J. Phys. Ther. Sci.
24: 169–174, 2012

Skin Cold Stimulation of the Dermatome Modulates Activation of the Quadriceps

Hitoshi Sugawara, PT, MS[1)], Ryota Shimose, PT, MS[1)],
Chigaya Tadano, PhD[2)], Masuo Muro, PhD[2)]

[1)] *Department of Physiology, Graduate School of Medicine, Toho University, 5–21–16 Omori-Nishi, Ohta-ku, Tokyo, 143-8540, Japan. TEL: +81 3-6424-2204, E-mail: sugawarahi@hs.teu.ac.jp*
[2)] *Department of Exercise Physiology, Facutly of Medicine, School of Medicine, Toho University*

Abstract. [Purpose] To examine electromyographic (EMG) activity change during dynamic contraction of the quadriceps with skin cold stimulation (SCS) over the vastus lateralis (VL) and L4 dermatome area on the medial side of the lower leg. [Subjects and Methods] Seventeen healthy male volunteers participated. Dynamic knee extension was performed at 15% maximum voluntary contraction (MVC). SCS is a method used to cool the skin to 25 °C using a gel-cooling pad. The SCS method has no effect on the muscle below the cooled skin. Subjects performed dynamic knee extension under 4 randomly selected conditions: (1) SCS of skin over the VL (SCS_{VL}), (2)without SCS of skin over the VL (non-SCS_{VL}), (3) SCS of L4 dermatome area on the medial side of the lower leg (SCS_{L4}), and (4) without SCS of L4 dermatome area on the medial side of the lower leg (non-SCS_{L4}). Surface EMG from the rectus femoris (RF), VL, and vastus medialis (VM) were recorded using miniature electrodes. [Results] The root mean square of the EMG (rmsEMG) of the VL with SCS was significantly greater than activation without SCS, but was decreased by SCS_{L4}. However, the activity of RF and VM did not change in any condition. [Conclusion] Our results suggest that the influence of cutaneous input can demonstrably modulate muscle activation.
Key words: Skin cold stimulation, Dermatome, Muscle activation

(This article was submitted Sep. 7, 2011, and was accepted Oct. 12, 2011)

INTRODUCTION

Cutaneous stimulation is used as a physical therapy intervention for the treatment of neurological and musculoskeletal dysfunction. In clinical studies, it has been demonstrated that brushing or stroking of the skin over a muscle leads to modulation of the motor neuron (MN) pool in neurological disease[1,2)]. Studies utilizing electrical stimulation of the skin have demonstrated a change in MN excitability in patients with spinal cord injury[3,4)]. However, it is unclear whether alteration of the MN pool has a facilitative or inhibitory effect induced by cutaneous stimulation of the dermatome far from the working muscle. Loggie[5)] suggested that activation of MNs in the working muscle is affected by skin stimulation of the dermatome because of the neural connection between the dermatome and myotome.

In laboratory studies, it is well known that facilitatory and inhibitory responses of spinal MNs occur with electrical stimulation of cutaneous nerves[6,7)], skin brushing[8,9)] and skin anesthesia[10–13)]. These studies have shown that MN excitability is altered by activation of cutaneous afferents. Modulation of the MN pool differs depending on the type of stimulation or the area of stimulation. Hagbarth[14)] suggested that the motor response to noxious stimulation of the skin is either facilitative or inhibitory due to interaction of the skin with homogenous muscle. In contrast, Gassel et al.[15)] reported that non-noxious stimulation of the dermatome of linked muscles causes excitatory and inhibitory effects.

In a previous study, Yona suggested that skin cold stimulation (SCS) recruits high threshold-motor units (HT-MUs) at low load[16)]. The recruitment threshold of HT-MUs is reduced due to sensory input from cold receptors. In Yona's work, the recruitment threshold decreased when the skin temperature was 25 °C and there was no change in the temperature of the working muscle. This result was obtained when SCS was applied to the skin over the working muscle. Several other studies have also demonstrated a change in MU recruitment pattern. In some subjects HT-MU activation threshold was reduced, whereas in others, there was a reversal in the MU recruitment pattern when low-threshold (LT)-MUs were inhibited and HT-MUs were facilitated[17–22)].

