Atlas of the muscle motor points for the lower limb: implications for electrical stimulation procedures and electrode positioning

Alberto Botter · Gianmosè Oprandi · Fabio Lanfranco · Stefano Allasia · Nicola A. Maffiuletti · Marco Alessandro Minetto

Abstract The aim of the study was to investigate the uniformity of the muscle motor point location for lower limb muscles in healthy subjects. Fifty-three subjects of both genders (age range: 18–50 years) were recruited. The muscle motor points were identified for the following ten muscles of the lower limb (dominant side): vastus medialis, rectus femoris, and vastus lateralis of the quadriceps femoris, biceps femoris, semitendinosus, and semimembranosus of the hamstring muscles, tibialis anterior, peroneus longus, lateral and medial gastrocnemius. The muscle motor point was identified by scanning the skin surface with a stimulation pen electrode and corresponded to the location of the skin area above the muscle in which an electrical pulse evoked a muscle twitch with the least injected current. For each investigated muscle, 0.15 ms square pulses were delivered through the pen electrode at low current amplitude (<10 mA) and frequency (2 Hz). 16 motor points were identified in the 10 investigated muscles of almost all subjects: 3 motor points for the vastus lateralis, 2 motor points for rectus femoris, vastus medialis, biceps femoris, and tibialis anterior, 1 motor point for the remaining muscles. An important inter-individual variability was observed for the position of the following 4 out of 16 motor points: vastus lateralis (proximal), biceps femoris (short head), semimembranosus, and medial gastrocnemius. Possible implications for electrical stimulation procedures and electrode positioning different from those commonly applied for thigh and leg muscles are discussed.

Keywords Neuromuscular electrical stimulation · Motor entry point · Motor branch · Lower limb

Introduction

Neuromuscular electrical stimulation (NMES) involves the transcutaneous application of electrical stimuli to superficial skeletal muscles, with the main objective to trigger visible muscle contractions due to the activation of motor neuron axons or intramuscular axonal branches (Hultman et al. 1983).

Two stimulation techniques are commonly used for NMES-based testing and training of the neuromuscular function: they are referred to as monopolar and bipolar stimulation. The differences between these two techniques are mainly related to the geometry and relative position of the stimulation electrodes over the skin area. In the monopolar configuration, two electrodes of different dimensions are used and the stimulation takes place in the
proximity of only one of the two electrodes and not at the other (Merletti et al. 1992). The active stimulation electrode (usually called “negative” electrode) has small dimensions (usually a few square centimeters) and is located either near a nerve (nerve stimulation) or above a muscle motor point (muscle stimulation). The second electrode (usually called “reference” or “dispersive” or “positive” or “return” electrode) is larger than the active electrode (around tens of square centimeters) and is generally placed over the antagonist muscle or opposite to the active electrode. With this electrode configuration, for a certain current level, the current density in the proximity of the active electrode may exceed the excitation level of the axons/axonal branches, whereas the large dimensions of the reference electrode assure that in its proximity the current density remains below their excitation threshold. Therefore, this technique allows the stimulation of localized populations of superficial motor units. In the bipolar arrangement, two electrodes of similar dimensions are applied over the muscle. With respect to the monopolar stimulation, current distribution is more confined in space and current density is more uniform along the current path. Another difference between the two configurations is the number of electrodes needed for a multichannel stimulation: in the monopolar arrangement there is only one reference electrode shared by all the active ones, while in the bipolar case each active electrode has its own reference electrode. In both monopolar and bipolar muscle stimulation, the position of the stimulation electrodes is a critical issue: a proper electrode positioning over the main muscle motor points is necessary to optimize the stimulation paradigm, that is, to maximize muscle tension and therefore force output (Gobbo et al. 2011) and avoid/minimize discomfort.

Muscle motor point, also known as motor entry point, represents the location where the motor branch of a nerve enters the muscle belly. It can be non-invasively identified by NMES as the skin area above the muscle in which an electrical pulse evokes a visible muscle twitch with the least injected current. Its precise localization is paramount not only for proper positioning of the stimulation electrodes, but also for improving therapeutic effectiveness and minimizing complications of anesthetic or neurolytic motor nerve blocks (Karaca et al. 2000). Despite the pervasive diffusion of anatomic motor point charts (Prentice 2005; Reid 1920), that are often provided with the user manuals of commercially available stimulators, the uniformity of the motor point position for lower limb muscles has never been investigated in a large group of healthy subjects. Therefore, the aim of this study was to assess the inter-individual variability of muscle motor point positions. Some of these data have been presented in abstract form (Oprandi et al. 2010).

