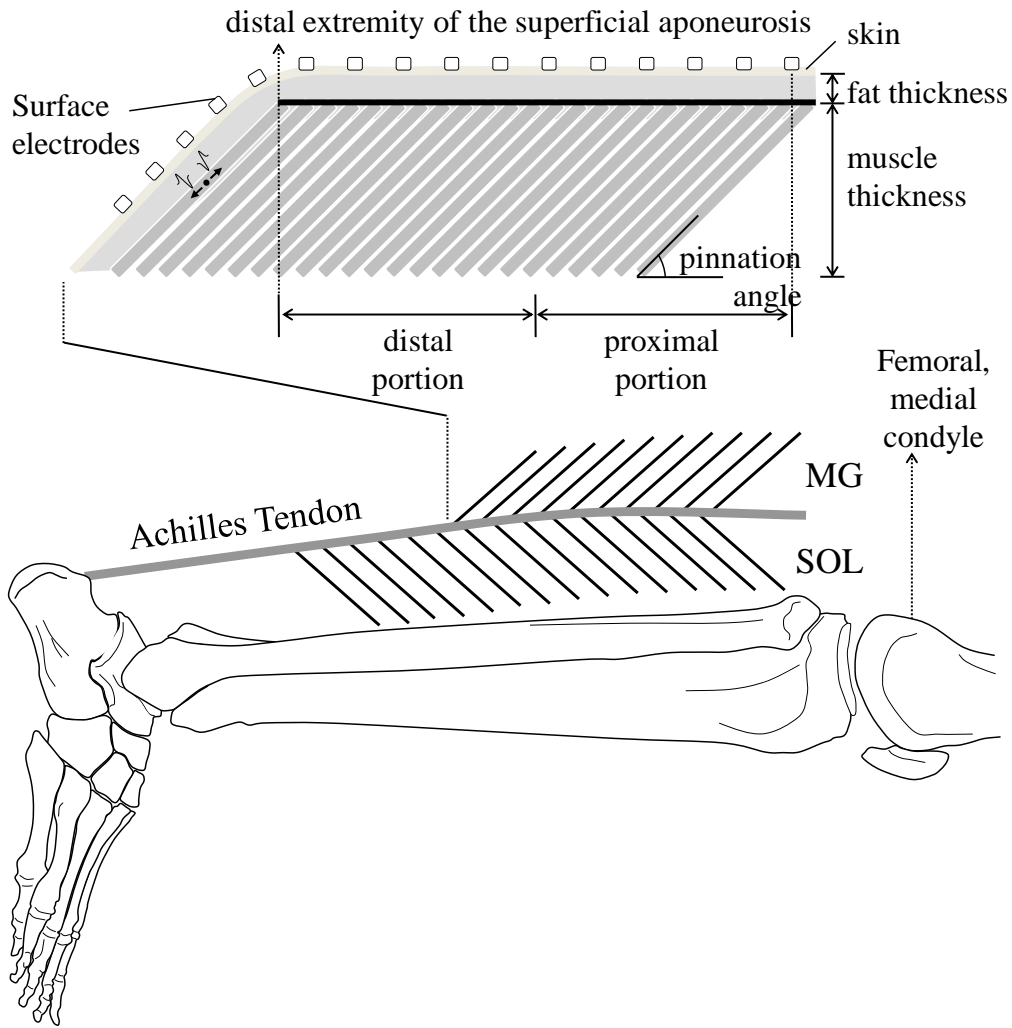


Figure 1. *Electrodes positioning and gastrocnemius architecture.* A schematic illustration of the relative position of surface electrodes on the medial gastrocnemius (MG) muscle is shown. The parameters considered to characterise architectural differences between the MG proximal and distal regions are further illustrated in the figure; pinnation angle, fibre length and subcutaneous thickness. Proximal and distal MG regions were respectively defined as the proximal and distal half of the distance between the distal extremity of the superficial aponeurosis and the most proximal electrode. Only the surface EMGs detected by electrodes positioned in correspondence of the superficial aponeurosis were retained for analysis.

### 3.4 Electrode placement and EMG recordings

Surface EMGs were detected from multiple skin regions covering the MG muscle with a flexible, adhesive array of electrodes. Such array (16 silver-bar electrodes; 10 x 1 mm; 10 mm inter-electrode distance; Spes Medica, Battipaglia, Italy)

was positioned parallel to the MG longitudinal axis (Figure 1). The most proximal electrode was positioned as proximally as possible to the femoral condyle, to avoid folding the array when subjects flexed their knees. Conductive paste (TEN 20 Conductive Paste, Weaver) ensured electrical contact between electrodes and skin. The reference electrode was placed on the lateral malleolus of the contralateral limb. Before positioning electrodes, the skin was carefully shaved and cleaned with abrasive paste to reduce skin impedance.

Surface EMGs were recorded in single-differential derivation. To ensure the highest signal to noise ratio without saturation, all signals were amplified by a variable factor, ranging from 2.000 to 5.000 (multi-channel amplifier; 10-900 Hz anti-aliasing filter; CMRR>100 dB; EMG-USB2, OTBioelettronica, Turin, Italy). EMGs were digitalised at 2048 Samples/s with a 12 bits A/D converter. The torque signal provided by the dynamometer machine was sampled synchronously with the EMGs. All signals were inspected prior to acquisition to check and correct for contact problems and power line interference.

### **3.5 Assessing the spatial distribution of EMG amplitude**

The distribution of the amplitude of surface EMGs collected from the MG muscle was quantified for each subject and knee position. First, all EMGs were filtered with a second order, band-pass filter (Butterworth, 15 – 350 Hz cutoff). After that, the root mean square (RMS) value was computed over the whole record duration (10 s), separately for each of the 15 channels (i.e., each pair of electrodes). Only channels located on skin regions covering the superficial aponeurosis (Figure 1) and detecting surface EMGs with RMS amplitude greater than 70% of the maximum amplitude (Vieira *et al.*, 2010b) were retained for analysis; these channels were termed *active*

*channels*. Finally, from the RMS values obtained for these channels, three indexes were computed: i) the global EMG amplitude, defined as the RMS value averaged over the *active channels*; ii) the barycentre coordinate of the *active channels*, which indicate the mean position of the RMS distribution along the muscle proximo-distal axis and; iii) the number of *active channels*, which denote the spread of the RMS amplitude distribution on the skin.