The modulation of muscle activation associated with the linkage between dermatome and myotome induced by SCS has yet to be examined. Therefore, the purpose of this study was to examine the change in EMG activity during dynamic contraction of the quadriceps with SCS of the medial L4 dermatome of the upper and lower leg.

SUBJECTS AND METHODS

Subjects

Seventeen healthy male subjects with an average age of 23.1 ± 5.3 years (range of 20–42 yrs) and an average body mass of 63.1 ± 7.4 kg voluntarily participated in the present

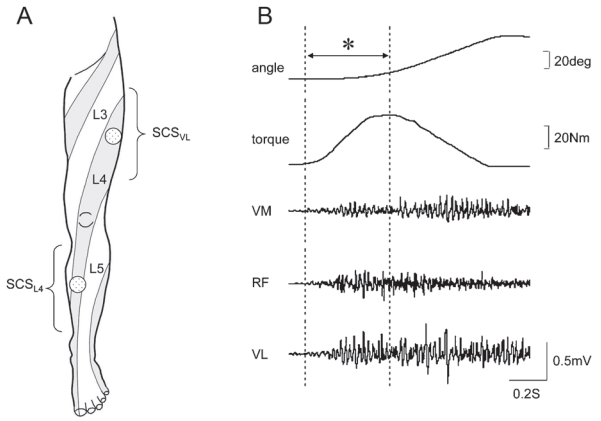

Fig. 1. The dermatome map showing SCS application sites and data samples showing areas of analysis. The dermatome map is from Keegan and Garrett (1948) (A). Position of the skin cooling gel pad for SCS of VL (SCS_{VL}) and SCS of the L4 dermatome area on the medial side of the lower leg (SCS_{L4}) are shown in A. Raw data samples of range, torque, and EMG activities of the vastus medialis (VM), rectus femoris (RF) and vastus lateralis (VL) during dynamic knee extension contraction (A). Range, peak torque and rmsEMG were analyzed at peak force from the rise in contractile force (✻).

study. The Human Subjects Institutional Review Board at Toho University (#21035) approved the research designs for this procedure and all volunteers provided their informed consent.

Methods

Subjects were comfortably seated in a custom-made chair and their left leg was positioned at an angle of 110° between the spine and the femur. A seatbelt was firmly secured over the pelvis. A torque meter (9E05-B1-50; NEC Co. Ltd., Japan) was attached to the custom-made chair to measure the torque of isometric and dynamic extension of the left knee. The output of the torque meter was amplified, filtered (100 Hz filter) and sampled at 1 kHz. For the conditioning test, a dynamometer utilizing a bicycle ergometer (Power-Max-V; Combi Co. Ltd., Japan) was used.

Surface EMG of the muscle bellies of the rectus femoris (RF), vastus lateralis (VL), and vastus medialis (VM) were recorded using miniature pair electrodes (Unique Medical Co., Ltd., Japan). These silver/silver electrodes are circular with a diameter of 5 mm and the distance between the center of each electrode pair was 10 mm. The electrode for VL was placed at 25% of the distance between the superior border of the patella and the greater trochanter, because the EMG amplitude is a little greater at this point than at the midpoint location[23]. The electrode for RF was placed at 50% of the distance between the anterior superior iliac spine of the pelvis and the superior border of the patella, and the electrode for VM was placed at 20% of the distance between the medial gap of the knee joint and the anterior superior iliac spine of the pelvis[24]. Prior to electrode placement, leg hair was shaved and the skin was abraded gently with fine sandpaper to reduce skin impedance in the area where electrodes were to be positioned. Surface EMG signals were recorded at a sampling frequency of 1 kHz using an A–D converter (Power Lab; ADInstruments, Melbourne, Australia). Data analysis was performed using Chart 7 software (ADInstruments). In addition, real-time frequency analysis of the continuous wavelet transformation was carried out using a signal-processing toolbox (Km-Mercury; ASAP System Co., Ltd., Japan). EMG signals were digitally high-pass filtered at 5 Hz for the root mean square of the EMG (rmsEMG) analysis and band-pass filtered from 10 to 500 Hz for real-time frequency analysis of the power spectrum of the frequency domain.

