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Research Article

Does Electrode Sensor Positioning over Motor Points Affect Different Portions of Quadriceps Muscle Architecture during Submaximal Evoked Torque?

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Background and Objectives. Few studies have evaluated differences in muscle architecture in quadriceps femoris constituents with sensor electrodes positioned over vastus lateralis (VL) and vastus medialis (VM) motor points during a neuromuscular electrical stimulation (NMES) session. We aimed to investigate the changes in muscle architecture of the rectus femoris (RF), VL, VM, and vastus intermedius (VI) portions during evoked contractions with sensor electrodes placed over VL and VM motor points. *Materials and Methods*. The study is a crossover, repeated-measure design, conducted with healthy males aged 24.0 ± 4.6 years. Ultrasonography at rest and evoked contraction at 40% of maximum voluntary contraction (MVC) were used to assess the pennation angle (θp) and fascicle length (Lf) of RF, VL, VM, and VI portions. *Results*. The mean torque observed was 201.14 ± 50.22 N.m during MVC and at 40% of MVC was 80.45 ± 20.08 N.m. There was no difference for θp comparing four components of the quadriceps femoris ($p = 0.27$). There was a significant ($p < 0.05$) muscle evoked contraction interaction for Lf without relevant clinical importance to the study. *Conclusions*. There is no difference in the changes in the muscle architecture of quadriceps femoris constituents during stimulation with the electrodes placed on the VL and VM motor points. Therefore, clinicians can choose either VL or VM motor points for sensor electrode positioning and expect similar muscle architecture adaptation for a given evoked torque. Future clinical studies should be conducted to establish the optimal electrode positioning over different portions of the quadriceps muscle to optimize more rational NMES clinical settings.

1. Introduction

Neuromuscular electrical stimulation (NMES) is a tool used in clinical practice to promote the activation of peripheral motor nerves to produce skeletal muscle contraction and restore strength [1, 2]. Muscle architecture is one of the main factors influencing muscle force generation [3–5]. The fascicle length (Lf) and pennation angle (θp) are special features of pennate muscles, which are expected to reduce and increase during an isometric contraction, respectively [3, 6, 7]. These variables can measure contraction intensity, as assessed *in vivo* through ultrasonography [3]. Ultrasonography is a resource used in biomedical engineering settings that can assist in the real-time visualization of muscle architecture. This method observes fascicular movement and deep aponeurosis *in vivo*, allowing the measurement of changes in θp and Lf during skeletal muscle contraction [3].

NMES is known to activate the motor units distinctly from voluntary activation. For example, it is claimed that contraction intensity is greater under and close to the placement of the electrodes [8]. Additionally, evoked force is considered the most important variable when determining the effectiveness of electrical stimulation [8]. Thus, sensor electrode configuration could lead to different degrees of contraction intensity in large muscle groups, such as the quadriceps femoris. Although varying stimulus variables might play a role in evoked torque, different stimulating electrode types and electrode placement configurations for testing activation need to be determined systematically so that outcomes can be compared between laboratories and clinics in biomedical settings [9].

Previous studies assessed different sensor electrode positioning on the skin of the quadriceps femoris muscle. The authors generally reported two types of sensors positioning, including a *rectus femoris* (RF) [10, 11] configuration, with electrodes placed over the proximal and distal RF, and a vastus configuration with electrodes positioned over the proximal *vastus lateralis* (VL) [9, 12, 13] and the distal *vastus medialis* (VM) [10, 11]. Positioning sensor electrodes at RF may produce lower muscle activation than positioning at VL and VM, because RF is smaller than VL, which is the largest muscle of QF [9]. In addition, sensors at VL and VM sites increase the distance between the electrodes, which may enable deeper penetration of the current. As a result, the number of motor units activated increases, since the greater the distance between the anode and cathode, the greater the electric field magnitude [14]. Thus, positioning sensor electrodes at VL and VM could reduce Lf and increase θp differently. However, to date, no studies have compared the changes in quadriceps muscle architecture between evoked and voluntary contraction with matched torque. In addition, the behavior of the quadriceps components (RF, VL, VM, and *vastus intermedius* (VI)) needs to be determined for a given placement of the electrodes during NMES procedures.