Materials and methods

Subjects

Fifty-three healthy subjects of both genders (28 males, 25 females; age range: 18–50 years; body mass, mean ± SD: 64.4 ± 11.4 kg; stature: 1.69 ± 0.08 m; body mass index: 22.5 ± 3.5 kg/m²) volunteered to participate in the study. They were free from neuromuscular or skeletal impairments. Health status was assessed by medical history, physical exam, blood count and chemistry, urinalysis, and electrocardiogram. The subjects received a detailed explanation of the procedures and gave written informed consent prior to participation. The study conformed with the guidelines in the Declaration of Helsinki and was approved by the local ethics committee.

Motor point identification, stimulation technique, and ultrasound examination

The muscle motor points were identified for the dominant side of ten muscles of the lower limb (see the list in Table 1). The motor points were identified while the subjects were positioned as follows: (a) seated, with the knee angle at 90°, for the investigation of the quadriceps muscles; (b) prone, with the knee fully extended and the ankle at 150° (180° corresponded to full plantar flexion), for the investigation of the hamstring muscles and gastrocnemii; (c) supine, with the knee fully extended and the ankle at 150° (180° corresponded to full plantar flexion), for the investigation of the tibialis anterior and peroneus longus muscles.

For each muscle, the position of the identified motor points was determined as absolute and relative distances along a reference line which was measured between a proximal and a distal anatomical landmark (see the list in Table 1).

The muscle motor points corresponded to the locations of the skin area above the muscle in which an electrical pulse evoked a muscle twitch (as determined by visual inspection and manual palpation of the muscle and its proximal or distal tendon) with the least injected current. These locations were identified by scanning the skin surface with a stimulation pen electrode (small size cathode: 1 cm² surface; Globus Italia, Codognè, Italy) and with a large (50 × 80 mm) reference electrode placed over the antagonist muscle to close the stimulation current loop (monopolar stimulation). The pen electrode was moved over the skin, while the stimulation current was slowly increased (starting from 1 to 2 mA) by the operator until a clear muscle twitch could be observed. Then, the stimulation current was decreased to a value that could still elicit a small mechanical response of the muscle. This motor point
The position was temporarily marked with ink and subsequently measured with respect to the reference line. The position of the reference electrode was the following: (a) just above the popliteal cavity/patella for the investigation of the quadriceps/hamstring muscles, respectively; (b) just below the tibial tuberosity/popliteal cavity for the investigation of the gastrocnemii/tibialis anterior and peroneus longus muscles, respectively. For all muscles and subjects, 0.15 ms square pulses were delivered through the pen electrode at a frequency of 2 Hz: the minimum current amplitude required to produce a visible contraction was 10 mA. Electrical stimulation was provided by a constant-current stimulator (DS7A, Digitimer Ltd, Welwyn Garden City, England).

Since the thickness of the subcutaneous layer significantly affects the effectiveness of the stimulation (and therefore the detectability of the muscle motor points), it was measured by ultrasonography (FFSonic UF-4000L, 7.5 MHz linear array transducer, Fukuda Denshi, Tokyo, Japan), at the position of the identified motor points, as the perpendicular distance between the bottom of the skin and the superficial fascial layers, excluding the superficial aponeurosis (Nordander et al. 2003). A water-soluble transmission gel was placed over the head of the probe to increase acoustic coupling. Care was taken to exert minimal pressure to avoid compression of the underlying tissues. For the different muscles, the mean values of the subcutaneous layer thickness (Table 1) were comparable to previously reported data for normal weight subjects (Davies et al. 1986; Jones et al. 1986; Wallner et al. 2004).

