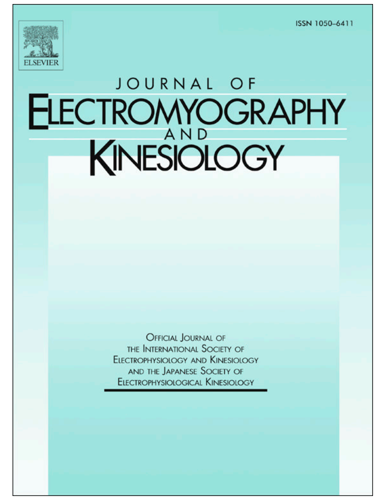
Accepted Manuscript



Ultrasonographic quantification of architectural response in tibialis anterior to neuromuscular electrical stimulation

Emilie Simoneau-Buessinger, Sébastien Leteneur, Alix Bisman, François Gabrielli, Jennifer Jakobi

PII: S1050-6411(17)30001-9
DOI: http://dx.doi.org/10.1016/j.jelekin.2017.07.008
Reference: JJEK 2099

To appear in: *Journal of Electromyography and Kinesiology*

Received Date: 3 January 2017
Revised Date: 25 July 2017
Accepted Date: 25 July 2017

Ultrasonographic quantification of architectural response in tibialis anterior to neuromuscular electrical stimulation

Emilie SIMONEAU-BUESSINGER[1]*, Sébastien LETENEUR[1], Alix BISMAN[2], François GABRIELLI[1], Jennifer JAKOBI[3]

[1] *Laboratoire d'Automatique, de Mécanique et d'Informatique industrielles et Humaines (LAMIH) – UMR CNRS 8201, Université de Valenciennes et du Hainaut-Cambrésis (UVHC), F-59313 Valenciennes, France*

[2] *Laboratoire de l'Effort et du Mouvement, Haute Ecole Provinciale de Hainaut (HEPH) - Condorcet, Tournai, Belgium*

[3] *School of Health and Exercise Sciences, University of British Columbia Okanagan, Kelowna, Canada*

Key words: Dorsiflexion; Fascicle length; Pennation angle; Plantarflexion; Ultrasonography

Running head: NMES and muscle architecture

*** Corresponding author:** Emilie SIMONEAU - BUESSINGER, Laboratoire d'Automatique, de Mécanique et d'Informatique industrielles et Humaines (LAMIH) – UMR CNRS 8201, Université de Valenciennes et du Hainaut Cambrésis (UVHC), Le Mont Houy, F-59313 Valenciennes Cedex 09, France; Phone: +33 3 27 51 14 60; Fax: +33 3 27 51 13 16; E-mail: emilie.simoneau@univ-valenciennes.fr.

Conflict of Interest: The authors have no conflict of interest or financial disclosure to report.

ABSTRACT

While muscle contraction in voluntary efforts has been widely investigated, little is known about contraction during neuromuscular electrical stimulation (NMES). The aim of this study was to quantify *in vivo* muscle architecture of agonist and antagonist muscles at the ankle joint during NMES. Muscle fascicle lengths and pennation angles of the tibialis anterior (TA) and lateral gastrocnemius muscles were assessed via ultrasonography in 8 healthy young males. Measures were obtained during maximal NMES and torque-matched voluntary dorsiflexion contractions. In the TA, NMES induced a shorter fascicle length (67.2 ± 8.1 mm *vs* 74.6 ± 11.4 mm; p = 0.04) and a greater pennation angle (11.0 ± 2.4° *vs* 9.3 ± 2.5°; p = 0.03) compared with voluntary torque-matched dorsiflexion contractions. Architectural responses in the antagonist lateral gastrocnemius muscle did not significantly differ from rest or between voluntary and electrically induced contractions (p > 0.05). Contraction of the antagonist muscle was not a contributing factor to a greater fascicle shortening and increased pennation angle in the TA during NMES. TA architectural response during NMES likely arose from the contribution of muscle synergists during voluntary contractions coupled with a potentially localized contractile activity under the stimulation electrodes during NMES induced contractions.

INTRODUCTION

Neuromuscular electrical stimulation (NMES) is defined as the application of transcutaneous electrical stimuli to artificially induce muscle contractions through excitation of motor nerves creating depolarizing of the motor endplates. While numerous practitioners and researchers from diverse fields are interested in using NMES to optimize skeletal muscle function, to complement or as a substitute for voluntary training (Maffiuletti et al., 2011; Needham et al., 2009), this can only be accomplished with an understanding of the fundamental differences between voluntary and electrically induced contractions. Considerable research has been undertaken to define motor unit activation strategies during NMES (Bickel et al., 2011; Feiereisen et al., 1997; Gregory and Bickel, 2005; Heyters et al., 1994; Trimble and Enoka, 1991) but there is little information on the contractile response of muscle fascicles to electrical stimulation (Maganaris, 2001; Oda et al., 2007).