Subjects rapidly performed two maximal voluntary isometric knee extension contractions (MVC) for 2–3 sec, with the knee at 70° flexion. The mean MVC of all subjects was 150.9 ± 34.5 Nm (range 115.2–228.7). The peak torque was determined as the maximum torque generated by each MVC. The resistance of the dynamometer was set at 15% of MVC. Unilateral dynamic knee extension contractions were performed for 1 sec at 15% MVC from 70° to 0° of knee extension in all conditioning tests. Moreover, the subjects could view the range of motion generated on an oscilloscope (DCS-7020; Kenwood Co. Ltd., Japan). Subjects performed dynamic knee extension under 4 randomly selected conditions: (1) SCS of the skin over the VL (SCS_{VL}), (2) without SCS of the skin over the VL (non-SCS_{VL}), (3) SCS of the L4 dermatome area on the medial side of the lower leg (SCS_{L4}), and (4) without SCS of the L4 dermatome area on the medial side of the lower leg (non-SCS_{L4}). The conditioning test involving the dynamic task was repeated 5 times under the conditions described. The dermatome was mapped using Keegan and Garrett's map[25], which was generated in a study that included a large number of patients. Figure 1 illustrates the dermatome map and the area of SCS.

A thermal control pad was used as a gel-cooling pad (Alcare Co. Ltd, Japan). The size of the pad was 16 × 18 cm. The pad, which is comprised of 2 sheets, was placed into a case purpose-built for this study. This pad was used in order to maintain the skin temperature at 25 °C. The SCS condition was defined as when the skin temperature was at 25 °C while the dynamic task was being executed. Furthermore, non-SCS_{VL} and non-SCS_{L4} utilized a gel pad at a temperature the same as skin temperature.

The data obtained from the third to fifth trial of 5 repetitions under each condition were utilized in the analysis, which was carried out on data obtained from the rise in contractile force to its peak. Impulse (Nm · time), %MVC, the rate of force development, skin temperature and rmsEMG were calculated (Fig. 1). The mean power frequency (MPF) of the real-time frequency was analyzed at 0.5 s from the rise in contractile force.

The SCS/non-SCS ratio was determined after performing parametric tests, the paired t-test, on the data from SCS and non-SCS conditions (SCS_{VL} and SCS_{L4}). The level of significance was chosen as 5%.

Table 1. Task and skin temperature values (mean ± SD) under each experimental condition

		VL		dermatome	
		non-SCS_{VL}	SCS_{VL}	non-SCS_{L4}	SCS_{L4}
%MVC		32.0 ± 8.3	32.6 ± 7.3	33.3 ± 8.2	32.4 ± 8.9
Impulse(Nm · sec)		13.8 ± 2.8	13.0 ± 2.0	14.0 ± 2.6	14.1 ± 2.5
Rate of force development (Nm · sec)		105.9 ± 47.4	116.8 ± 49.8	113.2 ± 43.9	104.1 ± 46.4
Skin temperature					
Skin over the VL	pre-test	32.0 ± 1.0	24.9 ± 0.7*	32.1 ± 0.8	32.2 ± 0.7
	post-test	32.2 ± 0.9	6.4 ± 1.2*	32.1 ± 0.7	32.2 ± 0.7
Medial surface of tibia	pre-test	31.2 ± 1.0	31.1 ± 1.0	31.1 ± 0.8	25.0 ± 1.3*
	post-test	31.1 ± 1.0	31.1 ± 0.9	31.2 ± 0.7	24.5 ± 2.1*

Asterisks indicate significant differences from non-SCS ($p<0.01$). SCS_{VL}: SCS of skin over the VL, non-SCS_{VL}: non-SCS of skin over the VL, SCS_{L4}: SCS of L4 dermatome area on the medial side of the lower leg, non-SCS_{L4}: non-SCS of L4 dermatome area on the medial side of the lower leg

Table 2. Change in rmsEMG and MPF values (mean ± SE) due to stimulation over the worked muscle (SCS_{VL}) and stimulation of dermatome (SCS_{L4})