### Table 1: Muscles, anatomical landmarks, and thickness of the subcutaneous layer are reported

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Proximal–distal anatomical landmarks of the reference line</th>
<th>Average (±SD) values of subcutaneous layer thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vastus lateralis: proximal motor point</td>
<td>Anterior superior iliac spine–superolateral border of the patella</td>
<td>10 ± 5</td>
</tr>
<tr>
<td>Vastus lateralis: central motor point</td>
<td>Apex of greater trochanter–superolateral border of the patella</td>
<td>7 ± 3</td>
</tr>
<tr>
<td>Vastus lateralis: distal motor point</td>
<td>Apex of greater trochanter–superolateral border of the patella</td>
<td>7 ± 3</td>
</tr>
<tr>
<td>Rectus femoris: proximal motor point</td>
<td>Anterior superior iliac spine–superior border of the patella</td>
<td>10 ± 5</td>
</tr>
<tr>
<td>Rectus femoris: distal motor point</td>
<td>Anterior superior iliac spine–superior border of the patella</td>
<td>10 ± 4</td>
</tr>
<tr>
<td>Vastus medialis: proximal motor point</td>
<td>Anterior superior iliac spine–superomedial border of the patella</td>
<td>8 ± 3</td>
</tr>
<tr>
<td>Vastus medialis: distal motor point</td>
<td>Anterior superior iliac spine–joint space in front of the anterior border of the medial collateral ligament</td>
<td>6 ± 3</td>
</tr>
<tr>
<td>Biceps femoris: long head</td>
<td>Ischial tuberosity–apex of the fibular head</td>
<td>12 ± 4</td>
</tr>
<tr>
<td>Biceps femoris: short head</td>
<td>Ischial tuberosity–apex of the fibular head</td>
<td>9 ± 4</td>
</tr>
<tr>
<td>Semitendinosus</td>
<td>Ischial tuberosity–medial epicondyle of the tibia</td>
<td>10 ± 4</td>
</tr>
<tr>
<td>Semimembranosus</td>
<td>Ischial tuberosity–medial epicondyle of the tibia</td>
<td>7 ± 3</td>
</tr>
<tr>
<td>Tibialis anterior: proximal motor point</td>
<td>Apex of the fibular head–apex of the medial malleolus</td>
<td>5 ± 2</td>
</tr>
<tr>
<td>Tibialis anterior: distal motor point</td>
<td>Apex of the fibular head–apex of the medial malleolus</td>
<td>4 ± 2</td>
</tr>
<tr>
<td>Peroneus longus</td>
<td>Apex of the fibular head–apex of the lateral malleolus</td>
<td>5 ± 2</td>
</tr>
<tr>
<td>Medial gastrocnemius</td>
<td>Medial knee joint line–posterior superior portion of the calcanea tuberosity</td>
<td>7 ± 2</td>
</tr>
<tr>
<td>Lateral gastrocnemius</td>
<td>Apex of the fibular head–posterior superior portion of the calcanea tuberosity</td>
<td>6 ± 2</td>
</tr>
</tbody>
</table>

Motor point positions along the reference lines are reported in both absolute (mean ± SD) and percentage values in relation to the total length of the reference line, starting from the proximal or distal anatomical landmark (that corresponded to a landmark of the knee joint for most of the investigated muscles).

The uniformity (across all subjects) of the motor point position along the reference line was estimated for each muscle on the basis of the spread (standard deviation, SD) of the normalized motor point position: normalization was
done with respect to the estimated length of the muscle (i.e., average length of the reference line/2 for the short head of the biceps femoris; average length of the reference line for all the other muscles). We arbitrarily defined “good” uniformity for values <4%, “fair” uniformity for values in the range 4–6%, and “poor” uniformity for values >6%. To verify the statistical significance of the differences among these three uniformities, we adopted the $F$ test (MedCalc Software, Mariakerke, Belgium) for comparing the standard deviations (of the normalized motor point positions) of different motor points identified in each muscle.

Results

Sixteen motor points were identified in the ten investigated muscles of almost all subjects: the average positions of these motor points along the respective reference lines and their uniformity are reported in Table 2.

Three different motor points were identified for the vastus lateralis muscle: a proximal motor point (blue circles in Fig. 1a) was identified in 51 out of 53 subjects, a central motor point (white circles in Fig. 1a) was identified in 42 out of 53 subjects, and a distal motor point (yellow circles in Fig. 1a) was identified in all subjects. Visual inspection and manual palpation of the muscle and its patellar tendon during stimulation allowed to distinguish among these different motor points which activated different muscle portions (identified along the reference line from the proximal to distal aspect of the muscle): stimulation of the proximal motor point excited muscle fibers located proximally and medially, stimulation of the distal motor point excited fibers located distally and laterally, and stimulation of the central motor point excited fibers located in an intermediate position.