Skeletal muscle architecture, largely inclusive of fascicle length and pennation angle, is the structural property of whole muscles that directs contractile function. Ultrasonography is becoming a widely-used tool to measure muscle fascicle lengths and pennation angles *in vivo* across various positions and activities such as standing, walking or running. This understanding of muscle architecture through ultrasonography investigation has been applied to healthy young and old as well as in conditions of physical challenge (eg., joint replacement), disease (eg., stroke) and in response to a perturbation such as stretch- or strength-training (Maffiuletti et al., 2011; Needham et al., 2009). It is well established that muscle fascicles shorten and pennation angle increases during isometric contractions (Kawakami et al., 1998; Lieber and Fridén, 2000), yet little is known about muscle architecture under conditions of NMES: it might respond differently to voluntary contractions. The purpose of this study was thus to investigate, for a given level of dorsiflexion (DF) torque, the *in vivo* behaviour of muscle fascicle lengths and pennation angles during voluntary and NMES contractions of the tibialis anterior (TA) muscle. However, since a torque output corresponds to a resultant compilation of agonist and antagonist torques, muscle architecture of the lateral gastrocnemius (LG) was also assessed, in order to determine whether the contribution of the antagonist was comparable between voluntary and electrically induced contractions.

METHODS

Participants

Eight healthy male adults (age 28.8 ± 5.5 years; height 1.82 ± 0.05 m; body mass 84.4 ± 7.7 kg (mean ± SD)) took part in this study. In a previous session, all participants were familiarized with the ergometer and the NMES. Participants gave written informed consent prior to participation in the study and all procedures complied with the Declaration of Helsinki and were approved by the local institutional review board. Exclusion criteria included contraindications to electrical stimulation, acute musculoskeletal injury, neuropathy and neurological disease.

Mechanical recordings

An ankle ergometer 'Booted, Open-unit device, Three-dimension sensor, Transportable, Ergometer (B.O.T.T.E.)' was used to record isometric torque at the ankle joint in DF (Simoneau-Buessinger et al., 2015; Toumi et al., 2015). It is composed of a footplate, seat and adjustable orthosis that when fastened from mid-shank to mid-thigh ensures consistent forward extension of the leg. The foot was fixed into a plate mounted with a 6-component force-torque sensor (Sensix, Poitiers, France) positioned under the foot-plate and used for the tridimensional ankle torque calculation (Toumi et al., 2015). The participant was situated directly against the chair back with the hip at ~60° of flexion in order to extend the dominant leg in front of the body with the ankle joint positioned so that the angle between the foot and the leg was 110°. The axis of rotation of the ankle joint was aligned with the axis of rotation of the ergometer. The foot was held in this position and within the ergometer through custom straps at the heel, ankle joint and midfoot. An additional strap was placed over the metatarsophalangeal joints to maintain and standardize forefoot position. This fixation system prevented any movement of the lower extremity during isometric contractions. The dominant leg was tested and defined as the self-reported leg which was preferred to kick a ball (Chapman et al., 1987). The participant's arms were folded across the chest during testing. Torque was sampled at 100 Hz using a custom built Matlab program (Matlab 7.12, The MathWorks Inc., MA, USA) and a 16-bit A/D board (National Instruments, Texas, USA) interfaced to a computer.

Ultrasonography

Fascicle length and pennation angle of the TA and LG muscles were measured with real-time B-mode ultrasonography (M7, Mindray, Shenzhen, China) with a 45-mm, 12-MHz linear-array probe at rest and during voluntary and electrically induced isometric DF contractions. The longitudinal sections of the TA were imaged with the probe placed on the anterior aspect of the lower leg at the site corresponding to the thickest portion of the muscle, identified by ultrasound (Reeves and Narici, 2003). Longitudinal ultrasonic images of the LG were obtained at 30% of the distance from the popliteal crease to the centre of the lateral malleolus (Kawakami et al., 1998). Eco-absorptive markers (thin adhesive tapes) were placed on the skin over the sites of the scanned regions to measure and confirm stability of the ultrasound probe and to provide a reference for architectural measurements. The probe was coated with a water-soluble transmission gel to provide acoustic contact and was secured with adhesive tape on the skin over the TA or LG.

Neuromuscular electrical stimulation

A clinical stimulator (Combi 500, GymnaUniphy, Belgium) was used to deliver biphasic symmetric rectangular pulses of 350 μs at 80 Hz through conductive electrical stimulation pads (Maffiuletti et al., 2002). Stimulating pads (5 x 5 cm) were placed over the proximal motor point of the TA muscle at approximately 27% of the distance distal from the apex of the fibular head to the apex of the medial malleolus and the distal pad (10 x 5 cm) was placed longitudinally ~43% the distance from the same fibular head landmark on the same reference line (Botter et al., 2011) (Figure 1).