Specific procedures were applied to normalise each of the three indexes considered. The global EMG amplitude was normalised with respect to the maximal RMS amplitude obtained at 100% MVC during the knee extended condition. The barycentre coordinate was calculated from the most proximal electrode in the grid and represented as a percentage of the distance between the femoral condyle and the distal extremity of the superficial aponeurosis, measured with the knee extended. The number of *active channels* was ultimately normalised with respect to the number of channels located over the superficial aponeurosis. Because of the MG lengthening with knee flexion, the length of the superficial aponeurosis and, thus, the number of channels located over it may change. For this reason, changes in the number of channels located in correspondence of the superficial aponeurosis were assessed through changes in the innervation zone position. Whenever a distal shift in the innervation zone position with knee flexion was observed (Figure 2), the number of channels considered for normalisation of the *active channels* was increased; one channel per centimetre shift.

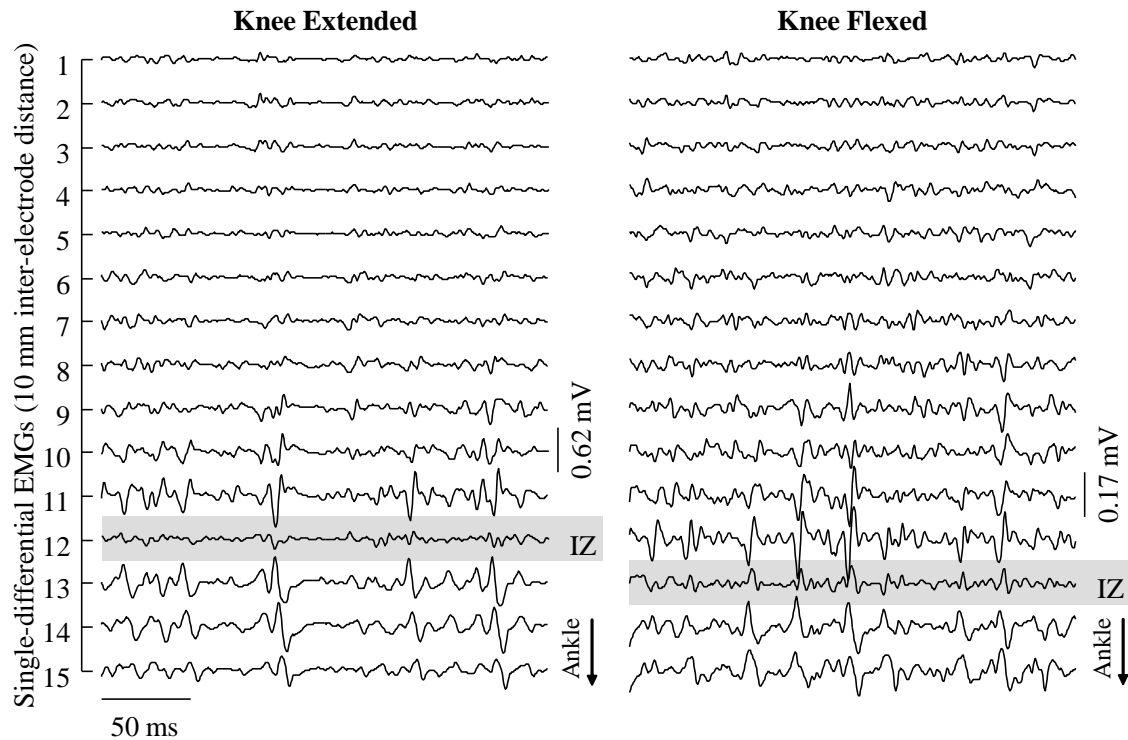


Figure 2. *Displacement of innervation zone with knee flexion.* Short epochs (250 ms) of the 15 single-differential EMGs collected from a single participant are shown. Signals in the left and right panels were obtained during knee extended and knee flexed positions, respectively. Propagating potentials are observed in the most distal channels, which were covering the most distal MG fibres. The channel in the array positioned most closely to the innervation zone of the muscle distal fibres is indicated as grey, shaded rectangles. Note the innervation zone moved distally from knee extended to knee flexed position.

### 3.6 Statistical analysis

After ensuring the homogeneity of variance with Levene's test (W values greater than 0.2 for all architecture variables considered) and the data Gaussian distribution (Shapiro-Wilk statistics  $p > 0.075$  for all cases), parametric tests were considered to assess the changes in MG architecture with variation in knee joint angle. Two-way analysis of variance (ANOVA) was used to test for the differences in fibre length, pinnation angle and fat thickness of MG muscle between and within knee positions and muscle portions. Gaussianity and homogeneity of variance were however not confirmed for the MVC torque scores and for the electromyographic variables. Wilcoxon rank sum test was applied to compare the MVC torque value and the global



RMS value, the barycenter longitudinal position and the number of *active channels* obtained for knee extended and flexed positions. All analyses were carried out with IBM SPSS Statistics 20.0 (IBM SPSS, Chicago, USA) and the level of significance was set at  $P < 0.05$ .

# Chapter 4

## Results

The potential to produce maximal scores of plantar flexion torque depended on the knee position. Average plantar flexion torque at 100% MVC was significantly greater with knee extended ( $131 \pm 51$  Nm) than with knee flexed ( $104 \pm 53$  Nm; Wilcoxon test;  $P = 0.009$ ;  $N = 22$  subjects). As outlined below, differences in MVC scores were accompanied by marked changes in the amplitude distribution of surface EMGs though not by regional variations in MG architecture.