Two different motor points were identified for the rectus femoris muscle: a proximal motor point (blue circles in Fig. 1b) was identified in all subjects and a distal motor point (yellow circles in Fig. 1b) was identified in 52 out of 53 subjects. Proximal and distal stimulation excited fibers located laterally and medially to the reference line, respectively.

Table 2: Muscles, number of cases, average positions of the motor points and their uniformity are reported

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Number of cases</th>
<th>Average (±SD) position of the motor point along the reference line (cm)</th>
<th>Average (95% confidence limits) position of the motor point along the reference line (%)</th>
<th>Uniformity of the motor point position (%)</th>
<th>$F$ statistics (significance level)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vastus lateralis: proximal motor point</td>
<td>51</td>
<td>22.5 (±4.1)$^a$</td>
<td>50.3 (47.7–53.1)$^a$</td>
<td>9.6 Poor</td>
<td>$F = 2.61$ $(P = 0.002)$</td>
</tr>
<tr>
<td>Vastus lateralis: central motor point</td>
<td>42</td>
<td>15.0 (±3.2)$^b$</td>
<td>34.3 (29.5–39.1)$^b$</td>
<td>6.0 Fair</td>
<td>$F = 3.79$ $(P &lt; 0.001)$</td>
</tr>
<tr>
<td>Vastus lateralis: distal motor point</td>
<td>53</td>
<td>9.5 (±1.6)$^b$</td>
<td>20.6 (19.7–21.4)$^b$</td>
<td>3.1 Good</td>
<td></td>
</tr>
<tr>
<td>Rectus femoris: proximal motor point</td>
<td>53</td>
<td>24.8 (±2.8)$^b$</td>
<td>53.2 (51.8–54.6)$^b$</td>
<td>5.1 Fair</td>
<td>$F = 1.10$ $(P = 0.73)$</td>
</tr>
<tr>
<td>Rectus femoris: distal motor point</td>
<td>52</td>
<td>16.0 (±2.4)$^b$</td>
<td>35.8 (34.5–37.2)$^b$</td>
<td>4.9 Fair</td>
<td></td>
</tr>
<tr>
<td>Vastus medialis: proximal motor point</td>
<td>53</td>
<td>10.3 (±1.6)$^b$</td>
<td>22.7 (21.8–23.6)$^b$</td>
<td>3.3 Good</td>
<td>$F = 1.53$ $(P = 0.13)$</td>
</tr>
<tr>
<td>Vastus medialis: distal motor point</td>
<td>53</td>
<td>7.5 (±1.3)$^b$</td>
<td>15.6 (14.9–16.4)$^b$</td>
<td>2.7 Good</td>
<td></td>
</tr>
<tr>
<td>Biceps femoris: long head</td>
<td>53</td>
<td>12.5 (±1.8)$^a$</td>
<td>33.5 (32.3–34.8)$^a$</td>
<td>4.5 Fair</td>
<td>$F = 10.22$ $(P &lt; 0.001)$</td>
</tr>
<tr>
<td>Biceps femoris: short head</td>
<td>53</td>
<td>13.2 (±2.6)$^b$</td>
<td>39.3 (37.4–41.4)$^b$</td>
<td>14.5 Poor</td>
<td></td>
</tr>
<tr>
<td>Semitendinosus</td>
<td>53</td>
<td>13.6 (±2.0)$^a$</td>
<td>37.5 (36.1–39.0)$^a$</td>
<td>5.3 Fair</td>
<td>–</td>
</tr>
<tr>
<td>Semimembranosus</td>
<td>53</td>
<td>15.5 (±2.5)$^b$</td>
<td>42.6 (40.1–44.4)$^b$</td>
<td>6.5 Poor</td>
<td>–</td>
</tr>
<tr>
<td>Tibialis anterior: proximal motor point</td>
<td>52</td>
<td>10.5 (±1.6)$^a$</td>
<td>27.5 (26.4–28.7)$^a$</td>
<td>4.0 Fair</td>
<td>$F = 1.45$ $(P = 0.18)$</td>
</tr>
<tr>
<td>Tibialis anterior: distal motor point</td>
<td>52</td>
<td>16.5 (±1.9)$^a$</td>
<td>43.1 (41.8–44.4)$^a$</td>
<td>4.8 Fair</td>
<td></td>
</tr>
<tr>
<td>Peroneus longus</td>
<td>53</td>
<td>7.8 (±1.5)$^a$</td>
<td>20.2 (19.1–21.3)$^a$</td>
<td>3.9 Good</td>
<td>–</td>
</tr>
<tr>
<td>Medial gastrocnemius</td>
<td>53</td>
<td>10.1 (±2.6)$^a$</td>
<td>26.0 (24.2–26.7)$^a$</td>
<td>6.4 Poor</td>
<td>–</td>
</tr>
<tr>
<td>Lateral gastrocnemius</td>
<td>53</td>
<td>9.8 (±2.3)$^a$</td>
<td>25.3 (23.8–26.8)$^a$</td>
<td>5.5 Fair</td>
<td>–</td>
</tr>
</tbody>
</table>