Previous studies have already evaluated different electrode positioning on different portions of quadriceps constituents but only to check variations in evoked torque produced and muscle properties using different sensor configurations [9–13]. The short-term effects on NMES evoked contraction and long-term effects on muscle architecture of quadriceps constituents remain to be confirmed. In our study design, RF and VI muscle portions were not directly stimulated during NMES, which leads to the hypothesis that positioning over the VL and VM could affect the degree of motor unit recruitment [15–17]. Pietrosimone et al. [9] assessed the quadriceps central activation ratio (CAR) and percentage-of-activation measurements, and no differences were found between the electrode configurations, but RF elicited greater torque than vastus. However, that study used physiological metrics, while our study intended to elucidate this question with mechanical properties such as θp and Lf. Aagaard et al. [18] showed that increases in θp and Lf are associated with hypertrophy and gain in maximal force generation. Thus, assessing the muscle architecture by ultrasonography is a practical way to predict greater hypertrophy and strengthen the potential of the electrode configuration because the differences in the number of changes in θp or Lf reflect differences in the contribution of that muscle to the observed torque during an isometric contraction [18, 19]. Furthermore, during arthrogenic inhibition, the vastus is more affected than RF muscle. The greater the distance between electrodes, the greater the number of motor fibers stimulated, showing the importance of stimulating VL and VM directly instead of RF [20]. However, the contributions of the sensor electrodes placed at RF and the VL and VM during an NMES session are not clear.

The purpose of this study was to investigate whether there is a difference in the behavior of the quadriceps constituents during an evoked contraction with sensor electrodes placed over the motor point of the VL and VM. As the muscle length was standardized for isometric contractions, we hypothesized that any difference in the degree of increase in θp, as well as reduction in Lf, would be greater in the VL and VM constituents due to the direct sensor electrode position during an evoked contraction. This knowledge may help biomedical engineers and clinicians establish a methodological impact for future studies that might lead to better understanding of evoked torque related to the positions of the electrodes for potential clinical NMES quadriceps activation.

2. Materials and Methods

2.1. Participants. Twenty men with no known neuromuscular disorders volunteered to participate in the study. The volunteers had not engaged in systematic lower limb strengthening or sports competitions in the previous six months but were physically active according to the International Physical Activity Questionnaire and tolerated a minimum torque of 40% of the maximum voluntary contraction (MVC) during the NMES. All procedures were approved by the Institutional Review Board (protocol number 94388718.8.0000.8093) and followed the Declaration of Helsinki.

2.2. Experimental Design. This article is part of a crossover trial dealing with muscle-tendon behavior at hip and knee angles during maximum evoked and voluntary contractions [21, 22]. The full protocol is available at ClinicalTrials.gov (Identifier: NCT03822221). The volunteers were instructed not to participate in exhaustive activities in 48 hours before the tests and to sleep and eat properly.

The procedures took place during two visits, separated by seven to 21 days. The first visit was a familiarization session, during which the volunteers were informed of the research procedures, and characterization outcomes were measured (height, weight, and physical activity level θp and Lf in rest conditions). In addition, the research assistants identified the motor point localization for stimulation on the VL and VM using a ballpoint pen electrode [23]. The pen electrode was moved over the skin, while the stimulation current was slowly increased by the operator until a clear muscle twitch was observed. For each muscle, the position of the identified motor points was determined by the distance along a reference line, measured between the medial aspect of the anterosuperior iliac spine and the upper edge of the patella, starting from proximal to distal, as reported by Botter et al. [23]. The motor points of the VL and VM were mapped again prior to the experimental session to reproduce the identification of the motor point from the familiarization session [24]. Subsequently, participants underwent two MVC and two maximum electrically induced contractions (MEIC) to verify each participant's ability to tolerate a current amplitude sufficient to generate an MEIC $\geq 40\%$ of the MVC and to familiarize the participant with the dynamometer and verify responsiveness and comfort during NMES.

