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ORIGINAL ARTICLE

The importance of cutaneous feedback on neural activation during maximal voluntary contraction

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Abstract
Purpose The purpose of this study was to investigate the importance of cutaneous feedback on neural activation during maximal voluntary contraction (MVC) of the ankle plantar flexors.
Methods The effects of cutaneous plantar anaesthesia were assessed in 15 subjects and compared to 15 controls, using a one-day pre/post-repeated measures design. Cutaneous plantar anaesthesia was induced by lidocaine injection at the centre of forefoot, lateral midfoot, and heel. Each subject performed isometric MVCs of the ankle plantar flexors. During each isometric ramp contraction, the following variables were assessed: maximal isometric torque; surface electromyography (EMG) activity of the medial gastrocnemius (MG) and tibialis anterior (TA) muscles; and co-contraction index (CCI) between the MG and TA.
Results For ankle torque, two-way ANOVA showed no significant interaction between the pre/post-measurements × group ($p = 0.166$). However, MG activity presented significant interactions between the pre/post-measurements × group ($p = 0.014$). Post hoc comparisons indicated a decrease of MG activity in the experimental group, from 85.9 ± 11.9 to $62.7 \pm 30.8\%$ ($p = 0.016$). Additionally, the post-anaesthesia MG activity of the experimental group differed statistically with pre- and post-MG activity of the control group ($p = 0.027$ and $p = 0.008$, respectively). For TA activity and CCI, two-way ANOVA detected no significant interactions between the pre/post-measurements × group ($p = 0.605$ and $p = 0.332$, respectively).
Conclusion Our results indicate that during MVC, cutaneous feedback modulates neural activity to MG muscle, without changing the extent of MG–TA co-contraction.

Keywords Cutaneous feedback · Muscle mechanics · Surface electromyography · Medial gastrocnemius · Maximum voluntary contraction · Co-contraction

Abbreviations

MVC	Maximal voluntary contraction
sEMG	Surface electromyography
MG	Medial gastrocnemius
TA	Tibialis anterior
MIT	Maximal isometric torque
CCI	Co-contraction index

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Introduction

Cutaneous feedback is transmitted via sensory Aβ-fibers to the central nervous system through vibrations, stretching or pressure on the skin (Abraira and Ginty 2013). Deprivation of this information can modulate the muscle response during maximum voluntary contraction (MVC) (Augurelle et al. 2003; Kim et al. 2013; Shim et al. 2012), as well as during different daily activities, including hand movements such as grasping (Augurelle et al. 2003; Kim et al. 2013; Shim et al. 2012) and tasks using the feet, such as standing (Meyer et al. 2004) or walking (Choi et al. 2016; Gregor et al. 2006; Hohne et al. 2012).

Plantar cutaneous receptors could be relevant for posture and walking (Jenkins et al. 2009; Kavounoudias et al. 2001; Roll et al. 2002). This would be applicable not only to neurological conditions, such as diabetic neuropathy (Said 2007) and in stroke patients (Parsons et al. 2016), but also in elderly individuals (Cruz-Almeida et al. 2014; Deshpande et al. 2008) and patients with musculoskeletal conditions, such as chronic ankle instability (Burcal and Wikstrom 2016; Powell et al. 2014). Previous studies on the effects of blocking/removing cutaneous feedback on maximal force generation have focused on hand muscles. These studies report decreases (20–29%) in the force produced by the fingers during MVC in gripping and pressing tasks (Augurelle et al. 2003; Shim et al. 2012; Kim et al. 2013).

The mechanisms involved in the reduction of maximal force during cutaneous feedback abolition are not entirely understood. Two mechanisms have been proposed; the first postulates that cutaneous feedback abolition can affect the primary somatosensory cortex, thus leading to decreased motor output from the central nervous system, and hence, a lower MVC (Augurelle et al. 2003; Shim et al. 2012). However, there is some evidence that cutaneous feedback abolition would not affect the evoked potential and excitability of agonistic muscles during MVC (Duque et al. 2005; Ernberg et al. 2009; Kim et al. 2013). The second mechanism that may explain a decrease in maximal force exerted at an end effector is that cutaneous anaesthesia reduces agonist–antagonist co-contraction, and thereby, decreases the stability of more proximal joints (Kim et al. 2013). This mechanism was suggested specifically to explain changes in forces exerted at the fingertip during a finger pressing task for which fixation of more proximal joints is important for force exertion distally.