### 4.1 Amplitude and spatial distribution of MG myoelectric activity

Surface EMGs detected along the MG muscle during knee extended and flexed positions were markedly different. As shown in Figure 3 for a representative participant, these differences manifested in the amplitude of surface EMGs and in its distribution. For the knee extended condition, relatively larger action potentials were observed in the more distal MG regions (cf. the amplitude of surface EMGs detected by different channels in Figure 3*a*). Consequently, greatest RMS values were obtained for the two most distal channels; these channels provided RMS values greater than 70% of the maximum RMS value in the grid (Figure 3*a*). For the knee flexed position, on the other hand, the RMS amplitude of surface EMGs distributed somewhat evenly across

channels in the array; seven out of the nine channels located over the MG superficial aponeurosis for this subject provided similarly large RMS values (Figure 3b).

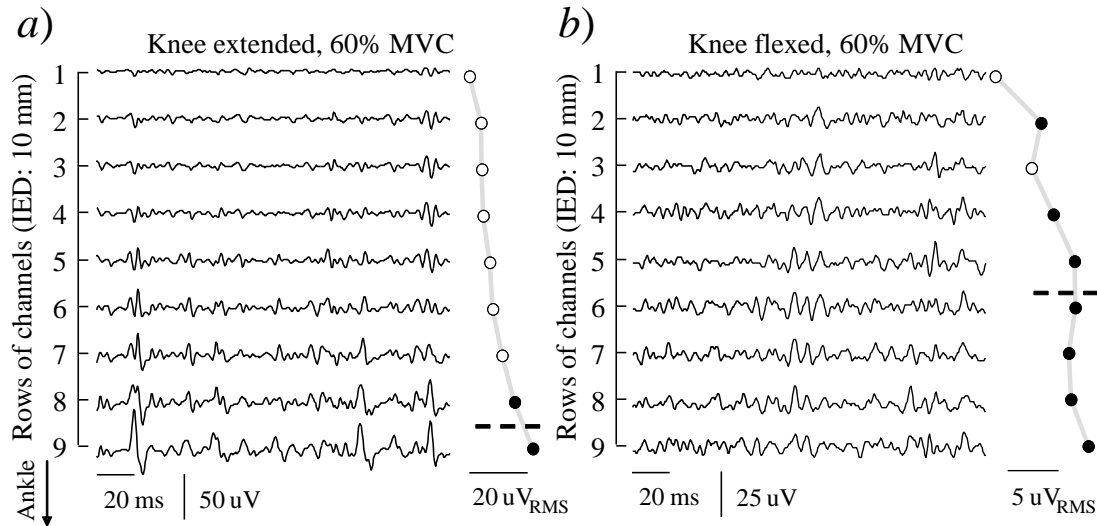


Figure 3. *Changes in the surface EMGs with changes in knee position.* A short epoch of raw, surface EMGs is shown during plantar flexion contractions exerted with the knee fully extended (*a*) and the knee flexed at 90 deg (*b*). Only nine of the 15 channels in the array were positioned on skin regions covering the MG superficial aponeurosis. The RMS amplitude computed from EMGs detected by each of these nine channels is shown on the right side of each panel, with black circles denoting the channels providing RMS amplitudes greater than 70% of the maximum. Dashed lines indicate the barycentre coordinate computed for these channels.

The differences in EMG amplitude shown in Figure 3 were consistently observed across the 22 participants tested. The normalised, mean RMS amplitude observed during the knee extended position (interquartile interval: 28-45%) was approximately five times higher than that observed for the knee flexed position (4-12%; Figure 4a; Wilcoxon test;  $P = 0.001$ ;  $N = 44$ ; 22 subjects x 2 knee positions). The spatial distribution of RMS amplitude was however significantly more diffused on the skin during knee flexed than extended position. With knee extended, the relative number of *active channels* (33-75%) was significantly smaller than that obtained with knee flexed (81-100%; Figure 4b; Wilcoxon test;  $P = 0.001$ ). Finally, the barycentre

coordinate obtained for knee extended position was located at significantly more distal regions than that obtained for knee flexed position (Wilcoxon test;  $P = 0.001$ ). For the knee flexed and extended conditions, the barycentre median position was located at respectively 50% (39-53%) and at 63% (50-74%) of the distance from the femoral condyle to the distal extremity of the MG superficial aponeurosis (Figure 4c).

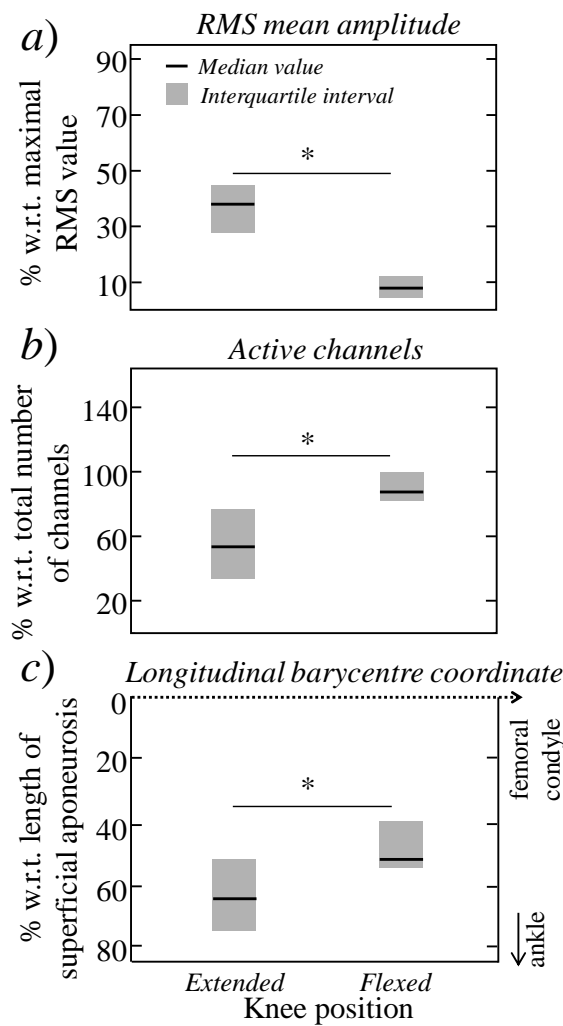


Figure 4. Changes in the spatial distribution of RMS values with knee position. Median values and interquartile intervals are shown for the RMS amplitude (a), the active channels (b) and the barycentre coordinate (c). These variables were respectively normalised with respect to the maximal RMS value obtained at 100% MVC attempts performed during knee extended position, the total number of channels located over the MG superficial aponeurosis and the distance between the femoral condyle and the distal extremity of the superficial aponeurosis (see Figure 1). Asterisks denote statistical significance at  $P < 0.05$ .