The second visit was the experimental session. After proper positioning on the dynamometer chair, the participants performed a warm-up of 6 submaximal isometric contractions with 5- and 10-second rest intervals between them. The percentages of the maximum effort perception were 50% (x3), 75% (x2), and 90% (x1). All participants were submitted to eight MEIC at a rate of 1 per minute, the number of contractions required to assess all quadriceps constituents (two contractions for each one). The outcomes observed were θp and Lf at rest and evoked contraction at 40% of MVC.

2.3. Torque. The Biodex System 4 ™ isokinetic dynamometer (Biodex Medical Systems, Inc., Shirley, New York) assessed the torque during MVC and MEIC. Individuals were positioned on the isokinetic dynamometer chair (hip flexed at 85° of flexion and knee at 60° of flexion). The equipment axis was aligned with the anatomical axis of the knee and the lever arm with a force transducer, which was firmly fixed 2-3 cm above the lateral malleolus with a strap. The dynamometer contains two belts which cross the chest and one which crosses the pelvic girdle to minimize unwanted body movement during force production and to stabilize each participant firmly in the chair. The resting torque was used for subsequent gravity correction due to the limb weight and forces from the passive tension of structures crossing the knee [25]. A total of eight MEIC were required, separated by one minute of rest.

2.4. NMES. The Neurodyn 2.0 electrical stimulation device (Ibramed, São Paulo, Brazil) was connected to two isolated cables. All physical parameters of the stimulator were verified using a digital oscilloscope (DS1050E, Rigol, Ohio, United States). Two separate sensor electrode pairs of self-adhesive electrodes of 25 cm^2 were placed on the motor point of the VL and VM. A biphasic pulse symmetrical current was applied, with a frequency of 100 Hz, pulse duration of 400 μs, rise time of three seconds, on time of four seconds, decay time of three seconds, and off time of two minutes. This study used the specifications of the on time to mimic a ramp contraction and allow the ultrasonographic assessment of the quadriceps, as recommended for voluntary contractions [21, 26]. Participants were instructed to fully relax during NMES to achieve the evoked contraction. The current amplitude was gradually increased. Participants reported their discomfort after each evoked contraction using a 0–10 numeric scale, where 0 represented no discomfort and 10 represented the maximum bearable discomfort. According to a previous study, participants were informed that a perceived discomfort of 8 out of 10 should correspond to the maximum current amplitude they were willing to tolerate [26].

2.5. Muscle Architecture. θp and Lf were obtained using a portable ultrasound device (M-Turbo®, Sonosite, Bothwell, WA, USA) in B mode, with a 7.5 MHz linear transducer and visualization depth adjusted to 6 cm. The compression and stabilization of the transducer were controlled using an apparatus made with styrofoam and VELCRO. Two videos were obtained for each quadriceps component. The transducer was positioned in the longitudinal plane of each muscle belly, keeping it parallel with the direction of the muscle fascicles. Proper transducer alignment was achieved when several fascicles were tracked without interruption. The RF (lateral compartment), VL, and VM were evaluated, respectively, at the percentages of 50%, 60%, and 75% of the distance between the medial aspect of the anterosuperior iliac spine and the upper edge of the patella, starting from proximal to distal, adapted from Blazevich et al. [27]. For the VI, although it could be seen on the same window as the RF or VL [27], its visualization was often partially lost during contraction. Thus, it was recorded more distally in the anterior aspect of the thigh. The RF and VI were visualized on the anterior part of the thigh, and the VL and VM were visualized on the lateral and medial aspects. Video files were recorded during rest and the MEIC. The θp was calculated considering the angle between deep aponeurosis and fascicles. The Lf was measured as the length of the fascicular path between superficial and deep aponeuroses. The remaining fascicle portion, from the field-of-view boundary to the superficial aponeurosis, was estimated using an equation, according to previous studies [28].