The measurement of spinal cord excitation resulting from muscle activation via surface electromyography (sEMG) is one of the most commonly used techniques for evaluating muscle strategies during isometric ramp contractions (Alkner et al. 2000; Arampatzis et al. 2006; De Luca 1997; Disselhorst-Klug et al. 2009). While the most prior research has focused on the effects of cutaneous feedback on muscle force generation, the measurements of muscle excitation through sEMG to understand the modulation of muscle activation and co-contraction strategies associated with the loss of cutaneous afferents feedback have not been thoroughly explored.

Consequently, the aim of this study was to investigate the effects of cutaneous feedback on muscle activation during MVC of the ankle plantar flexors. Our hypothesis was that cutaneous feedback modulates the neural activity of agonistic muscles during MVC.

Materials and methods

Ethical approval was obtained from the Northern Metropolitan Health Service of Santiago, Chile, and signed informed consent was required of each participant. All procedures were in accordance with the Declaration of Helsinki. All subjects were required to provide signed informed consent before being allowed to participate. The exclusion criteria were as follows: a history of cardiac or hepatic diseases; history of lidocaine allergies; chronic instability of the ankle; history of central and/or peripheral neurological diseases; and a history of acute lumbar hernias.

Subjects

Thirty healthy male subjects participated in the study. All subjects were randomly distributed between either the control ($n = 15$) or the experimental group ($n = 15$). The average traits of each group were as follows: Control, 22.7 ± 5.8 years old, 1.72 ± 0.04 m tall and 23.7 ± 6.0 body mass index; Experimental, 25.8 ± 7.4 years old, 1.75 ± 0.04 m tall and 24.5 ± 6.4 body mass index. Age was the only parameter in which the groups differed significantly ($p < 0.05$).

Isometric torque and surface electromyography

The force signal was obtained through a FMON-1 analogue-to-digital load cell (ArtOficio, Santiago, Chile) at an accuracy of 0.048 N. All subjects were sitting on a chair with a back support, the hips at 80°, knees fully extended, and ankles at 90° (Fig. 1). Each subject performed isometric MVCs of the ankle plantar flexors. Load cell measurements were corrected for forces due to gravity. Isometric ankle torque was calculated by multiplying force by the linear distance between the lines through the point of force application to the joint centre in each subject.

Muscle electrical activity was recorded by sEMG (bandwidth 20–500 Hz, differential amplification), with parallel bar electrodes (1 mm thickness, 10 mm spacing) (ArtOficio, EMG VIII, Chile). The skin was cleaned and the electrodes were positioned on the medial gastrocnemius (MG)

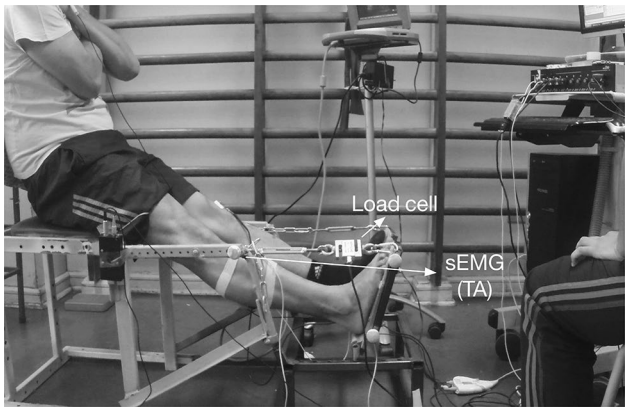

Fig. 1 Setup for isometric ramp contraction measurement. Surface electromyography (sEMG); Tibialis anterior (TA). sEMG of the medial gastrocnemius not shown