	VL		dermatome	
	non-SCS_{VL}	SCS_{VL}	non-SCS_{L4}	SCS_{L4}
rmsEMG (mV)				
VM	0.056 ± 0.011	0.055 ± 0.007	0.058 ± 0.011	0.059 ± 0.011
RF	0.038 ± 0.003	0.037 ± 0.003	0.040 ± 0.004	0.037 ± 0.003
VL	0.065 ± 0.007	0.073 ± 0.008*	0.069 ± 0.007	0.064 ± 0.006*
MPF (Hz)				
VM	95.1 ± 24.3	92.3 ± 25.1	97.2 ± 31.5	95.5 ± 28.4
RF	98.6 ± 23.0	94.4 ± 16.3	92.1 ± 17.9	98.7 ± 17.8
VL	101.2 ± 17.0	108.6 ± 30.9	102.4 ± 19.1	102.1 ± 21.4

Significant differences between non-SCS and SCS are indicated by *($p<0.05$). SCS_{VL}: SCS of skin over the VL, non-SCS_{VL}: non-SCS of skin over the VL, SCS_{L4}: SCS of L4 dermatome area on the medial side of the lower leg, non-SCS_{L4}: non-SCS of L4 dermatome area on the medial side of the lower leg

RESULTS

The raw data for each condition are presented in Table 1. No significant differences were found between SCS and non-SCS for the impulse (Nm · second) from rise in contractile force to peak, %MVC and rate of force development ($p > 0.05$). The mean baseline skin temperature before SCS was 32.4 °C (range 30.4–34.4 °C) over VL and 31.3 °C (range 30.0–32.5 °C) on the medial side of the lower leg. Pre and post-test baseline skin temperatures over VL with SCS_{VL} were significantly different ($p<0.01$). Furthermore, there was a significant difference between the pre- and post-test baseline skin temperatures of the medial side of the lower leg for SCS_{L4} ($p<0.01$).

Examples of surface EMG recordings are shown in Figure 2 in the bottom panel (VM, RF, VL). Figure 2A shows EMG activities in both non-SCS and SCS over VL. During SCS over VL, EMG activity of VL increased only during dynamic contraction, but EMG activity of VM and RF did not change during dynamic contraction with SCS. The surface skin temperature clearly decreased with SCS in all subjects (Table 1). In addition, Figure 2B shows EMG activities during non-SCS and SCS of the dermatome of the lower limb. During SCS of the dermatome, EMG activities of VM and RF did not change during dynamic contraction but EMG activity of VL decreased. There was no significant difference in skin temperature pre- and post-task under both conditions (Table 1).

The rmsEMG of VL with SCS_{VL} was significantly greater than activation with non-SCS_{VL}, but the rmsEMG was decreased by SCS_{L4} ($p<0.05$; Table 2). However, the RF and VM demonstrated no modulation with both SCS_{VL} and SCS_{L4}. The MPF of SCS_{VL} displayed a trend towards upper frequency bands in VL, but this was not seen for either RF or VM (Table 2). Furthermore, there was no change of MPF of VL with SCS_{L4}.

In the results of the t test for VL, there was a significant difference between the relative rmsEMG (SCS / non-SCS (%)) of SCS_{VL} and SCS $_{L4}$, 13.1 ± 2.8% and −6.1 ± 2.6% respectively ($p<0.05$; Table 3). However, the relative rmsEMG of VM and RF remained unchanged. There was a tendency of increase in the relative MPF of VL and RF, 7.4 ± 5.7% and 8.7 ± 4.1% in SCS_{L4} and SCS_{VL} respectively, but the other muscles did not change under the other conditions ($p<0.05$; Table 3).