Motor point position was measured starting from the $^a$ proximal or $^b$ distal anatomical landmark (landmarks are defined in Table 1)
Two different motor points were identified in all subjects for the vastus medialis muscle: a proximal motor point (blue circles in Fig. 1c) and a distal motor point (yellow circles in Fig. 1c). Proximal and distal stimulation excited fibers of the longus and obliquus portions of the muscle, respectively.

Two different motor points were identified in all subjects for the biceps femoris muscle: stimulation of the proximal motor point excited fibers of the long head (Fig. 2a), whereas stimulation of the distal motor point excited fibers of the short head (Fig. 2b).

Two different motor points were identified (by visual inspection and manual palpation of the muscle and its distal tendon during stimulation) in 52 out of 53 subjects for the tibialis anterior muscle: stimulation of the proximal motor point (blue circles in Fig. 3a) excited fibers located superficially and medially to the reference line, whereas stimulation of the distal motor point (yellow circles in Fig. 3a) excited fibers located deeply and laterally to the reference line.

One motor point was identified in all subjects for the other muscles investigated: semitendinosus (Fig. 2c), semimembranosus (Fig. 2d), peroneus longus (Fig. 3b), medial (blue circles in Fig. 3c) and lateral gastrocnemius (yellow circles in Fig. 3c).

An important inter-individual variability was observed for the position of the following 4 out of 16 motor points ("poor" uniformity of the motor point position): vastus lateralis (proximal), biceps femoris (short head), semimembranosus, and medial gastrocnemius. On the contrary, low variability was observed for the following 4 out of 16 motor points ("good" uniformity of the motor point position): vastus lateralis (distal), vastus medialis (proximal and distal), and peroneus longus (Table 2).

Discussion

Sixteen motor points were identified as maximum number in each subject and the uniformity of their position along the respective reference lines was quantified for ten lower limb muscles. Quadriceps and tibialis anterior muscles showed two or three motor points innervating different
muscle portions, whereas the other muscles showed only one motor point.

Motor point location and uniformity

The existence of three motor points for the vastus lateralis is in agreement with the anatomical dissection study by Sung et al. (2003) who found that the motor branch of the vastus lateralis branches out from the femoral nerve trunk and divides into two primary sub-branches that penetrate the medial surface of the muscle at the proximal (superior sub-branch) and distal (inferior sub-branch) one-third of the vastus lateralis, respectively (Fig. 4a). Moreover, in one case out of 22 cadaveric dissections (5%) they found three sub-branches of the vastus lateralis motor branch. In a recent anatomical investigation, Becker et al. (2010) showed that on the basis of architecture and innervation, the vastus lateralis comprises four partitions which were named the superficial proximal, deep proximal, central, and deep distal partitions. Each of these partitions was found to receive its unique nerve branch: two primary nerve branches (proximal and distal) which arise from the femoral nerve and subdivide in two secondary sub-branches (superficial proximal and deep proximal sub-branches from the proximal primary branch and mid-distal and distal sub-branches from the distal primary branch) were found in most of the specimens (Fig. 4b). We observed in almost all subjects two motor points (proximal and distal) and in the 80% of the subjects, an additional (central) motor point innervating an intermediate portion of the muscle. It may be hypothesized that the three motor points we identified in the vastus lateralis (by visual inspection and manual palpation of the muscle and its patellar tendon during stimulation) corresponded to the innervation pattern of the superficial proximal, central, and deep distal partitions and that the motor point of the deep proximal partition was not identified due to the deep course of the deep proximal secondary sub-branch. Alternatively, it may be hypothesized that the proximal motor point we identified corresponding to the entry point of the superficial proximal secondary sub-branch in some subjects and of the deep proximal secondary sub-branch in other subjects. This

![Fig. 2 Position of the motor points for the hamstring muscles in 53 healthy subjects, along the respective reference lines (continuous black lines): a long head of the biceps femoris; b short head of the biceps femoris; c semitendinosus; d semimembranosus. The arrows indicate the average positions of the motor points along the respective reference lines](image-url)
could explain the poor uniformity of the proximal motor point position observed in this study.