Experimental protocol

Prior to testing, each participant performed a standardized warm-up consisting of several submaximal isometric contractions of increasing intensity and three maximal contractions in both DF and plantar-flexion to ascertain maximal strength and to ensure preconditioning of the muscle–tendon complex (Maganaris et al., 2002). Each participant was then familiarized with several submaximal electrical stimuli. The stimulation intensity was progressively increased until torque output plateaued for further increases in stimulation intensity. The stimulator was then set for a supramaximal intensity (120%) and maintained for the entire session of NMES. Torque output was monitored to ensure that it was consistent for the entire session of NMES. Following the warm-up and determination of maximal stimulation intensity, the NMES protocol and the torque-matched voluntary contractions were executed, a minimum of 2-min rest was provided between all contractions. The NMES protocol was conducted and submaximal voluntary contractions were subsequently performed at the torque-matched level for each subject. Initial ultrasound images captured the TA at rest and during the 10-s supramaximal NMES. The probe was then repositioned over the LG to measure antagonist muscle architecture during NMES. The torque output from NMES was then verified to be equal to the first series of NMES induced contractions. When NMES torque did not correspond between the two stimulation trials, which happened for 4 participants, additional NMES contractions were performed. The LG acting as an antagonist was also measured at rest and during the 10-s DF NMES. Following the NMES contractions a target line was placed on the screen and participants were provided with real-time visual feedback to produce 10-s torque-matched submaximal isometric contractions. Images were acquired from the LG and the TA during the voluntary submaximal torque-matched efforts.

Data analysis

A minimum of two ultrasound scans for each muscle were obtained for all conditions (resting state, MVC, NMES, voluntary torque-matched contractions). Measurements of pennation angle and fascicle length were repeated three times by a single researcher on each ultrasound scan and the averages were used for analyses. For the pennation angle and fiber length measurements, the coefficients of variation were less than 9 % (Kwah et al., 2013). Fascicle length was measured as the span of the fascicle between superficial and deep aponeuroses (Figure 2). Pennation angle was defined as the angle of insertion of the fascicles into the central aponeuroses for the TA, and into the deep aponeuroses for the LG. When fascicles extended off the acquired scan the length of the missing portion was estimated by linear extrapolation. Ultrasound images were analysed with Image J (National Institutes of Health, Bethesda, Maryland, USA).

Statistical analysis

All statistical tests were performed with Statistica® software (StatSoft, Tulsa, OK, USA). Data are reported as means ± SD in text and figures. Normality of the data was checked using the Shapiro-Wilk's test and equality of variances was verified by the Levene test. To test the differences in muscle architecture (fibre length and pennation angle) between the conditions (resting state, voluntary and NMES contractions at the same level of torque), a one-way repeated measures analysis of variance was performed for each of the muscles (TA and LG). When necessary, a Tukey HSD post hoc test was used. For all analyses, the level of significance was set at $p < 0.05$. Partial eta-squared (η_p^2) was calculated for statistically significant parameters to estimate effect size.

RESULTS

Maximal voluntary DF torque was 36.0 ± 3.6 N.m, and maximal NMES stimulation was 11.9 ± 3.3 N.m and torque matched in the submaximal voluntary efforts was 12.1 ± 3.5 N.m ($p > 0.05$). The fibre length of the TA differed between resting, voluntary and NMES conditions ($F_{3,21} = 25.36$, $p < 0.001$). Fibre length of the TA was longer at rest than during stimulated and torque-matched voluntary contractions ($p < 0.01$) (Figure 3a). Moreover, TA fibre length during the NMES induced contractions was shorter than during submaximal voluntary contractions ($p = 0.04$) but NMES induced contractions did not differ from MVC ($p > 0.05$). Pennation angle of the TA also differed significantly between the four conditions ($F_{3,21} = 28.59$, $p < 0.001$). It was significantly smaller at rest than during the stimulated and submaximal voluntary efforts ($p < 0.01$) (Figure 3b). The pennation angle of the TA during stimulated efforts was greater than the angle during submaximal voluntary contractions ($p = 0.03$) but lower than during MVC ($p < 0.01$). The antagonist LG muscle did not differ between conditions for fascicle length ($p > 0.05$) and pennation angle ($p > 0.05$).

DISCUSSION

The primary finding of this study was that NMES induces greater architectural responses in the TA than torque-matched voluntary DF contractions. These responses occurred without alteration in fascicle lengths and pennation angles of the antagonist LG muscle. These findings suggest that contraction of the antagonist is not a contributing factor to greater fascicle shortening and increased pennation angles in the TA during NMES. Differential responses in muscle architecture between conditions likely stem from the contribution of synergists during voluntary contractions coupled with a potentially localized contractile activity under the stimulation electrodes in NMES. These results have implications for understanding contractile output and its influence on architectural adaptations when NMES is used for clinical rehabilitation and training.