## **4.2 MG architectural changes revealed from US images**

Marked differences in MG architecture were observed when subjects moved their knee from extended to flexed position. As schematically illustrated in Figure 5 for a single, representative subject, the total muscle portion considered for analysis (Figure 1) was larger for knee flexed than extended condition. Specifically, the position of the distal extremity of the superficial aponeurosis shifted towards the most distal electrode with knee flexion (cf. the distance between the dashed, vertical lines shown in Figure 5). Moreover, flexing the knee from full extension to 90 deg led to a decrease in the length of MG fibres for both portions. Changes in knee position seem however to have affected more markedly the fibre length than the fat thickness and pinnation angle. Although the thickness of the subcutaneous tissue did not show clear changes with knee position, it was greater at the proximal than at the distal region (Figure 5).

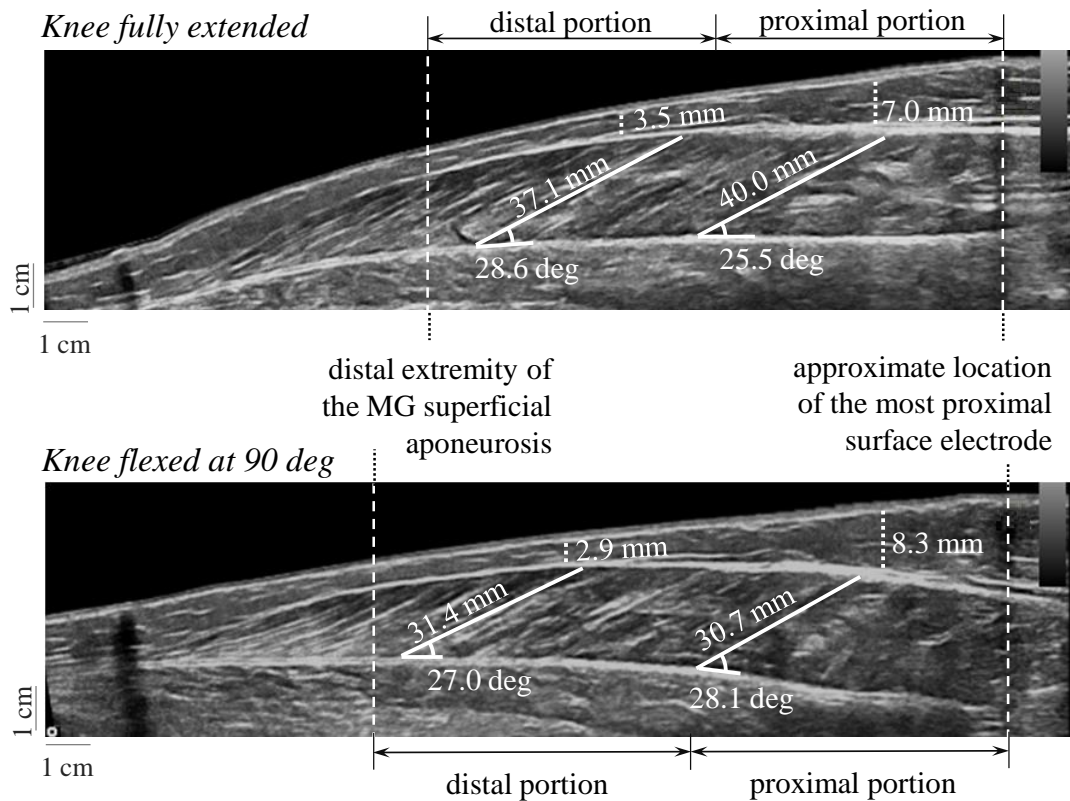


Figure 5. *Ultrasound images and gastrocnemius architecture.* The images shown in the top and bottom panels were collected with knee fully extended and flexed at 90 deg, respectively. Dashed lines superimposed on the images indicate the MG portion analysed, from the distal extremity of the superficial aponeurosis to the position of the most proximal electrode (see Figure 1). Dotted lines indicate estimates of subcutaneous thickness. Pinnation angles were estimated from each pair of white, solid lines; these lines were placed in correspondence of the deep aponeurosis and MG fascicles.

When considering all participants, the proximo-distal differences in MG architecture were not significantly associated with knee position. With knee extended, the fat tissue was significantly thicker proximally ( $6.5 \pm 2.4$  mm) than distally ( $3.5 \pm 1.9$  mm; Figure 6a; Tukey HSD post-hoc,  $P < 0.001$ ). Similarly, for the knee flexed position, estimates of fat thickness ( $7.4 \pm 3.4$  mm; Figure 6a) obtained from the MG proximal region were significantly greater than those obtained from the distal region ( $3.3 \pm 2.3$  mm; Tukey HSD post-hoc;  $P < 0.001$ ). These proximal-distal differences did not change however with knee position (ANOVA interaction effect;  $P = 0.37$   $N = 88$ ; 22 subjects x 2 MG regions x 2 knee positions). Regardless of the MG region considered, the proximal

( $32.0 \pm 5.6$  mm) and distal ( $34.0 \pm 5.4$  mm) values obtained for MG fibre length with knee flexed was significantly smaller than those observed for the proximal ( $42.0 \pm 6.8$  mm) and distal ( $43.2 \pm 8.5$  mm) MG regions with knee extended (Figure 6b; ANOVA main effect,  $P < 0.001$  for all cases). No significant interaction or additive effect of knee position and/or muscle region was observed for the MG pinnation angle (Figure 6c; ANOVA main and interaction effects;  $P > 0.27$  for all cases).