In the above-mentioned anatomical dissection study by Sung et al. (2003), it has also been shown that the motor branch of the rectus femoris divides into two sub-branches: (a) the superior sub-branch, which runs laterally under the posterior surface of the muscle and enters it on the posterior surface at a proximal one-third point of the rectus femoris; (b) the inferior sub-branch that pierces the muscle fascia at the medial border of the muscle and runs downward along the medial margin of the muscle. This finding is in agreement with our observation of two motor points for the rectus femoris whose stimulation activated different portions of the muscle.

The observation of two motor points for the vastus medialis is also in agreement with two anatomical studies (Thiranagama 1990; Lefebvre et al. 2006) in which the motor branch of the vastus medialis has been shown to divide into two sub-branches (Fig. 4c): (a) the short and lateral sub-branch supplying the proximal muscle fibers, that is the longus portion of the muscle (Lieb and Perry 1968; Travnik et al. 1995), and (b) the long and medial sub-branch supplying the distal fibers, that is the obliquus portion of the muscle (Lieb and Perry 1968; Travnik et al. 1995).

Only few anatomical studies investigated the motor point location for the hamstring muscles. Sunderland and Hughes (1946) and Seidel et al. (1996) studied the biceps femoris of adult cadaver limbs and found a dominant innervation pattern consisting of two primary motor branches issued from the sciatic nerve which supply the long head of the biceps femoris. Differently, An et al. (2010) showed in most of the examined muscles (41 out of 50 lower limbs from adult human cadavers) an innervation pattern consisting of one primary motor branch with the motor entry point located at ~40% of a reference line that connected the ischial tuberosity to the most proximal aspect of the medial femoral epicondyle. This result is in line with our observation of one motor point of the biceps femoris long head located at ~33% of a reference line that connected the ischial tuberosity to the apex of the fibular head. Our observation of one motor point of the biceps femoris short head at ~60% of the same reference line (starting from the proximal anatomical landmark) is also in agreement with the study of An et al. (2010) who observed one primary motor branch with the motor entry point located at ~56% of the reference line between ischial tuberosity and medial femoral epicondyle. They also found one primary motor branch for the semimembranosus with the motor entry point located at ~60% of the distance between ischial tuberosity and medial femoral epicondyle, in agreement with our observation of one motor point at ~60% of the distance between ischial tuberosity and medial epicondyle of the tibia (starting from the proximal anatomical landmark). Differently from our observation of one motor point for the semitendinosus muscle, An et al.
(2010) showed a dominant innervation pattern consisting of two primary motor branches supplying the upper and lower part of the muscle, with a proximal and a distal entry point located, respectively, at ~20 and ~60% of the distance between ischial tuberosity and medial femoral epicondyle. They also indicated that the motor entry point of the lower part of the semitendinosus and that of the semimembranosus were closely located to each other. Since the semimembranosus can be found at a deeper level than the semitendinosus, it may be hypothesized that the stimulation level we adopted to localize the motor point of the semimembranosus also activated the lower part of the more superficial semitendinosus. The inspection and palpation method we adopted has the advantages of simplicity and quickness. However, visual inspection of muscle contraction and surface palpation of semitendinosus and semimembranosus and their distal tendons could not aid in distinguishing between the two muscles. Accordingly, a localization of the distal motor point of the semitendinosus more precise than that obtained by the inspection and palpation method we adopted may be required.

The course of the tibial nerve has been widely studied. However, only a few authors investigated the course of its branches (which run under the vastus medialis and rectus femoris muscles). Yoo et al. (2002) performed the anatomic dissection of 40 cadaver knees and localized the motor points of the medial and lateral gastrocnemius muscles at an absolute distance of ~4.0 and ~3.5 cm, respectively, from the medial and lateral epicondyle of the femur. In another dissection study, Sook Kim et al. (2002) showed a dominant innervation pattern consisting of one motor branch supplying the lateral gastrocnemius and one motor branch supplying the medial gastrocnemius, with the respective motor entry points located at ~10% of the distance between the intercondylar and the intermalleolar line. The same authors also localized, in healthy subjects, the motor points of the medial and lateral gastrocnemius at ~12 and ~10% of the same distance, respectively (Lee et al. 2009). Further, Kim et al. (2005) showed that the motor points of the medial and lateral gastrocnemius were diffusely distributed along the longitudinal bulk of the two muscle heads: the range of motor point locations was from ~10 to ~37% of the distance between the intercondylar and the intermalleolar line for the medial gastrocnemius, and from ~12 to ~38% of the same distance for the lateral gastrocnemius. Consistently, we found an average