Traditionally, activity of the antagonist muscle is measured with electromyography (EMG) (Carolan and Cafarelli, 1992; Simoneau et al., 2009); however, ultrasonography offers a viable alternative through assessment of muscle architecture via quantification of fascicle lengths and pennation angles (Raiteri et al., 2015; Simoneau et al., 2012). To our knowledge no study has reported architectural changes of antagonist muscles during electrical stimulation, but herein we show that similar to voluntary contractions changes in muscle architecture of the antagonist LG does not differ from rest or from voluntary torque-matched efforts. These data identify that the greater fascicle shortening and increased pennation angle of the TA in NMES compared with torque-matched contractions is not a consequence of the antagonist LG muscle.

Inasmuch as the antagonist muscles lessen torque output, synergist muscles contribute. The contribution of muscle synergists to DF torque is coupled between descending neural drive and torque transmission from muscle through tendon to the bone (Huijing and Baan, 2003). During voluntary contractions, the synergist extensor hallucis longus, extensor digitorum brevis and peroneus tertius would actively contribute to torque output, whereas this voluntary drive is unlikely in the NMES condition. Appropriate stimulation over the TA motor point would isolate current spread and minimize adjacent muscle contraction (Gobbo et al., 2011). Moreover, unlike the plantar-flexors which share a common distal tendon, the DF synergists have independent origins and insertions, thus the greater TA fascicle shortening in NMES induced contractions is likely due in-part to the contribution of DF synergists in the voluntary contraction. Although the net contribution of these DF synergists cannot be determined, these muscles would support the voluntary rather than NMES torque output, thereby lessening the amount of contractile shortening needed to generate a 30% effort.

NMES creates a localized electric field that depolarizes the motor axons beneath the stimulating electrodes resulting in the synchronous discharge of motor units in a time locked manner to each electrical pulse which is unlike the motor unit discharge variability inherent in the asynchronous rate coding strategies of voluntary contractions (Bergquist et al., 2012). Recruitment of motor units through NMES also does not align with voluntary contractions in the submission to Henneman's size principle (Bickel et al., 2011; Henneman et al., 1965). Although controversy remains over whether NMES activation of motor units is reversed or random the unique recruitment coupled with non-physiological discharge of motor units likely contributes to different muscle fibres being activated between torque matched conditions. Because this unique activation is localized to the electrode area while voluntary contractions induce activation and fascicle shortening throughout the TA (Maganaris and Baltzopoulos, 1999) it is probable that greater shortening in a localized area of the muscle is required in NMES to induce a similar torque as voluntary contractions.

Isometric torque as well as resting length of the muscle and tendon influence fascicle shortening (Kawakami et al., 1998; Oda et al., 2007). In this study, the controlled participant position and joint angle would result in constant muscle and tendon length between conditions. Thus, it would be surprising if the tendon held to a similar length influenced architectural responses in one condition more than the other.

Typical of electrically induced and voluntary contractions the maximal torque output was higher in the MVC than the maximal NMES condition. Because fascicle length did not differ between maximal NMES and MVC it seems that the amount of torque generated in an NMES induced contraction is not limited by the shortening range of fascicles. Therefore, when applying NMES consideration must be given to not only the net torque output desired but the localized area of activity that has a greater amount of architectural change relative to torque-matched voluntary contractions.

Results from this study suggest that there is a potentially localized contractile shortening induced by NMES compared with voluntary torque-matched efforts. This observation should be restricted to stimulation over a muscle rather than through activation of the nerve. The experimental protocol was limited by accessibility to a nerve stimulator, but also constrained to muscle as there are conditions in which muscle stimulation is recommended, notably when selective activation of a single muscle is of interest, such as in rehabilitation after knee surgery (Gatewood et al., 2016) or after stroke (Cho et al., 2015). In addition, muscle stimulation allows self-use by patients at home for example for the treatment of sarcopenia (Nishida et al., 2016). Future work should be extended to clinical patients as well as large and bi-articular muscles to further consider the effect of muscle length and muscle mass.

Although NMES is a common modality used in rehabilitation, the mechanisms associated with its long-term effects are not well understood. This study highlights that during NMES, the activation of muscle fibers is localized to the electrode area and that fascicle shortening between NMES and voluntary activity is unique to each condition. Because the muscle fibers respond differently between NMES and voluntary contraction care should be taken when applying NMES to induce a similar level of force as a voluntary contraction as the individual fibers are likely placed under higher stress as demonstrated through greater shortening under the stimulation electrode. Further studies are needed to assess the long-term effects of non-homogeneous recruitment of the muscle. Observations from this study of differences in fiber shortening between NMES and voluntary contractions were made at an ankle joint angle of 110°. Further study is required to determine whether this observation applies across the entirety of the length-tension relationship.