and tibialis anterior (TA) muscles, according to the recommendations described by surface EMG for the non-invasive assessment of muscles (Hermens et al. 1999). The sEMG and load cell measurements were recorded simultaneously by a PC data acquisition board (1000 Hz sampling frequency; model PCI-6013, National Instruments, Austin, TX). All tasks were analysed through a 2D video analysis (60 fps recording rate, 0.05 mm/pixel resolution; GoPro, San Mateo, CA, USA) to confirm the correct execution of the task (see below).

Task execution

Prior to the measurements, three maximal voluntary contractions of TA were requested in each patient, for later normalization of EMG signals.

Each participant performed ten submaximal isometric plantar flexion contractions to learn and ensure correct task execution. Correct execution was defined as an isometric plantar flexion with full plantar contact on the footplate, without flexion of the knee, and with both arms at the level of the sternum. Even though it is difficult to prevent (Karamanidis et al. 2005), this setup minimized angular rotation of the ankle joint during isometric MVC. Performing isometric contraction with full-foot contact to the footplate was a critical instruction point. This emphasis was given since no strap was placed on the dorsal surface of the foot to minimize additional cutaneous feedback and proprioception through direct pressure and skin stretching (Mildren et al. 2016). After performing the submaximal practice trials, subjects rested for 10 min before exerting three MVCs, with 2 min of rest in between.

If any task criteria were not met, the results were excluded, and the subject was invited to repeat the task following a 2-min rest period. During execution, subjects received verbal and visual feedback of the plantar flexion force curve, as well as verbal encouragement (e.g. "go, go, go"). The subjects were asked to perform ramp contractions with a 5-s increase and 5-s plateau to ensure the same contraction velocity. During task execution, emphasis was placed on reaching the peak force within 5 s and maintaining that force for 5 s. For data analysis (see below), the focus was placed on isometric ramp contraction.

Experimental group

After finishing the three repetitions of MVC, intradermic anaesthesia (2% lidocaine HCl; 1:8 sodium bicarbonate; 1:200,000 epinephrine; 12 U/mg hyaluronidase) was applied to the plantar aspect of the foot at the metatarsal heads, sole, and heel by an anaesthesiologist. The administration procedure was performed according to an established protocol that has no reported adverse effects (Hohne et al. 2012). A total of 0.8 mL was administered through 8–12 injections distributed over the centre of the forefoot, lateral midfoot, and heel (Hohne et al. 2012).

Semmes–Weinstein monofilaments (North Coast Medical, Inc., San Jose, CA) were used to evaluate the extent of plantar cutaneous anaesthesia for the heel, forefoot, and midfoot following a previously established protocol (McPoil and Cornwall 2006). No additional lidocaine was injected once the subject no longer perceived the monofilament, which exerted 300 g of pressure, i.e. equivalent to deep-pressure sensation (Gondring and Shields 2011). The plantar cutaneous anaesthesia required 30–40 min to act. During this time, subject comfort was considered, and each subject was placed in a resting position (i.e. sitting with knees and ankles in free position). Immediately after the effect of anaesthesia was confirmed, all subjects performed another three MVCs (Fig. 2).

Control group

After finishing the first three MVCs, control subjects were placed in the same resting position as that of the experimental group for 30 min, with emphasis on the comfort of the subject. Then, all subjects performed another three repetitions of MVC.

Data analysis

During each ramp of maximal isometric contraction, the maximum peak of all signals in the pre- and post-conditions was compared within and between each group.