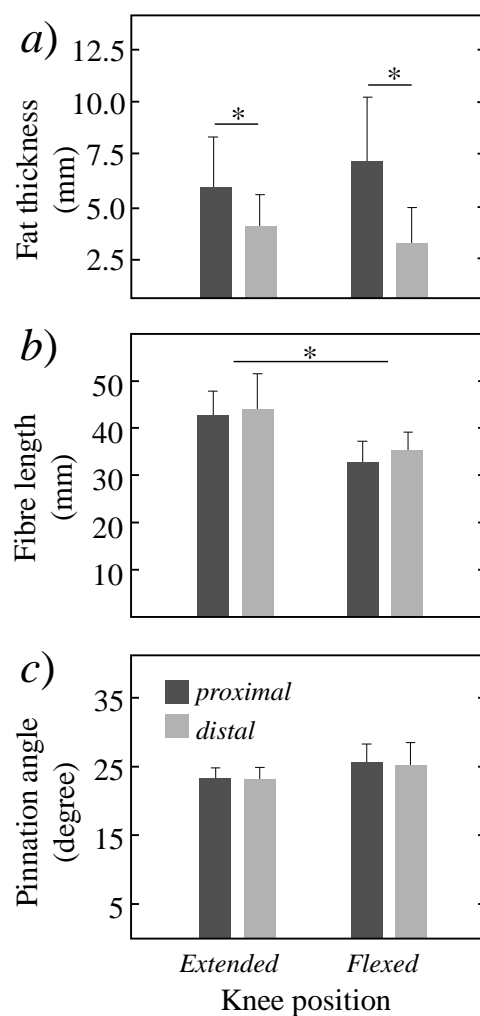


Figure 6. *Regional changes in gastrocnemius architecture with knee position.* Mean values and standard deviation (whiskers) are shown for the subcutaneous thickness (panel a), the MG fibre length (panel b), and their pinnation angle (panel c). These values were obtained from panoramic ultrasound images (see Figure 5), separately for the proximal (dark, shaded bars) and distal (light, shaded bars) muscle regions. Asterisks denote statistical differences at  $P < 0.05$ .

# Chapter 5

## Discussion

In this study we investigated whether changes in the amplitude distribution of surface EMGs detected from the MG muscle were associated with knee position. We further assessed whether variations in EMG amplitude may be explained by MG architectural changes. Our main finds revealed that: i) the distribution of EMG amplitude along the skin surface changed markedly with knee flexion; ii) proximo-distal differences in MG fibre length and pinnation angle, as well as in the fat thickness, whenever present, were not affected by knee position. These results suggest the redistribution of activity within the MG muscle, resulting from knee flexion, is unlikely related to anatomical factors.

### **5.1 EMG amplitude distribution rather than EMG amplitude is affected by knee position**

When flexing the knee by 90 deg from full extension, the amplitude of surface EMGs decreased markedly. Even though our subjects sustained plantar flexion torque at the same, relative effort level (60% MVC), the RMS amplitude of surface EMGs detected from the MG muscle was significantly lower with knee flexed than extended (Figure 4a). This observation is in agreement with previous accounts reporting diminished EMG amplitude in the MG muscle during isometric contractions performed with knee flexed (Arampatzis *et al.*, 2006; Wakahara *et al.*, 2007; Hahn *et al.*, 2011). A



common explanation for this reduction in EMG amplitude is the distribution of the neural input to ankle plantar flexors according to their mechanical efficiency (Kawakami *et al.*, 1998; Hahn *et al.*, 2011). With knee flexion, the gastrocnemius fibres shorten from their optimal length whereas the length of soleus fibres changes marginally (Kawakami *et al.*, 1998; Lauber *et al.*, 2014). It is therefore reasonable to expect the gastrocnemius muscle to be activated to a lesser degree with knee flexion than other plantar flexors. As we recorded EMGs exclusively from the MG muscle, we could not verify whether the decrease in RMS amplitude observed for MG was compensated by increased EMG amplitude in e.g., soleus muscle. It must be noted however we were focused on the distribution of activity within the MG muscle rather than on the load sharing between plantar flexor synergists. From our results, indeed, it seems questionable whether descriptors of EMG amplitude (e.g., RMS, average rectified value, and others) sufficiently characterise the changes in the neural drive to plantar flexors with knee flexion.

In addition to changes in the degree of MG activity, knee flexion seems to lead to a redistribution of activity within the MG muscle. With knee extended, surface EMGs with greater RMS amplitude were detected by a few channels, located at the more distal MG regions. During knee flexed, notwithstanding their smaller RMS amplitude in relation to knee extended position, surface EMGs with relatively greater RMS amplitude were observed over a larger, and more proximal, skin region (Figure 4c-b). These differences in the amplitude distribution of surface EMGs must be interpreted with respect to the MG pinnate architecture. From skin parallel-fibred muscles, the spread of the RMS amplitude distribution of surface EMGs reflects the length and the orientation of muscle fibres (Gallina *et al.*, 2013); in this case, surface EMGs detected by an array of electrodes sample from different, longitudinal sections of

the same muscle fibres. From muscles pinnate in depth direction, the distribution of RMS amplitude on the skin surface indicates the location and the number of active fibres within the muscle (Mesin *et al.*, 2011; Vieira *et al.*, 2011); in this case, surface EMGs detected by electrodes positioned consecutively over the muscle superficial aponeurosis sample from different muscle fibres. Presumably, therefore, results presented in Figure 4 suggest a marked difference in the distribution of active fibres within the MG muscle for different knee joint angles. With the knee fully extended, isometric plantar flexions seem to demand activation of fibres grouped at the MG distal region (Figure 3a). At the 90 deg knee flexed position, the active fibres seem to spread within the MG muscle, spanning a large proximo-distal region (Figure 3b). With different methodologies, other researchers obtained direct evidence on the uneven distribution of active fibres within the MG muscle, both during isometric (McLean and Goudy 2004) and dynamic plantar flexions (Kinugasa *et al.*, 2011). A corollary of current and previous findings is that the degree of MG activity, and by degree we intend the relative amount of active MG fibres, cannot be inferred exclusively from a given RMS amplitude; the relative number of MG active fibres is not directly related to the amplitude of surface EMGs detected on a small skin region. While this remains the subject of future investigations, here we are concerned with the potential causes and implications of the redistribution of MG activity with knee position.