In conclusion, these *in vivo* measures undertaken with ultrasonography indicate that for the same torque output as a voluntary contraction NMES induces greater fascicle shortening and increased pennation angles. Thus, care should be applied when torque output is being used as the criterion for NMES training in rehabilitation and exercise applications. Knowledge of greater architectural change with NMES relative to torque-matched contractions should be applied to clinical methodological guidelines for electrical stimulation.

REFERENCES

Bergquist, A.J., Wiest, M.J., Collins, D.F., 2012. Motor unit recruitment when neuromuscular electrical stimulation is applied over a nerve trunk compared with a muscle belly: quadriceps femoris. J. Appl. Physiol. 113, 78–89. doi:10.1152/japplphysiol.00074.2011

Bickel, C.S., Gregory, C.M., Dean, J.C., 2011. Motor unit recruitment during neuromuscular electrical stimulation: a critical appraisal. Eur. J. Appl. Physiol. 111, 2399–407. doi:10.1007/s00421-011-2128-4

Botter, A., Oprandi, G., Lanfranco, F., Allasia, S., Maffiuletti, N.A., Minetto, M.A., 2011. Atlas of the muscle motor points for the lower limb: implications for electrical stimulation procedures and electrode positioning. Eur. J. Appl. Physiol. 111, 2461–71. doi:10.1007/s00421-011-2093-y

Carolan, B., Cafarelli, E., 1992. Adaptations in coactivation after isometric resistance training. J. Appl. Physiol. 73, 911–7.

Chapman, J.P., Chapman, L.J., Allen, J.J., 1987. The measurement of foot preference. Neuropsychologia 25, 579–584.

Cho, M.K., Kim, J.H., Chung, Y., Hwang, S., 2015. Treadmill gait training combined with functional electrical stimulation on hip abductor and ankle dorsiflexor muscles for chronic hemiparesis. Gait Posture 42, 73–78. doi:10.1016/j.gaitpost.2015.04.009

Feiereisen, P., Duchateau, J., Hainaut, K., 1997. Motor unit recruitment order during voluntary and electrically induced contractions in the tibialis anterior. Exp. brain Res. 114, 117–23.

Gatewood, C.T., Tran, A.A., Dragoo, J.L., 2016. The efficacy of post-operative devices following knee arthroscopic surgery: a systematic review. Knee Surgery, Sport. Traumatol. Arthrosc. 1–16. doi:10.1007/s00167-016-4326-4

Gobbo, M., Gaffurini, P., Bissolotti, L., Esposito, F., Orizio, C., 2011. Transcutaneous neuromuscular electrical stimulation: influence of electrode positioning and stimulus amplitude settings on muscle response. Eur. J. Appl. Physiol. 111, 2451–9. doi:10.1007/s00421-011-2047-4

Gregory, C.M., Bickel, C.S., 2005. Recruitment patterns in human skeletal muscle during electrical stimulation. Phys. Ther. 85, 358–64.

Henneman, E., Somjen, G., Carpenter, D.O., 1965. Functional significance of cell size in spinal motoneurons. J. Neurophysiol. 28, 560–80.

Heyters, M., Carpentier, A., Duchateau, J., Hainaut, K., 1994. Twitch analysis as an approach to motor unit activation during electrical stimulation. Can. J. Appl. Physiol. 19, 451–61.

Huijing, P.A., Baan, G.C., 2003. Myofascial force transmission: muscle relative position and length determine agonist and synergist muscle force. J. Appl. Physiol. 94, 1092–107. doi:10.1152/japplphysiol.00173.2002

Kawakami, Y., Ichinose, Y., Fukunaga, T., 1998. Architectural and functional features of human triceps surae muscles during contraction. J. Appl. Physiol. 85, 398–404.

Kwah, L.K., Pinto, R.Z., Diong, J., Herbert, R.D., 2013. Reliability and validity of ultrasound measurements of muscle fascicle length and pennation in humans: a systematic review. J. Appl. Physiol. 114, 761–9. doi:10.1152/japplphysiol.01430.2011

Lieber, R.L., Fridén, J., 2000. Functional and clinical significance of skeletal muscle architecture. Muscle Nerve 23, 1647–66.

Maffiuletti, N.A., Minetto, M.A., Farina, D., Bottinelli, R., 2011. Electrical stimulation for neuromuscular testing and training: state-of-the art and unresolved issues. Eur. J. Appl. Physiol. 111, 2391–7. doi:10.1007/s00421-011-2133-7

Maffiuletti, N.A., Pensini, M., Martin, A., 2002. Activation of human plantar flexor muscles increases after electromyostimulation training. J Appl Physiol 92, 1383–1392.