2.6. Analysis at 40% of Maximum Voluntary Contraction. To synchronize the torque tracing with the ultrasonographic recordings, we used the New Miotool data acquisition device (Miotec Biomedical Equipment Ltd., POA, Brazil®) collected with a sampling rate of 2,000 Hz per channel, A/D converter of 14 bits, and common rejection mode of 110 dB (at 60 Hz). The data acquisition device was interfaced with the computerized dynamometer, and a high-definition camera positioned to capture the ultrasound screen. When the assessor started recording cine-loop ultrasound images before contraction, a visual indicator appeared on the ultrasound screen, which enabled the synchronization of all data on a torque-time recording generated by the device [29]. In this torque-time screen, it was possible to move a cursor to the time point where the torques were 0% (i.e., at rest) and 40% of the MVC, both corrected by the limb's weight. The time for each percentage was used to obtain the respective frames using the Tracker 4.87 software. The frames (at rest and MEIC plateau) were saved as image files and analyzed in the ImageJ software (v. 1.46; National Institutes of Health, Bethesda, Maryland, United States).

2.7. Statistical Analysis. Values of θp and Lf are reported as mean ± standard deviation (SD), mean difference, and 95% confidence interval (CI). For θp and Lf, analyses were performed with the rest and contracting values (starting from rest up to 40% of the maximum voluntary torque). A two-way ANOVA was performed to verify the interaction between "muscle" (RF, VL, VM, and VI) and "contraction" (rest and evoked contraction at 40% of MVC) for the θp and Lf. A one-way ANOVA was used to verify the interaction between "muscle" during evoked contraction at 40% of MVC for the θp and Lf. The Tukey post hoc test was applied to identify differences whenever a significant difference was detected. The effect sizes and statistical power were calculated. The effect size was determined using the partial eta squared ($\eta\rho 2$): small ($\eta\rho 2 = 0.01$), medium ($\eta\rho 2 = 0.06$), and large ($\eta\rho 2 = 0.14$). The significance threshold was set at $p < 0.05$ for all procedures. All analyses were performed using Statistica 23.0 (StatSoft Inc., Tulsa, Oklahoma, USA), and the GraphPad Prism 8.3.0 software (San Diego, CA, USA) was used for graphic design.

Table 1: Fascicle length and pennation angle of the rectus femoris, vastus lateralis, vastus medialis, and vastus intermedius at rest and during neuromuscular electrical stimulation at 40% of maximum voluntary contraction.

	Rest (mean ± SD)	NMES (mean ± SD)	Mean difference (95% CI)
Rectus femoris			
θp	13.74 ± 2.57	16.00 ± 4.68	-2.94 (-6.22, 0.34)
Lf	11.25 ± 2.49	11.21 ± 2.47	0.58 (-1.79, 2.96)
Vastus lateralis			
θp	11.42 ± 1.91	14.64 ± 3.26	-2.87 (-6.15, 0.40)
Lf	12.95 ± 2.81	11.20 ± 2.23	2.01 (-0.37, 4.39)
Vastus medialis			
θp	11.87 ± 2.21	15.20 ± 4.10	-3.50 (-6.78, 0.22)
Lf	12.61 ± 3.18	10.58 ± 2.46	1.87 (-0.51, 4.25)
Vastus intermedius			
θp	13.52 ± 2.49	15.12 ± 3.25	-1.39 (-4.67, 1.88)
Lf	10.87 ± 2.20	11.03 ± 2.68	-0.43 (-2.81, 1.94)

[1]Values expressed as mean ± SD and mean difference (95% CI). Legend: θp: pennation angle; Lf: fascicle length; NMES: neuromuscular electrical stimulation; CI: confidence interval.

3. Results

Twenty men (mean ± SD age: 24.0 ± 4.6 years, body mass: 77.0 ± 9.3 kg, height: 177.6 ± 6.3 cm) participated in the study. The mean torque observed was 201.14 ± 50.22 N.m during MVC, and torque at 40% of MVC was 80.45 ± 20.08 N.m.

There was no interaction for muscle × contraction for θp (F3. 57 = 1.33, $p = 0.27$, $\eta\rho 2$: 0.06, power: 0.33). Lf showed a muscle × contraction interaction (F3. 57 = 3.17, $p = 0.03$, $\eta\rho 2$: 0.14, power: 0.70). There were statistical differences for VL rest compared to VM contraction ($p = 0.003$), VL rest compared to VI rest ($p = 0.004$), and VL rest compared to VI contraction ($p = 0.0028$).