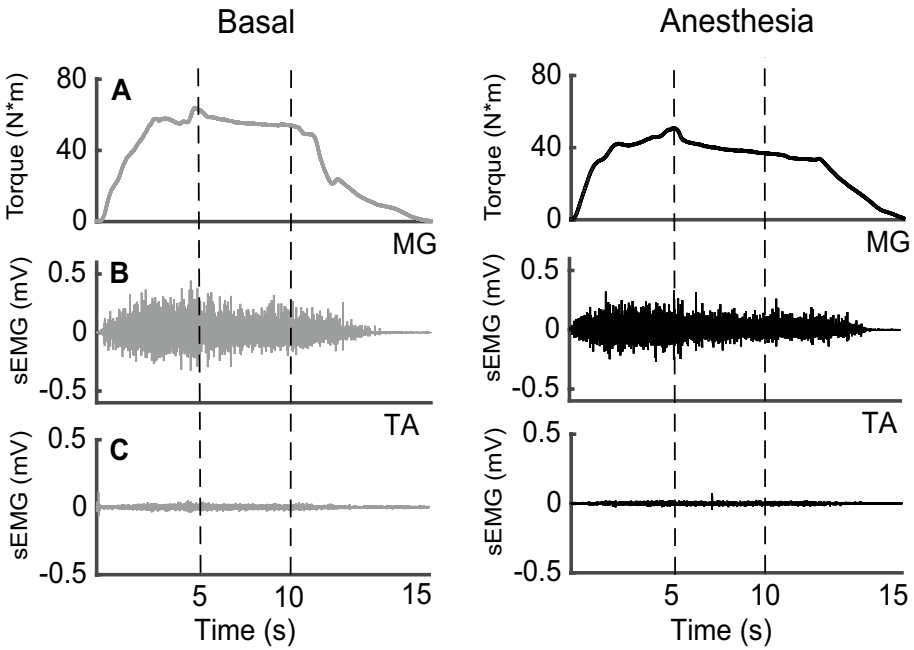

Fig. 2 Example of row signals pre- and post-cutaneous anaesthesia application in one subject. **a** Isometric torque; **b** surface electromyography of the medial gastrocnemius (MG); **c** surface electromyography of the tibialis anterior (TA). The vertical dashed line expresses times from resting to maximal voluntary contraction to maintained force

Surface electromyography analysis

The sEMG signal was filtered using Empirical Mode Decomposition and Hilbert Spectral Analysis with a soft-threshold of the mean plus one standard deviation of the baseline signal (Andrade et al. 2006; Chang 2010; Zhang and Zhou 2013). To determine the amplitude of sEMG signals in the MG and TA, the root mean square, with a window length of 250 ms, was applied. For the experimental and control groups, the signal of the MG was normalized to the peak found in the pre-condition. The TA sEMG signal was normalized to the maximal value found during the MVCs. To calculate the co-contraction index (CCI) between the MG and TA, the integral of the sEMG signal was calculated as a function of time (%) during isometric ramp contraction. Specifically used was the overlap between sEMG signal integrals, normalized to the MVCs of the TA and MG muscles; see Eq. (1), which is used frequently for calculating the CCI in neurological conditions (Hesse et al. 2000; Rosa et al. 2014; Keefer et al. 2004).

$$\mathrm{CCI} = 2 \times \left[\frac{\text{common area between MG and TA}}{\text{area MG} + \text{area TA}}\right] \times 100 \quad (1)$$

Force signal processing

The force signal was processed by a low-pass, fifth-order Butterworth filter (25 Hz cut-off frequency) (Jones et al. 2002).

Statistics

Signal and statistical analyses were performed in the MATLAB software (The Mathworks, Natick, MA, USA). For absolute measures of reliability, the coefficient of variation was calculated for all the variables from the control group. Normal distribution was determined using the Shapiro–Wilk test, and was found on ankle torque and sEMG variables.

To assess the effects of cutaneous anaesthesia on MIT, sEMG, and CCI, two-way ANOVAs (pre/post measurements × group) were performed. If a significant interaction was found between factors, post hoc *t* tests with Bonferroni correction for multiple comparisons were applied. Statistical significance was established at $p < 0.05$.

Results

Reliability of measurements

For the pre-condition control group, the coefficient variations were 1.7% for MVC force, 3.8 and 4.7% for the normalized sEMG signals in the MG and TA, respectively, and 2.7% for the CCI.