Fig. 4 Schematic view of the motor branches of the femoral nerve supplying the quadriceps muscle. a 1 Femoral nerve; 2 inguinal ligament; 3 motor branch of the rectus femoris; 4 motor branch of the vastus lateralis with its superior (5) and inferior (6) sub-branches; 7 motor branch of the vastus intermedius; 8 motor branch of the vastus medialis (adapted from Sung et al. 2003). Dotted lines indicate the deep course of the motor branch of the vastus lateralis and its sub-branches (adapted from Becker et al. 2010). b Short and lateral (1) and long and medial (2) sub-branches of the motor branch of the vastus medialis (adapted from Thiranagama 1990).

(2010) showed a dominant innervation pattern consisting of two primary motor branches supplying the upper and lower part of the muscle, with a proximal and a distal entry point located, respectively, at ~20 and ~60% of the distance between ischial tuberosity and medial femoral epicondyle. They also indicated that the motor entry point of the lower part of the semitendinosus and that of the semimembranosus were closely located to each other. Since the semimembranosus can be found at a deeper level than the semitendinosus, it may be hypothesized that the stimulation level we adopted to localize the motor point of the semimembranosus also activated the lower part of the more superficial semitendinosus. The inspection and palpation method we adopted has the advantages of simplicity and quickness. However, visual inspection of muscle contraction and surface palpation of semitendinosus and semimembranosus and their distal tendons could not aid in distinguishing between the two muscles. Accordingly, a localization of the distal motor point of the semitendinosus more precise than that obtained by the inspection and palpation method we adopted may be required.

The course of the tibial nerve has been widely studied. However, only a few authors investigated the course of its branches (which run under the vastus medialis and rectus femoris muscles). Yoo et al. (2002) performed the anatomic dissection of 40 cadaver knees and localized the motor points of the medial and lateral gastrocnemius muscles at an absolute distance of ~4.0 and ~3.5 cm, respectively, from the medial and lateral epicondyle of the femur. In another dissection study, Sook Kim et al. (2002) showed a dominant innervation pattern consisting of one motor branch supplying the lateral gastrocnemius and one motor branch supplying the medial gastrocnemius, with the respective motor entry points located at ~10% of the distance between the intercondylar and the intermalleolar line. The same authors also localized, in healthy subjects, the motor points of the medial and lateral gastrocnemius at ~12 and ~10% of the same distance, respectively (Lee et al. 2009). Further, Kim et al. (2005) showed that the motor points of the medial and lateral gastrocnemius were diffusely distributed along the longitudinal bulk of the two muscle heads: the range of motor point locations was from ~10 to ~37% of the distance between the intercondylar and the intermalleolar line for the medial gastrocnemius, and from ~12 to ~38% of the same distance for the lateral gastrocnemius. Consistently, we found an average

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position of the two gastrocnemius motor points at ~25% of respective reference lines, with poor (for medial gastrocnemius) or fair (for lateral gastrocnemius) uniformity across subjects.

The innervation of the tibialis anterior and peroneus longus muscles is provided by the common peroneal nerve which first originates from the sciatic nerve in the popliteal fossa region and travels across the lateral head of the gastrocnemius toward the fibular head, and then separates into the superficial and deep peroneal nerves. The superficial peroneal nerve innervates the peroneus longus and brevis muscles, while the deep peroneal nerve innervates the anterior leg muscles. In agreement with our findings, Lee et al. (2011) recently demonstrated that the motor entry points of the superficial peroneal nerve supplying the peroneus longus muscle were located from 10 to 60% of the distance between the apex of the fibular head and the apex of the lateral malleolus. To our knowledge, no previous study attempted to localize the motor points of the deep peroneal nerve to the tibialis anterior muscle. However, it has been shown that the muscles of the deep posterior compartment of the leg (popliteus, flexor hallucis longus, tibialis posterior, flexor digitorum longus) are innervated by one or two primary motor branches arising from the tibial nerve (Apaydin et al. 2008). Similarly, it is not surprising that the tibialis anterior muscle had more than one motor point in our study, which could correspond to the entry points of different nerve branches supplying different portions of the muscle. In fact, the bipennate muscle architecture (Maganaris and Baltzopoulos 1999) could imply that the superficial and deep unipennate parts have a distinct pattern of innervation: this hypothesis is in agreement with our observation of a differential activation of the superficial and deep portion of the muscle following stimulation of the proximal and distal motor point, respectively.