## **5.2 Architectural differences within the gastrocnemius muscle unlikely explain the changes in activation with knee position.**

Previous researchers reported an uneven variation of MG fibre length in dynamic contractions. Lichtwark and collaborators (2007), for instance, observed greater fascicle shortening at the more distal MG regions during walking. Calf raising

exercises seem to also demand a greater shortening-lengthening of the more distal MG fascicles (Kinugasa *et al.*, 2005). It is therefore possible that the distribution of activation within the MG muscle and, thus, the distribution of EMG amplitude across channels in the array, could be shaped by proximo-distal differences in fibre shortening resulting from knee flexion. Potentially, in view of the MG force-length curve, the MG regions showing greater reductions in EMG amplitude with knee flexion would correspond to those exhibiting greater fibre shortening. Results shown in Figure 4 and 6, however, do not support this possibility. The amplitude of surface EMGs detected at the more distal MG regions decreased more strongly with knee flexion (Figure 4). If such uneven reduction in EMG amplitude was associated with fibre length, we would expect the fascicles residing in the MG distal region to shorten to a greater extent than the MG proximal fascicles when knee position changed from full extension to 90 deg flexion. Conversely though, and in agreement with Shin and colleagues (2009), with knee flexion, fascicles at the MG proximal and distal regions shortened by statistically equal amounts (Figure 6*b*). These results do not exclude a possible relationship between whole-MG fibre shortening and regional changes in MG activation, as discussed in the next subsection. Results presented in this study, on the other hand, do not support the hypothesis that regional changes in MG fibre length account for the regional changes in MG activation with knee flexion.

Alternative hypotheses positing the effect of anatomical factors on surface EMGs also do not explain the uneven variations in EMG amplitude observed from knee extended to flexed position. In the literature, it is well established that changes in EMG features may be not exclusively related to alterations in the neural input to pools of motor neurons of a given muscle (Farina *et al.*, 2002; Hug 2011). The thickness of subcutaneous tissue and the pinnation angle, for example, may affect markedly the

amplitude of surface EMGs. Theoretical and experimental accounts have, indeed, shown the amplitude of surface EMGs decrease with the thickness of the subcutaneous tissue interposed between the target muscle and the skin (Farina *et al.*, 2002; Kuiken *et al.*, 2003; Nordander *et al.*, 2003). For the 22 subjects tested in this study, the fat tissue covering the MG muscle was thicker at the more proximal regions (Figure 6a). On one hand, this suggests the amplitude of surface EMGs detected proximally was more attenuated by the fat tissue than that of EMGs recorded distally; i.e., the distance between electrodes and the superficial aponeurosis covering the proximal fascicles is greater proximally than distally. On the other hand, the proximo-distal difference in fat thickness did not depend on the knee position (Figure 6a). More specifically, the proximo-distal degree of attenuation of EMG amplitude, associated with the regional differences in subcutaneous thickness, unlikely explains the proximo-distal changes in RMS amplitude with knee position (Figures 3-4). A similar reasoning applies to MG pinnation angle. Sadly, the effect of pinnation angle on the amplitude distribution of surface EMGs is not so well documented as the fat tissue effect. Preliminary empirical data seems though to confirm theoretical evidence suggesting the spread of EMG amplitude distribution on the skin decreases with increases in pinnation angle, presuming a constant, neural drive to the MG muscle (Mesin *et al.*, 2011). In any case, regardless of the knee position considered, we did not observe significant proximo-distal differences in pinnation angle within the MG muscle (Figure 6c). Moreover, and contrarily to previous reports (Wakahara *et al.*, 2007), differences in MG pinnation angle from knee extended to flexed position did not reach statistical significance. Divergences between studies could be possibly related to methodological issues; in our study, an extended field of view was provided by the panoramic, ultrasound images and architectural measurements were made at rest. Collectively, rather than spurious

changes in the amplitude distribution of surface EMGs, our findings indicate that changes in knee position leads to a genuine alteration of the distribution of activity within the MG muscle.

### **5.3 What is the origin for the redistribution of activity within the gastrocnemius muscle with knee flexion?**

Different mechanisms could have contributed to triggering variations in activity within the MG muscle as the knee joint changed from extended to flexed position. The muscle mechanical efficiency, which is directly related with the length of MG fibres, has been suggested a crucial mechanism accounting for reduced MG activation with knee flexion (Kennedy and Cresswell 2001; Lauber *et al.*, 2014). If fibre length was the key mechanism underpinning changes in MG activation with knee position, then, the RMS distribution of surface EMGs (Figure 3) should have changed in amplitude rather than in shape; general decrease of fibre length within MG (Figures 5-6) should lead to a general decrease in RMS amplitude. According to our results, indeed, the contribution of fibre length to shaping MG activation seems less relevant than previously suggested. These results are in agreement though with the findings reported by Arampatzis and colleagues (2006). By mobilising the knee and ankle joints, Arampatzis *et al.*, (2006) observed significant reductions in the amplitude of surface EMGs collected from the gastrocnemius muscle without a corresponding, significant change in MG fibre length. It is therefore possible that sources other than fibre length substantially contribute to determining the net activation of the bi-articular, MG muscle. A potential candidate for sensing variations in knee joint and then providing key feedback information for the redistribution of activity within MG are the Achilles tendon receptors. During knee flexion, as shown in Figure 5 and as shown by others, the MG myotendinous junction

moves distally. Such distal shift progressively unloads the MG free tendon and the Achilles tendon, possibly explaining the increased muscle-tendon compliance with knee flexion (De Monte *et al.*, 2006). Considering the Achilles tendon compliance amounts to ~72% of the total muscle-tendon compliance (Farcy *et al.*, 2014), stiffening the Achilles tendon may thus be as important as, or perhaps more important than, relying on the MG fibre length for shaping whole muscle activation with knee flexion. In this view, distributing activity within the whole MG proximo-distal axis rather than within the MG most distal region (Figures 3-4) possibly optimises whole MG shortening and then Achilles tendon stiffening. In agreement with this hypothesis, with respect to rest condition, other researchers have reported greater increases in Achilles tendon length and greater shortening of the whole MG muscle when plantar flexion contractions were exerted with the knee in more flexed positions (Herbert *et al.*, 2002). In this study we did not evaluate variations in Achilles tendon length during rest and during contractions. However, our results suggest that, although the force-length curve may explain the reduced ankle torque with knee flexion (Hahn *et al.*, 2011), it unlikely exclusively accounts for the changes in activity within the MG muscle during isometric contractions performed at different knee positions. Here we anticipate that in addition to MG fibres length, the degree of tendon slack may constitute a potentially crucial source of feedback for the distribution of activity within the MG muscle.