Table 1 and Figure 1 show the changes in θp and Lf for the four quadriceps femoris constituents during evoked contraction.

4. Discussion

This is the first study to investigate the potential effects of sensor electrode placement over the VL, and VM motor points to produce different changes in the θp and Lf of the quadriceps femoris constituents during an NMES session. Our results clearly suggest no difference in the behavior of the components. These results agree with a previous study which found no difference for the quadriceps central activation ratio (CAR) and percentage-of-activation comparing the same sensor electrode configuration; however, an interaction between muscles and contraction was found with nonclinically relevant significance to the study. Our data provide evidence that biomedical engineers, clinicians, and investigators can use NMES with this configuration of sensor electrodes because all the quadriceps muscles undergo similar short-term adaptation in terms of muscle architecture. Gaining better understanding of the possible physiological mechanisms that underlie different recruitment of quadriceps femoris constituents could provide a framework upon which to develop NMES protocols to produce more evoked torque contractions and improve outcomes of rehabilitation programs.

Previous studies postulated that in isometric contractions of the matching intensity in a given joint angle, the differences in the amount of changes in θp or Lf reflect differences in the contribution of that muscle to the observed torque [18, 19]. A systematic review evaluated the gain in strength and function utilizing NMES, after ACL reconstruction, and the majority of the included studies reported electrode configuration over the *vastus* muscles [18]. In addition, another study showed that a significant distance between electrodes in NMES provides greater torque because the relative number of motor fibers stimulated is affected by a larger area of current, which justifies the configuration of proximal placement on VL and distal placement on VM [20]. Considering this, it would be sensible to think that electrical stimulation from the vastus will promote greater quadriceps activation. However, Pietrosimone et al. [9] observed that electrode configuration did not alter the quadriceps activation, but electrode positioning on RF presented greater torque compared to positioning on vastus muscles. The authors described that the exact mechanisms behind this finding are unclear, leading to speculation that higher torque production with the rectus configuration might result from greater amounts of adipose tissue in the areas of electrode positioning on vastus muscles than on rectus muscle. Interestingly, Torry et al. [30] showed that vastus muscles are more affected during arthrogenic inhibition, which emphasizes the importance of the direct stimulation of vastus muscles during NMES in this clinical condition.

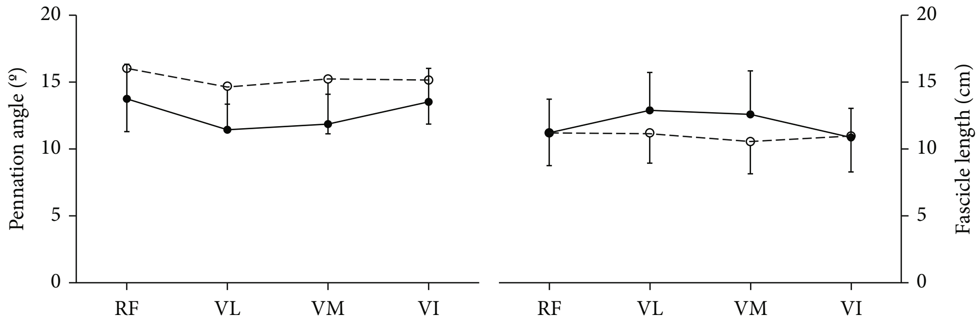

FIGURE 1: Changes in pennation angle and fascicle length of the quadriceps femoris constituents during neuromuscular electrical stimulation at 40% of the maximum voluntary contraction. Fascicle length (right y-axis) and pennation angle (left y-axis) of all constituents of the quadriceps femoris individually (x-axis), at rest (continuous line), and during NMES (dotted line). Data are presented as mean ± SD. NMES: neuromuscular electrical stimulation; RF: *rectus femoris*; VL: *vastus lateralis*; VM: *vastus medialis*; VI: *vastus intermedius*.