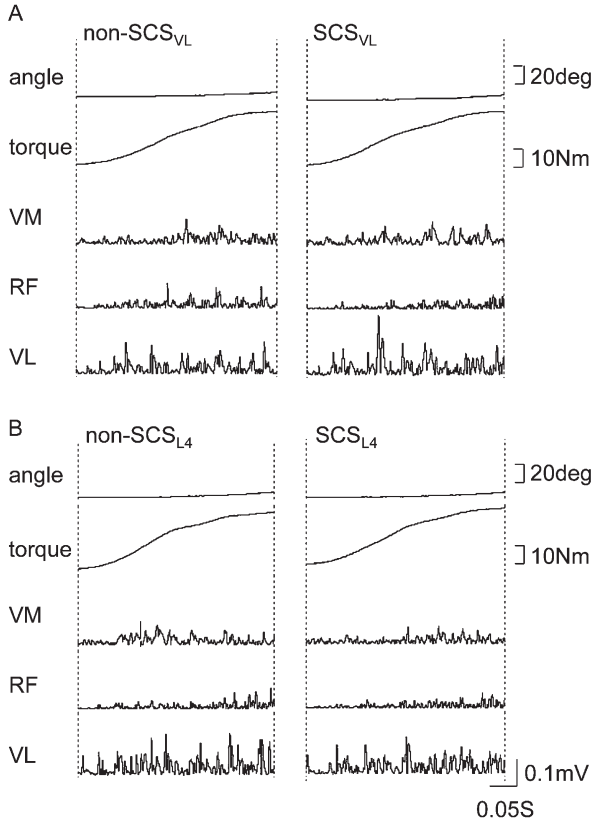

Fig. 2. Typical examples of surface-electromyographic data. Typical examples of full-wave rectified EMG from the areas of analysis, non-SCS and SCS over the VL(SCSVL) (A), non-SCS and SCS of the L4 dermatome area on the medial side of the lower leg (SCSL4) (B).

DISCUSSION

We derived some significant findings from this study. During dynamic contraction, activation of VL not only increased with SCS over the working muscle (SCS_{VL}), but also decreased with SCS of the dermatome (SCS_{L4}). However, significant changes in activation were not seen in the other muscles (VM and RF). This suggests facilitation of either LT-MUs or HT-MUs suggesting that MN excitability differs based on the area of skin stimulation. Other studies have proposed that extensor muscles are excited by noxious electrical stimulation[26], and the H-reflex in the triceps surae is inhibited by skin brushing[9]. The different sensory sensors of the skin behave in a complex manner when noxious electric, brushing or cold stimuli etc. are applied. Neuromuscular activation may increase the excitability of the Aδ and C-fibers with noxious electrical stimulation, and the excitability of the Aβ-fibers may decrease with skin brushing. Whether a MN pool's response is excitatory or inhibitory depends on the excitability of different axons. In this study, SCS_{VL} facilitated MN excitability increasing rmsEMG of the VL. Both Aδ and C-fibers are excited by skin cooling[27]. Therefore, SCS over a muscle may increase MN excitability.

Table 3. Change of relative rmsEMG and MPF with SCS of VL (SCS_{VL}) and the dermatome (SCS_{L4})

	rmsEMG(% of control)		MPF(% of control)	
	SCS_{VL}	SCS_{L4}	SCS_{VL}	SCS_{L4}
VM	7.7 ± 6.3	1.2 ± 4.4	-1.1 ± 4.6	2.2 ± 6.4
RF	2.5 ± 5.6	-2.8 ± 6.2	-0.6 ± 4.8	8.7 ± 4.1
VL	13.1 ± 2.8*	-6.1 ± 2.6	7.4 ± 5.7	0.8 ± 4.1

Data are presented as mean ± SE from a baseline before SCS (non-SCS) representing 100%. Significant differences between SCS_{VL} and SCS_{L4} are indicated by * ($p<0.05$).

In the present study, there was specific activation of the quadriceps with SCS_{VL} and SCS_{L4}. SCS_{VL} and SCS_{L4} modulated activation only in VL, not in VM and RF. rmsEMG of VL increased significantly with SCS_{VL} over the working muscle but decreased with SCS_{L4} of the dermatome. Although the task force was constant during the dynamic contractions, the EMG activity of VL showed completely opposite responses to skin stimulation over the working muscle (SCS_{VL}) and the dermatome (SCS_{L4}).