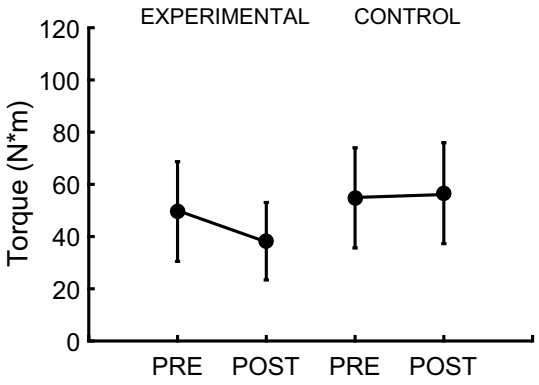

Fig. 3 Comparison of isometric development of plantar flexion torque during isometric ramp contraction in the experimental and control groups for changes in the pre- and post-conditions

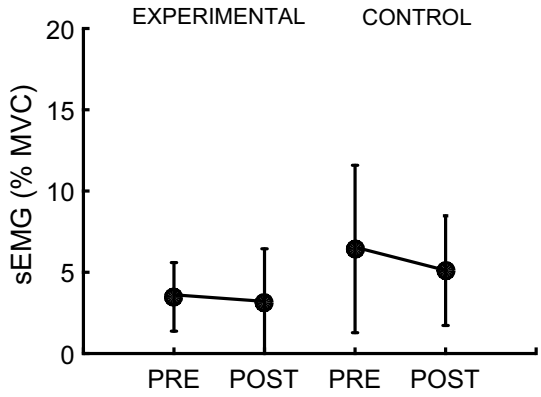

Fig. 5 sEMG activity of the tibialis anterior muscle in the experimental and control groups pre- and post-condition

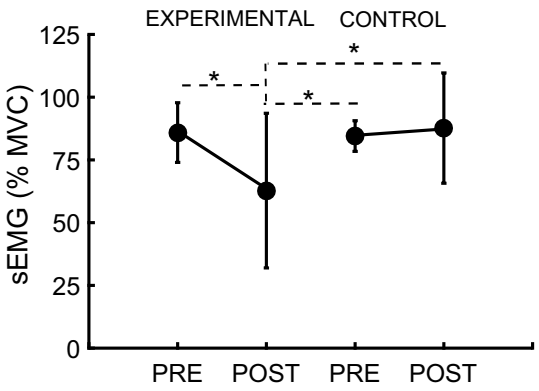

Fig. 4 sEMG activity of the medial gastrocnemius in the experimental and control groups pre- and post-condition. *$p < 0.05$

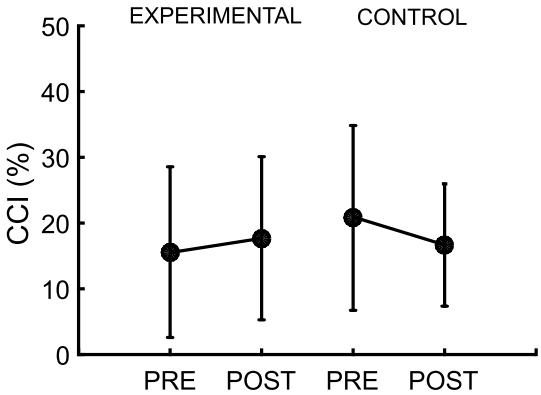

Fig. 6 Co-contraction index (CCI) in the experimental and control groups pre- and post-condition

Isometric torque and surface electromyography

For peak MIT (Fig. 3), two-way ANOVA indicated a significant difference between groups ($p = 0.015$). However, the effects of pre/post measurement ($p = 0.313$) and interaction ($p = 0.166$) were not significant. Therefore, despite an average 23% decrease of peak MIT (from 50.9 ± 19.6 to 39.2 ± 15.2 N m) in the experimental group and an average 3% increase of peak MIT (from 54.8 ± 19.2 to 56.6 ± 19.3 N m) in the control group, no statistically significant effects of cutaneous anaesthesia on peak MIT could be established.