Maganaris, C.N., 2001. Force-length characteristics of in vivo human skeletal muscle. Acta

Physiol. Scand. 172, 279–85. doi:10.1046/j.1365-201x.2001.00799.x

Maganaris, C.N., Baltzopoulos, V., 1999. Predictability of in vivo changes in pennation angle of human tibialis anterior muscle from rest to maximum isometric dorsiflexion. Eur. J. Appl. Physiol. Occup. Physiol. 79, 294–7. doi:10.1007/s004210050510

Maganaris, C.N., Baltzopoulos, V., Sargeant, A.J., 2002. Repeated contractions alter the geometry of human skeletal muscle. J. Appl. Physiol. 93, 2089–94. doi:10.1152/japplphysiol.00604.2002

Needham, D.M., Truong, A.D., Fan, E., 2009. Technology to enhance physical rehabilitation of critically ill patients. Crit. Care Med. 37, S436-41. doi:10.1097/CCM.0b013e3181b6fa29

Nishida, M.M., Tsuboyama, T., Moritani, T., Arai, H., 2016. Review of the evidence on the use of electrical muscle stimulation to treat sarcopenia. Eur. Geriatr. Med. 7, 267–271. doi:10.1016/j.eurger.2015.11.010

Oda, T., Kanehisa, H., Chino, K., Kurihara, T., Nagayoshi, T., Fukunaga, T., Kawakami, Y., 2007. In vivo behavior of muscle fascicles and tendinous tissues of human gastrocnemius and soleus muscles during twitch contraction. J. Electromyogr. Kinesiol. 17, 587–95. doi:10.1016/j.jelekin.2006.04.013

Raiteri, J., Cresswell, A.G., Lichtwark, G.A., 2015. Ultrasound reveals negligible cocontraction during isometric plantar flexion and dorsiflexion despite the presence of antagonist electromyographic activity. J Appl Physiol 118, 1193–1199. doi:10.1152/japplphysiol.00825.2014.—Because

Reeves, N.D., Narici, M. V, 2003. Behavior of human muscle fascicles during shortening and lengthening contractions in vivo. J. Appl. Physiol. 95, 1090–6. doi:10.1152/japplphysiol.01046.2002

Simoneau-Buessinger, E., Leteneur, S., Toumi, A., Dessurne, A., Gabrielli, F., Barbier, F., Jakobi, J.M., 2015. Bilateral strength deficit is not neural in origin; Rather due to dynamometer mechanical configuration. PLoS One 10, 1–11. doi:10.1371/journal.pone.0145077

Simoneau, E., Billot, M., Martin, A., Van Hoecke, J., 2009. Antagonist mechanical contribution to resultant maximal torque at the ankle joint in young and older men. J. Electromyogr. Kinesiol. 19, e123-31. doi:10.1016/j.jelekin.2007.11.006

Simoneau, E., Longo, S., Seynnes, O.R., Narici, M. V, 2012. Human muscle fascicle behavior in agonist and antagonist isometric contractions. Muscle Nerve 45, 92–99.

Toumi, A., Leteneur, S., Gillet, C., Debril, J.-F., Decoufour, N., Barbier, F., Jakobi, J.M., Simoneau-Buessinger, E., 2015. Enhanced precision of ankle torque measure with an open-unit dynamometer mounted with a 3D force-torque sensor. Eur. J. Appl. Physiol. doi:10.1007/s00421-015-3210-0

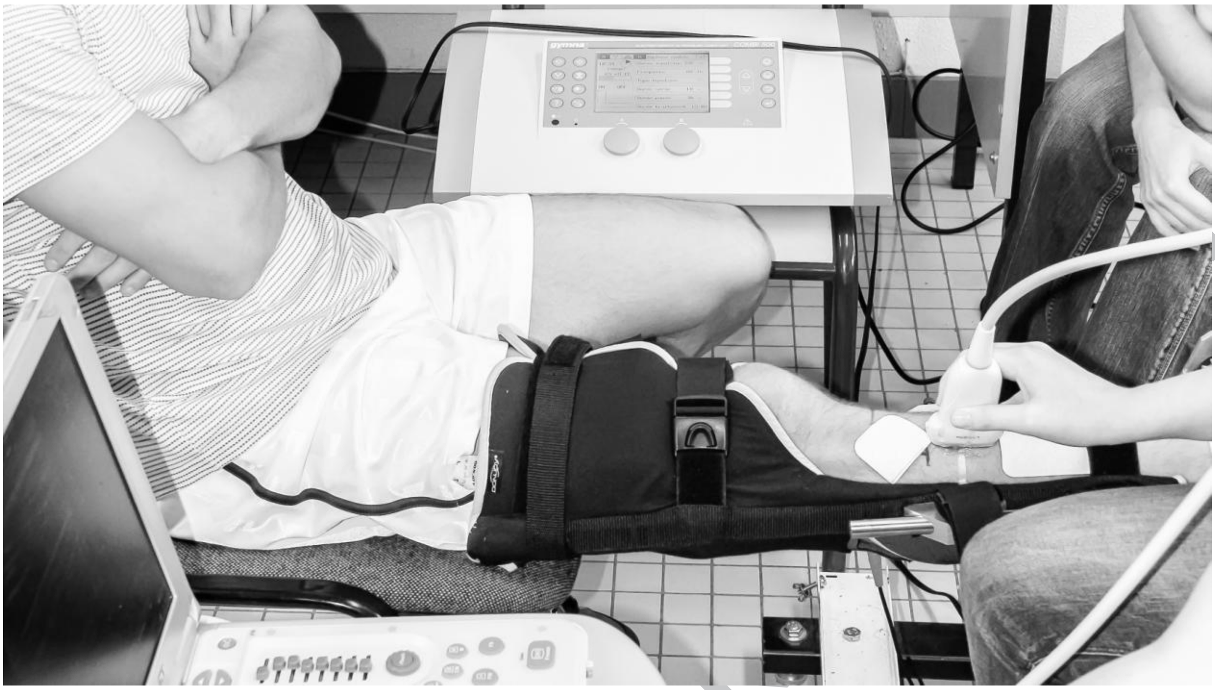
Trimble, M.H., Enoka, R.M., 1991. Mechanisms underlying the training effects associated with neuromuscular electrical stimulation. Phys. Ther. 71, 273–80.