The result of SCS_{VL} might be explained by a small increase in MPF in VL, where MUs with a higher firing frequency were recruited later, suggesting facilitation alone. The small increase in MPF and increase of rmsEMG in SCS_{VL} may occur due to the recruitment order of HT-MUs. Nielsen et al.[22] reported that lower firing frequency MUs are recruited early, whereas MUs with a higher firing frequency are recruited later but, as mentioned earlier, this recruitment pattern can change with electrical stimulation of the sural nerve. Although the relationship between rmsEMG and MPF has been found to be that of high-threshold MU recruitment[28,29], in reality, it is difficult to determine a change in MU firing frequency because low loads result in small EMG signals. On the other hand, excitatory or inhibitory behavior differs depending on the effective area of the cutaneous stimulation. Modulation of MNs may occur with either increased or decreased activation at a spinal segmental level.

In this study, SCS_{VL} increased rmsEMG in VL, but VL rmsEMG decreased with SCS_{L4} . Consequently, SCS_{L4} inhibits MNs of innervating surface muscle fibers in VL in the presence of sensory-motor linkage during dynamic contraction. This decrease in rmsEMG is difficult to detect because MNs of the L4 dermatome project to deep muscle fibres in the VL, therefore action potentials occur deep in the muscle rendering them difficult to pick up with surface electrodes. Accordingly, the decrease in rmsEMG does not clearly show whether there is modulation of excitatory and inhibitory connections[14]. These results suggest that the influence of cutaneous input can modulate muscle activation via transmission across interneurons. Based on the results of this study, SCS over the working muscle has a different effect from SCS of a dermatome innervated at the same segment level.

The quadriceps is generally innervated at the L2, L3, and L4 segment levels and muscular braches of the femoral nerve. VM is innervated at L2 and L3, VL is innervated at L3 and L4 and RF is innervated at L2–4. The skin area over

VL, however, is L4 dermatome, extending from the lateral side of the thigh to the medial side of the lower leg. The L4 dermatome on the medial side of the lower leg is innervated by the saphenous nerve in the terminal branch of the femoral nerve. The saphenous nerve, which is purely a sensory nerve, arises from the ventral primary branches of the L3 and L4 segments[30]. Accordingly, cutaneous stimulation modulates the MNs via polysynaptic pathways, where one or more interneurons connect to an afferent neuron (cutaneous sensory). Therefore, MNs of VL can be modulated through cutaneous stimulation of the same spinal segment, i.e., L3 and L4, and the size of the response may reflect the strength of the neural connection between skin cold receptors and the MN pool.

Surface EMG signals detect muscle activation but are not sensitive enough to detect activation of deep muscle fibers. However, when comparing ramp tasks with static force tasks, activation of both surface and deep sites of the worked muscle mass appears in surface EMG[31]. Johnson[32] reported a significant difference in fiber type proportion between deep and superficial areas of VL. Type 2 fibers have a high distribution rate of 67.3% at the surface and 53.1% deep in the muscle. Type 1 fibers are distributed at a rate of 46.9% deep in the muscle and 37.8% at the surface[32]. When EMG amplitude increased more than the control during skin stimulation over the working muscle (SCS_{VL}), with constant force output during weak muscle contraction, we consider that activation of type 2 fibers in the surface area of the muscle (fast MUs) increased because of skin stimulation over the working muscle (SCS_{VL}) . In contrast, when SCS_{L4} of the dermatome decreased rmsEMG of VL, it seems that type 2 fibers (HT-MUs) or type 1 fibers (LT- MUs) deep in the muscle were activated. Consequently, our results support the findings of other researchers that there are changes in EMG and proportion of fiber types between deep and surface area muscle[16, 33].

In other studies, electrical stimulation of the saphenous nerve (L4 dermatome) affected modulation of the soleus[11]. Moreover, Marchand-Pauvert et al.[7] reported that electrical stimulation of the lateral articular nerve in another segment (L5 dermatome) influenced modulation of the MNs of the quadriceps. Many investigations have reported the influence of electrical stimulation on the soleus muscle but no previous study has looked at the relationship between cutaneous stimulation and facilitation of the quadriceps via the dermatome. In the present study, the excitation of VL seems to have been produced through SCS of the L4 dermatome. Therefore, our results suggest that L4 dermatome MNs project to the VL.