# References

- ARAMPATZIS, A., KARAMANIDIS, K., STAFILIDIS, S., *et al.*, 2006, "Effect of different ankle- and knee-joint positions on gastrocnemius medialis fascicle length and EMG activity during isometric plantar flexion." *Journal of Biomechanics*, v. 39, n. 10, p.p 1891-1902. doi: 10.1016/j.jbiomech.2005.05.010
- CHOW, R.S., MEDRI, M.K., MARTIN, D.C., *et al.*, 2000, "Sonographic studies of human soleus and gastrocnemius muscle architecture: gender variability." *European Journal of Applied Physiology*, v. 82, n. 3, p.p 236-244.
- CRESSWELL, A.G., LÖSCHER, W.N., THORSTENSSON, A., 1995, "Influence of gastrocnemius muscle length on triceps surae torque development and electromyographic activity in man." *Experimental Brain Research*, v. 105, n. 2, p.p. 283-290. doi: 10.1007/BF00240964
- CRONIN, N.J., PELTONEN, J., SINKJAER, T., AVELA, J., 2010, "Neural compensation within the human triceps surae during prolonged walking." *Journal of Neurophysiology*, v. 105, n.2, p.p. 548-553. doi: 10.1152/jn.00967.2010
- DE MONTE, G., ARAMPTAZIS, A., STOGIANNARI, C., KARAMANIDIS, K., 2006, "In vivo motion transmission in the inactive gastrocnemius medialis muscle-tendon unit during angle and knee joint rotation." *Journal of Electromyography and Kinesiology*, v. 16, n. 5, p.p. 413-422. doi: 10.1016/j.jelekin.2005.10.001
- DE RUITER, C.J., DE HAAN, A., SARGEANT, A.J., 1995, "Physiological characteristics of two extreme muscle compartments in gastrocnemius medialis of

the anaesthetized rat." *Acta Physiologica Scandinavica*, v. 153, n. 4, p.p. 313-324.

doi: 10.1111/j. 1748-1716.1995.tb09869.x

FARCY, S., NORDEZ, A., DOREL, S., *et al.*, 2014, "Interaction between gastrocnemius medialis fascicle and Achilles tendon compliance: a new insight on the quick-release method." *Journal of Applied Physiology*, v. 116, n. 3, p.p. 259-266. doi: 10.1152/jappphysiol.00309.2013

FARINA, D., CESCO, C., MERLETTI, R., 2002 "Influence of anatomical, physical, and detection-system parameters on surface EMG." *Biological Cybernetics*, v. 86, n. 6, p.p. 445-456. doi: 10.1007/s00422-002-0309-2

FERGUSON, R.A., BALL, D., KRUSTRUP, P., *et al.*, 2001, "Muscle oxygen uptake and energy turnover during dynamic exercise at different contraction frequencies in humans." *Journal of Physiology*, v. 536, n. 1, p.p. 261-271. doi: 10.1111/j.1469-7793.2001.00261.x

FUKUNAGA, T., ROY, R.R., SHELLOCK, F.G., *et al.*, 1992, "Physiological cross-sectional area of human leg muscles based on magnetic resonance imaging." *Journal of Orthopaedic Research*, v. 10, n. 6, p.p. 926-934.

GALLINA, A., MERLETTI, R., GAZZONI, M., 2013, "Uneven spatial distribution of surface EMG: what does it mean?" *European Journal of Applied Physiology*, v. 113, n. 4, p.p. 887-894. doi: 10.1007/s00421-012-2498-2

GALLINA, A., MERLETTI, R., VIEIRA, T.M.M., 2011, "Are the myoelectric manifestations of fatigue distributed regionally in the human medial gastrocnemius muscle?" *Journal of Electromyography and Kinesiology*, v. 21, n. 6, p.p. 929-938. doi:10.1016/j.jelekin.2011.08.006



- HAHN, D., OLVERMANN, M., RICHTBERG, J., *et al.*, 2011, "Knee and ankle joint torque–angle relationships of multi-joint leg extension." *Journal of Biomechanics*, v. 44, n. 11, p.p. 2059-2065. doi: 10.1016/j.jbiomech.2011.05.011
- HERBERT, R.D., MOSELEY, A.M., BUTLER, J.E., GANDEVIA, S.C., 2002, "Change in length of relaxed muscle fascicles and tendons with knee and ankle movement in humans." *The Journal of Physiology*, v. 539, n. 2, p.p. 637-645. doi: 10.1113/jphysiol.2001.012756
- HODSON-TOLE, E.F., LORAM, I.D., VIEIRA, T.M.M., 2013, "Myoelectric activity along human gastrocnemius medialis: Different spatial distributions of postural and electrically elicited surface potentials." *Journal of Electromyography Kinesiology*, v. 23, n. 1, p.p. 43-50. doi: 10.1016/j.jelekin.2012.08.003
- HUG, F., 2011, "Can muscle coordination be precisely studied by surface electromyography?" *Journal of Electromyography and Kinesiology*, v. 21, n. 1, p.p. 1-12. doi:10.1016/j.jelekin.2010.08.009
- KAWAKAMI, Y., ICHINOSE, Y., FUKUNAGA, T., 1998 "Architectural and functional features of human triceps surae muscles during contraction." *Journal of Applied Physiology*, v. 85, n. 2, p.p. 398-404.
- KENNEDY, P.M., CRESSWELL, A.G., 2001, "The effect of muscle length on motor-unit recruitment during isometric plantar flexion in humans." *Experimental Brain Research*, v. 137, n. 1, p.p. 58-64. doi: 10.1007/s002210000623
- KINUGASA, R., KAWAKAMI, Y., FUKUNAGA, T., 2005, "Muscle activation and its distribution within human triceps surae muscles." *Journal of Applied Physiology*, v. 99, n. 3, p.p. 1149-1156. doi:10.1152/jappphysiol.01160.2004