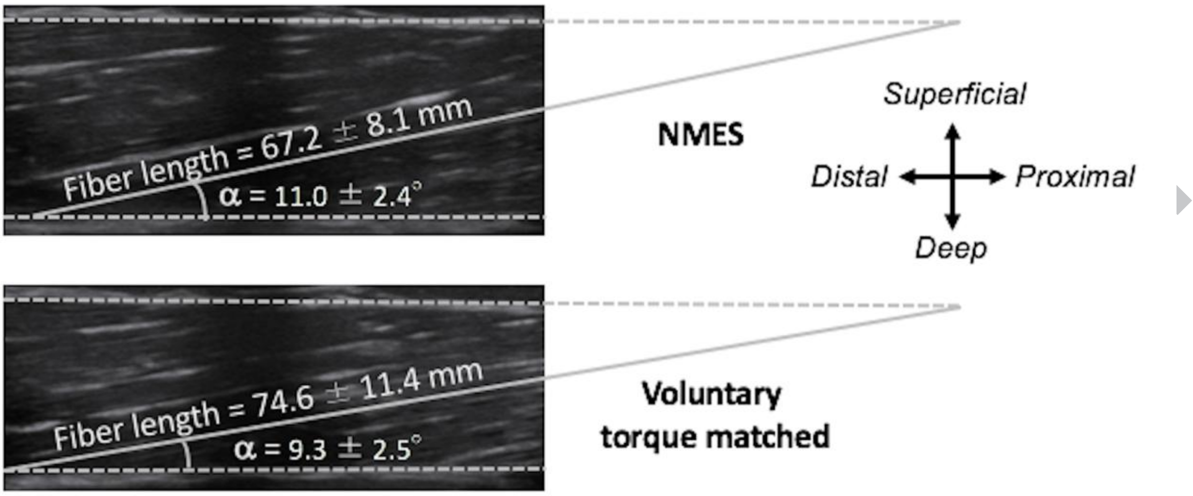
CAPTIONS TO ILLUSTRATIONS

Fig. 1 Experimental setup with stimulation pads and ultrasound probe over the tibialis anterior muscle.