Implications for electrical stimulation procedures and electrode positioning

The demonstration that different motor points can be identified in the three superficial muscles of the quadriceps, the most often stimulated muscle for NMES rehabilitation, “prehabilitation”, and training purposes (Bax et al. 2005; Maffulli et al. 2010), may have relevant implications for the placement of stimulation electrodes. It is well-known that motor unit recruitment during NMES is spatially fixed (Bigland-Ritchie et al. 1979; Gregory and Bickel 2005), thus implying that the same muscle units are repeatedly activated by the same amount of electrical current, which, in turn, hastens the onset of muscle fatigue (Bigland-Ritchie et al. 1979; Binder-Macleod and Snyder-Mackler 1993). Such early occurrence of fatigue represents a major limitation of NMES. In order to maximize the spatial recruitment during NMES, thus minimizing the extent of muscle fatigue, it has been recommended to adopt different subterfuges during a treatment session such as the progressive increase in current intensity, alteration in muscle length, and displacement of active electrodes (Maffulli et al. 2010). The existence of different motor points within each of the three superficial heads of the quadriceps suggests that a change in the population of activated fibers could also be obtained through a multichannel stimulation technique that involves a non-synchronous activation of different muscle volumes. Consistently, Malesević et al. (2010) recently showed in paraplegic patients that NMES delivered to one quadriceps via multi-pad electrodes (one anode positioned at the distal part of the quadriceps and four cathodes distributed over the quadriceps muscles) delayed the occurrence of fatigue with respect to a conventional stimulation (one electrode positioned over the top of the quadriceps and the other over the distal part of the muscle).

Besides neuromuscular training, NMES finds application in the in vivo assessment of muscle contractile properties, fatigue profile, and level of voluntary activation (Maffulli et al. 2010). For example, supramaximal stimulation of the femoral nerve during a maximal voluntary contraction is an established technique for the assessment of quadriceps activation (Gandevia 2001). Place et al. (2010) recently showed that quadriceps muscle belly stimulation can be used to assess the level of voluntary activation as a valid alternative to the femoral nerve stimulation that may be associated with discomfort and/or stimulation electrode displacement during the voluntary effort. It may be hypothesized that a multichannel NMES technique performed with several electrodes placed over the different motor points of the superficial heads of quadriceps can increase the validity of the neuromuscular testing and minimize subjective discomfort.

Electrical stimulation of the gastrocnemii is usually performed with two large rectangular electrodes placed below the popliteal cavity and over the distal portion of the two muscle heads, with the major side of the electrodes perpendicular to the longitudinal axis of the triceps surae (Bergquist et al. 2011). On the basis of the motor point distribution we found in the gastrocnemii, it may be proposed that an alternative placement of the electrodes (one over the lateral head and the other over the medial head), with their major side parallel to the muscle longitudinal axis, can be used as a valid and more effective alternative to the usual electrode placement.

Finally, the existence of two distinct motor points could imply that the tibialis anterior has to be stimulated with the two electrodes located above both motor points in case of bipolar arrangement, or with the active electrode properly
positioned over the main motor point in case of monopolar stimulation.

However, it is not possible to infer from the present data if these electrode configurations or the above-mentioned multichannel stimulation can improve the effectiveness of the electrical stimulation procedures. Further studies comparing the electromechanical responses obtained by different stimulation sites and modalities are required to resolve elements of confusion and controversy and improve standardization of electrical stimulation procedures.

In conclusion, this study demonstrates that muscle motor points can be easily and quickly localized in the lower limb through visual inspection and manual palpation of the muscle during electrical stimulation and that an inter-individual variability in the motor point position exists and may limit the usefulness of the anatomic motor point charts, especially for posterior thigh and leg muscles.

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References


Seidel PM, Seidel GK, Gans BM, Dijikers M (1996) Precise localization of the motor nerve branches to the hamstring...