- KINUGASA, R., KAWAKAMI, Y., SINHA, S., FUKUNAGA, T., 2011, "Unique spatial distribution of in vivo human muscle activation." *Experimental Physiology*, v. 96, n. 9, p.p. 938-948. doi: 10.1113/expphysiol.2011.057562
- KUIKEN, T.A., LOWERY, M.M., STOYKOV, N.S., 2003, "The effect of subcutaneous fat on myoelectric signal amplitude and cross-talk." *Prosthetics and Orthotics International*, v. 27, n. 1, p.p. 48-54. doi: 10.3109/03093640309167976
- LAUBER, B., LICHTWARK, G.A., CRESSWELL, A.G., 2014, "Reciprocal activation of gastrocnemius and soleus motor units is associated with fascicle length change during knee flexion." *Physiological Reports*, v. 2, n. 6, p.p. e12044. doi: 10.14814/phy2.12044
- LICHTWARK, G.A., BOUGOULIAS, K., WILSON, A.M., 2007, "Muscle fascicle and series elastic element length changes along the length of the human gastrocnemius during walking and running." *Journal of Biomechanics*, v. 40, n. 1, p.p. 157-164. doi: 10.1016/j.jbiomech.2005.10.035
- MCLEAN, L., GOUDY, N., 2004, "Neuromuscular response to sustained low-level muscle activation: within-and between-synergist substitution in the triceps surae muscles." *European Journal of Applied Physiology*, v. 91, n. 2-3, p.p. 204-216. doi:10.1007/s00421-003-0967-3
- MESIN, L., MERLETTI, R., VIEIRA, T.M.M., 2011 "Insights gained into the interpretation of surface electromyograms from the gastrocnemius muscles: A simulation study." *Journal of Biomechanics*, v. 44, n. 6, p.p. 1096-1103. doi: 10.1016/j.jbiomech.2011.01.031
- MIAKI, H., SOMEYA, F., TACHINO, K., 1999, "A comparison of electrical activity in the triceps surae at maximum isometric contraction with the knee and ankle at

- various angles." *European Journal of Applied Physiology and Occupational Physiology*, v. 80, n. 3, p.p. 185-191. doi: 10.1007/s004210050580
- NORDANDER, C., WILLNER, J., HANSSON, G.Å., *et al.*, 2003, "Influence of the subcutaneous fat layer, as measured by ultrasound, skinfold calipers and BMI, on the EMG amplitude." *European Journal of Applied Physiology*, v. 89, n. 6, p.p. 514-519. doi: 10.1007/s00421-003-0819-1
- NOURBAKHS, M.R., KUKULKA, C.G., 2004, "Relationship between muscle length and moment arm on EMG activity of human triceps surae muscle." *Journal of Electromyography and Kinesiology*, v. 14, n. 2, p.p. 263-273. doi: 10.1016/S1050-6411(03)00076-2
- SHIN, D.D., HODGSON, J.A., EDGERTON, V.R., SINHA, S., 2009, "In vivo intramuscular fascicle-aponeuroses dynamics of the human medial gastrocnemius during plantarflexion and dorsiflexion of the foot." *Journal of Applied Physiology*, v. 107, n. 4, p.p. 1276-1284. doi: 10.1152/jappphysiol.91598.2008
- STAUDENMANN, D., KINGMA, I., DAFFERTSHOFER, A., *et al.*, 2009, "Heterogeneity of muscle activation in relation to force direction: A multi-channel surface electromyography study on the triceps surae muscle." *Journal of Electromyography and Kinesiology*, v. 19, n. 5, p.p. 882-895. doi: 10.1016/j.jelekin.2008.04.013
- TAMAKI, H., KITADA, K., KURATA, H., *et al.*, 1997, "Electromyogram patterns during plantarflexions at various angular velocities and knee angles in human triceps surae muscles." *European Journal of Applied Physiology and Occupational Physiology*, v. 75, n. 1, p.p. 1-6. doi: 10.1007/s004210050118
- VIEIRA, T.M., LORAM, I.D., MUCELI, S., MERLETTI, R., FARINA, D., 2011, "Postural activation of the human medial gastrocnemius muscle: are the muscle

units spatially localised?" *The Journal of Physiology*, v. 589, n. 2, p.p. 431-443.

doi: 10.1113/jphysiol.2010.201806

VIEIRA, T.M.M., MERLETTI, R., MESIN, L., 2010b, "Automatic segmentation of surface EMG images: Improving the estimation of neuromuscular activity."

*Journal of Biomechanics*, v. 43, n. 11, p.p. 2149-2158. doi:

10.1016/j.jbiomech.2010.03.049

VIEIRA, T.M.M., WINDHORST, U., MERLETTI, R., 2010a, "Is the stabilization of quiet upright stance in humans driven by synchronized modulations of the activity of medial and lateral gastrocnemius muscles?" *Journal of Applied Physiology*, v.

108, n. 1, p.p. 85-97. doi: 10.1152/jappphysiol.00070.2009

WAKAHARA, T., KANEHISA, H., KAWAKAMI, Y., FUKUNAGA, T., 2007,

"Fascicle behaviour of medial gastrocnemius muscle in extended and flexed knee positions." *Journal of Biomechanics*, v. 40, n. 10, p.p. 2291-2298. doi:

10.1016/j.jbiomech.2006.10.006

WU, G., *et al.*, 2002, "ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion—part I: ankle, hip, and spine." *Journal of Biomechanics*, v. 35, n. 4, p.p. 543-548. doi: 10.1016/S0021-

9290(01)00222-6