Two-way ANOVA for the normalized sEMG activity of the MG showed a non-significant effect of pre/post measurements ($p = 0.059$) but significant effects of the group ($p = 0.027$) and interaction (pre/post measurement × group) ($p = 0.014$). Post hoc comparisons showed a decrease in sEMG activity in the experimental group, going from 85.9 ± 11.9 to $62.7 \pm 30.8\%$ ($p = 0.016$; Fig. 4), but no significant changes were found in the control group. In addition, MG activity of the experimental group post-anaesthesia differed significantly from pre- and post-MG activity of the control group ($p = 0.027$ and $p = 0.008$, respectively).

Two-way ANOVA for the normalized sEMG activity of the TA muscle showed a non-significant effect of pre/post measurements ($p = 0.374$) but a significant effect of the group ($p = 0.011$). Furthermore, a non-significant interaction between factors (pre/post measurement × group) was recorded ($p = 0.605$; Fig. 5).

Finally for CCI, two-way ANOVA showed a non-significant effect of the pre/post measurement factor ($p = 0.753$) and of the group factor ($p = 0.514$). Additionally, a non-significant interaction between factors (pre/post measurement × group) was found ($p = 0.332$; Fig. 6).

Discussion

The objective of the present study was to determine the effects of cutaneous feedback on muscle activation during

MVC of the ankle plantar flexors, as tested using the application of intradermic plantar anaesthesia. The main results were as follows: (1) sEMG activity of the MG muscle in the experimental group decreased significantly post-anaesthesia; and (2) no significant changes were found for the sEMG of the TA or for MG–TA co-contraction. Therefore, our results confirm our hypothesis that cutaneous feedback modulates the neural activity of agonistic muscles during a MVC.

Although not statistically significant, the magnitude of the non-significant decrease in average MIT value in the experimental group (by 23%) is in line with previous findings, as predominantly reported in the hand. These prior studies indicate that abolition of cutaneous feedback (between 20 and 29%) decreases the ability to exert force in the fingers (Augurelle et al. 2003; Kim et al. 2013; Shim et al. 2012). We found a significant main effect of group. However, a significant interaction between the pre/post measurements and groups was not detected. Therefore, a decreased ability for force exertion due to cutaneous anaesthesia could not be confirmed statistically.

MG activity of the experimental group decreased significantly from 86 to 63% of maximal activity. In contrast, no changes were observed in the control group (i.e. 85 and 88% of maximal activity). The MG normalized sEMG activity observed in the pre-anaesthesia condition was similar to a previous report on isometric MVC, which used knee and ankle positions similar to those used in the present study (Arampatzis et al. 2006).

The sEMG of the TA showed a significant effect between groups. However, there was a non-significant interaction between the pre/post measurements and group. Furthermore, the CCI remained constant. In addition to this, the mean CCI in the pre-condition of both groups (17%) was similar to that of a previous report (15%) during isometric MVC of the ankle plantar flexors (Billot et al. 2010). The observed results indicate that cutaneous plantar anaesthesia can modulate the activity of a synergistic muscle (MG) without a significant change in peak MIT or synergist–antagonist (MG-TA) co-contraction. This suggests a compensatory increase in the activity of other ankle plantar flexors (e.g. soleus, lateral gastrocnemius) or a decrease in the activity of other ankle dorsi flexors (e.g. extensor digitorum longus).

The observed absence of changes in co-contraction cannot be explained by previous mechanisms proposed for a reduction of agonist–antagonist co-contraction in the hand (Kim et al. 2013). A possible explanation for the difference between hand grip force and plantar isometric force could be the greater proximal joint stability needed by the hand than by the plantar flexors when exerting isometric force. As is already known, more co-contraction is expected for joints with a greater degree of freedom (Jinha et al. 2006). Additionally, the increased activation levels of the antagonist muscle could reduce agonist force output and net joint moment (Winter 2009).