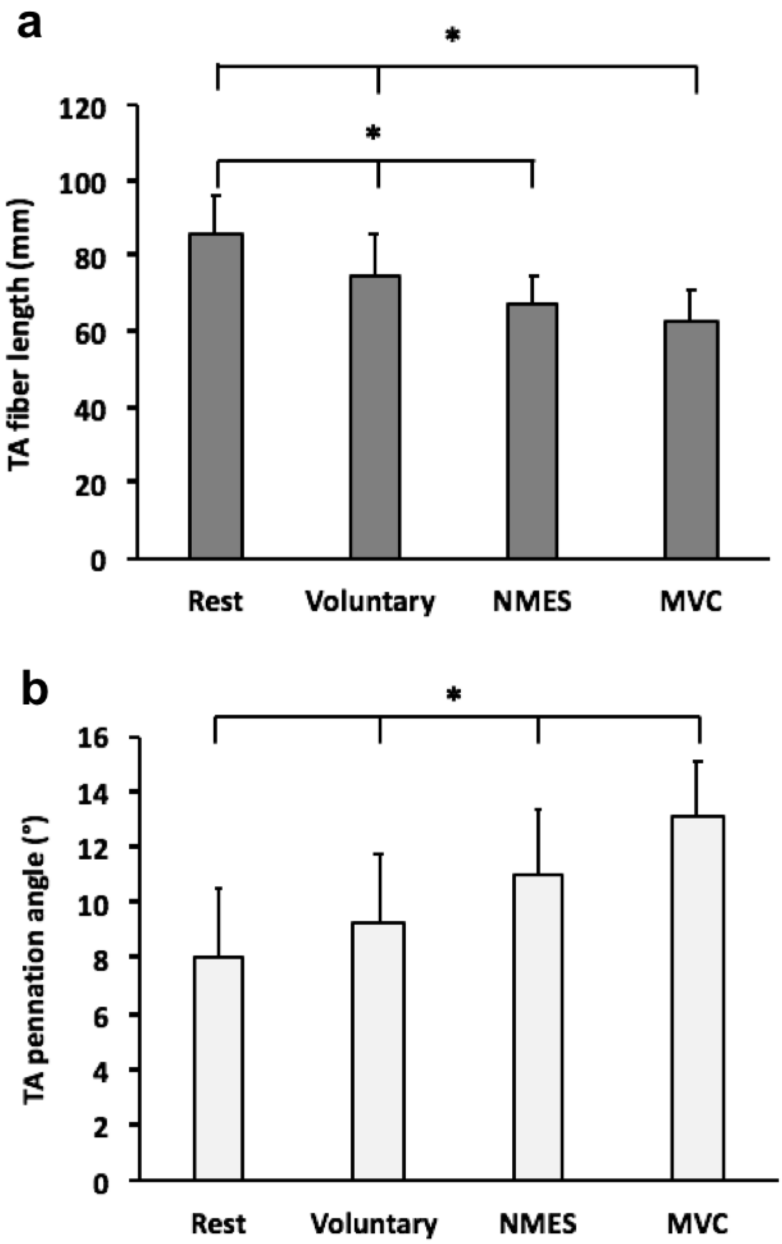
Fig. 2 Ultrasound scans of the tibialis anterior obtained during neuromuscular electrical stimulation (NMES) and during voluntary torque-matched dorsiflexion isometric contractions

Fig. 3 Fibre length (a) and pennation angle (b) of the tibialis anterior (TA) muscle were measured at rest, during voluntary submaximal contractions (torque-matched to NMES), neuromuscular electrical stimulation (NMES) and maximal voluntary contractions (MVC). Data are reported as means ± SD. There was a significant difference in fiber length across all conditions, except between NMES and MVC: *, significant difference in pennation angle between conditions ($p < 0.05$).





Fiber length = 67.2 ± 8.1 mm
α = 11.0 ± 2.4°
NMES
Superficial
Distal
Proximal
Deep
Fiber length = 74.6 ± 11.4 mm
α = 9.3 ± 2.5°
Voluntary
torque matched


a
*
*
120
100
80
60
40
20
0
TA fiber length (mm)
Rest
Voluntary
NMES
MVC
b
*
16
14
12
10
8
6
4
2
0
TA pennation angle (°)
Rest
Voluntary
NMES
MVC

Emilie Simoneau-Buessinger received her PhD in Neuromuscular Physiology from the Sport Science Department of the University of Burgundy (Dijon, France). She is currently a Profesor at LAMIH (UMR CNRS 8201), University of Valenciennes (France). Her major research interests focus on neuromuscular adaptations, especially with aging, strength training and chronic pathologies. The main objective of her research is based on the biomechanical characterization of the musculoskeletal system in order to optimize functional reconditioning.

Sébastien Leteneur is currently a half time Associate Professor at LAMIH (UMR CNRS 8201), University of Valenciennes (France). His research focuses on biomechanics of human locomotion, especially with clinical outcomes. He works on several rehabilitation topics, such as low back pain or ankle force assessment. He is currently the scientific manager of the GRAAL project: 'Gait Rehabilitation Analysis Amputee Locomotion'. He is also a half time physiotherapist in a neurological rehabilitation department at the hospital of Saint-Amand-Les-Eaux (France).

Alix Bisman received her Master's in Physiotherapy from the Haute Ecole Provinciale Condorcet (Belgium) in 2013 and her Master's in Engineering and Ergonomics of Physical Activity from the University of Valenciennes (France) in 2015. She teaches Biomechanics and Movement Analysis at the Haute Ecole Provinciale Condorcet since 2016. She is as well a physiotherapist at the University Hospital of Ambroise Paré (Belgium).

François Gabrielli is a post-doctoral researcher at LAMIH (UMR CNRS 8201), University of Valenciennes (France). He obtained his PhD in biomedical engineering, on the application signal processing to impact biomechanics. He specialized in the processing of biological signals, biomechanics and visual feedback, and is interested in all applications of engineering science to rehabilitation.

Jennifer (Jenn) Jakobi is an Associate Professor in Health and Exercise Sciences at the University of British Columbia Okanagan (Canada). Her work focusses on determining neural and musculoskeletal contributions to the control of functional movement. Studies concentrate on both normal physiology and its variance across age and between sexes, as well as in altered situations of Parkinson's disease, frailty and high performance training.