As the fact that sensor positioning seems not to alter muscle activation current amplitude is the best way to increase the generation of torque produced by the evoked contraction for a given frequency and pulse width [31]. However, the current amplitude is directly related to the discomfort perceived by the subjects. With the increase in current intensity, both the motor fibers and the nociceptive sensory fibers are stimulated, leading to a sensation of discomfort and pain. Therefore, it is crucial to consider NMES-efficiency, i.e., producing the highest torque output with the lowest current intensity [32]. Previous studies reported submaximal evoked torque levels (5 to 40%) of the maximum voluntary contraction to strengthen orthopedic, pulmonary, and intensive care patients [33, 34]. These studies also reported that an NMES training intensity of 40% MVC can improve MVC strength [33, 34], whereas another study demonstrated that when the perceived discomfort is reported at six on the Visual Analogue Scale, the evoked torque corresponds to 40% of MVC [32]. Therefore, an NMES session using a moderate current amplitude is an efficient way to introduce this resource into a rehabilitation protocol. Our main finding is that NMES at 40% of MVC with the electrodes positioned over the motor points of VL and VM does not elicit any effect on muscle architecture of the components of the quadriceps femoris. These findings are clinically relevant since the literature shows that an NMES training intensity of 40% MVC can improve MVC strength [33, 34]. This indicates that NMES can produce significant gains in quadriceps femoris strength independently of the placement of the electrodes, but this hypothesis should be tested in future long-term studies in clinical populations and for strength adaptations.

In addition to the discomfort perceived with NMES, there are further limitations and gaps that are not yet answered. One of the main limitations is the superficial fiber recruitment, which promotes faster fatigue compared with voluntary contraction [35]. A currently used feasible modality to hamper these limitations is the multiple-channel strategy, which uses multiple pairs of electrodes that dynamically change the current pathway within single pulses and temporal shifts between sensor pairs [36]. Some studies have already tested asynchronous frequency and rotation stimulation using computers and customized exciting sensor methods, showing lower fatigue than when using two conventional pairs of sensor electrodes [36–39]. Interestingly, there has been a massive growth in the science interested in using the Internet of Things (IoT) [40–43]. This technology has been extensively used with algorithms, metaheuristic algorithms, and blockchain smart contracts capable of identifying demands and collecting data in different areas [40–43]. For instance, the IoT has been used to guide drones to monitor gas concentration and heart rate, enabling the helmet to safeguard the health of mine workers [40, 42]. Therefore, we suppose that an NMES device using an algorithm system efficient to perceive the muscle region most susceptible to fatigue, with different sensors controlled by IoT (i.e., using CO_2 concentration or EMG signaling), might promote a safe and feasible stimulation. Meanwhile, there are still no definitive findings on the different placements of sensor electrodes in terms of evoked torque. Further studies should be performed to confirm the best placement of electrodes over the quadriceps femoris muscle for greater torque production.

Some potential limitations of this study are noteworthy: the exact observation of the Lf start and endpoint during the evoked contractions may have varied because NMES promoted a sudden muscle contraction, and the examiner held the transducer, making it challenging to acquire an accurate image. In addition, our ultrasound had a probe width of 40 mm, which limited the visualization of all muscle fascicles. We did not control the current delivered to the sensor electrodes or multiple pairs of sensor approaches. Future studies should provide the current dynamic using IoT, controlling with a multiple-channel strategy. Finally, our results are limited to our population and a single NMES session.

5. Conclusions

Our results suggest that NMES with the electrodes positioned over the VL and VM motor points does not elicit any effect on the muscle architecture of the components of the quadriceps femoris. Therefore, clinicians could choose either VL or VM motor points for sensor electrode positioning and expect similar muscle architecture adaptation for a given evoked torque. Future clinical studies should be conducted to establish the optimal sensor electrode positioning over different portions of the quadriceps muscle to optimize more rational NMES stimulation strategies in clinical settings.

Data Availability

The data sets generated during and/or analyzed during the current study are available from the corresponding author on request.

Conflicts of Interest

The authors declare no conflict of interest.

Authors' Contributions

Álvaro Ventura and Leandro Gomes contributed equally to this work.

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