The somatosensory cortical processing arising from the deformation of the foot, ankle joint, and the muscle receptors during MVC would undergo multimodal integration within the sensory cortex (Kim et al. 2015). The brain would play an important role, sending movement prediction signals directly to the parietal cortex. This interaction would be critical for controlling force and posture, as it would form an image of the body and its relation to the external environment (Bhanpuri et al. 2012; Freund 2002). Due to this, decreased cutaneous feedback would directly affect the corticospinal output to the muscle (Rossi et al. 1998). Furthermore, several studies report the effects of cutaneous afferent modulation on the excitability of motor neurons in the spinal cord in animals and humans (Seki et al. 2003; Sehle et al. 2016; Knikou 2007; Fallon et al. 2005; Sayenko et al. 2009; Frigon et al. 2012; Bui et al. 2013). Diverse studies also report H-reflex modulation through cutaneous excitation (Knikou 2007; Sayenko et al. 2009).

Regarding other afferent inputs that can affect voluntary force, visual feedback during MVC contributes to both force precision (Baweja et al. 2009; Limonta et al. 2015) and MVC force (Toumi et al. 2016). A recent report found that visual feedback could increment MVC by 15% (Toumi et al. 2016). In the present study, visual feedback was maintained during MVC execution to ensure that the task was correctly performed and to maintain another source of sensory information in addition to deformation of the foot.

The changes in muscle activity observed in the present study reflect complex sensory-motor integrations involved in controlling variables of the central nervous system. This is not only relevant for grasping strategies of the hand, but also for the sole of the foot in controlling gait, posture (Fallon et al. 2005), and during MVC (Augurelle et al. 2003; Kim et al. 2013; Shim et al. 2012). This is especially relevant for musculoskeletal function in certain conditions, such as following a stroke, and in the elderly (Boissy et al. 1999; Kim and Eng 2003; Skelton et al. 1994; Rantanen et al. 1994) in which muscle function is affected.

The observed change in activity for the ankle plantar flexor is important to consider in therapeutic strategies oriented towards the prevention of muscular atrophy, especially for those conditions that decrease plantar cutaneous information. Furthermore, the information derived from cutaneous receptors would be fundamental for sensory-motor interactions in more realistic and integrative prostheses (Ackerley and Kavounoudias 2015). Haptic feedback has been proposed as an alternative in prostheses for patients with peripheral neuropathy and limb amputations (Fan et al. 2008).

Study limitations

In this study, contributions were not measured for all of the plantar and dorsi flexors of the ankle. Such data would be needed for a comprehensive and integral assessment of the effects of cutaneous anaesthesia on neuromuscular control, in particular to investigate the potential increase in neural activity of other plantar flexors and/or decrease in neural activity of other dorsi flexors during a MVC.

MVCs were performed in a fixed-joint position, mechanically constraining the degrees of freedom, possibly unnaturally limiting the extent of agonist–antagonist co-contraction. No significant changes in the CCI were recorded, but future studies should investigate if the level of co-activation can be modulated by cutaneous anaesthesia if more degrees of freedom are allowed. Regarding the assessment of MVC, twitch interpolation was not used to assess the level of muscle excitation (Folland and Williams 2007). However, changes in neural activity were assessed using sEMG.

In addition, the present study did not consider variables attributable to changes in the motor cortex or somatosensory integration centres. This final point is important to consider in future studies to integrally understand the mechanisms involved in the loss of force following the plantar cutaneous anaesthesia. Future studies should also consider simultaneously evaluating cortical and peripheral signals to gain a better understanding of how the sensorymotor system interacts in the control of maximal voluntary force.

Conclusions

Our results confirm that cutaneous feedback modulates neural activity to the MG muscle without changing the extent of MG–TA co-contraction during MVC, as evidenced by changes in muscle electrical activity. We conclude that during MVC, the plantar cutaneous feedback plays an important role on neural activation in agonistic muscles.

Compliance with ethical standards

Conflict of interest There are no conflicts of interest.

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