Moreover, the force contributions in the quadriceps correlates with anatomical cross-sectional areas. The contributing fraction is 35% from RF and 40% from VL and 25% from VM[34]. In addition, muscle activities of VL and RF are significantly greater than that of the VM in the middle of the range of contraction intensity[35]. For this reason, it seems that activation clearly appears in VL with SCS rather than the other muscles of the quadriceps.

In conclusion, our study illustrated the change in VL rmsEMG activity with SCS of the L4 dermatome, during voluntary dynamic knee extension contraction, suggesting modulation of the L4 myotome. The change in MU recruitment pattern due to SCS may be a response to facilitation of the surface or deep muscle. When tasks under both conditions involved low loads (15% MVC), the observed effects were comparable with spinal interneuron responses induced by SCS modulation of the MN pool at low loads through the linkage between the dermatome and myotome. Therefore, we recommend training of spinal neural circuits with SCS as a strategy to improve muscle function by changing MU recruitment patterns.

ACKNOWLEDGEMENTS

We would like to thank the research group and students from Nippon Engineering College who helped with this study.

REFERENCES

1) Garland SJ, Hayes KC: Effects of brushing on electromyographic activity and ankle dorsiflexion in hemiplegic subjects with foot drop. Physiother Can, 1987, 39: 239–247.
2) Brouwer B, de Andrade VS: The effects of slow stroking on spasticity in patients with multiple sclerosis: a pilot study. Physiother Theory Pract, 1995, 11: 13–21. [CrossRef]
3) Bajd T, Gregoric M, Vodovnik L, et al.: Electrical stimulation in treating spasticity resulting from spinal cord injury. Arch Phys Med Rehabil, 1985, 66: 515–517. [Medline]
4) van der Salm A, Veltink PH, Ijzerman MJ, et al.: Comparison of electric stimulation methods for reduction of triceps surae spasticity in spinal cord injury. Arch Phys Med Rehabil, 2006, 87: 222–228. [Medline] [CrossRef]
5) Loggie M: Some aspects of the treatment of adult hemiplegia. Physiotherapy, 1966, 52: 353–356. [Medline]
6) Burke JR, Kamen G, Koceja DM: Long-latency enhancement of quadriceps excitability from stimulation of skin afferents in young and old adults. J Gerontol, 1989, 44: M158–M163. [Medline]
7) Marchand-Pauvert V, Nicolas G, Burke D, et al.: Suppression of the H reflex in humans by disynaptic autogenetic inhibitory pathways activated by the test volley. J Physiol, 2002, 542: 963–976. [Medline] [CrossRef]
8) Mason CR: One method for assessing the effectiveness of fast brushing. Phys Ther, 1985, 65: 1197–1202. [Medline]
9) Wood L, Nicol DJ, Thulin CE: The effects of skin brushing on H reflex amplitude in normal human subjects. Exp Physiol, 1998, 83: 175–183. [Medline]
10) Sabbahi M, De Luca CJ: Topical anesthesia: H-reflex recovery changes by desensitization of the skin. Electroencephalogr Clin Neurophysiol, 1981, 52: 328–335. [Medline] [CrossRef]
11) Delwaide PJ, Crenna P: Cutaneous nerve stimulation and motoneuronal excitability. II: Evidence for non-segmental influences. J Neurol Neurosurg Psychiatry, 1984, 47: 190–196. [Medline] [CrossRef]
12) Arsenault AB, Bélanger AY, Durand MJ, et al.: Effects of TENS and topical skin anesthesia on soleus H-reflex and the concomitant influence of skin/muscle temperature. Arch Phys Med Rehabil, 1993, 74: 48–53. [Medline]
13) Agostinucci J: The effect of topical anesthetics on skin sensation and soleus motoneuron reflex excitability. Arch Phys Med Rehabil, 1994, 75: 1233–1240. [Medline] [CrossRef]
14) Hagbarth KE: Spinal withdrawal reflexes in the human lower limbs. J Neurol Neurosurg Psychiatry, 1960, 23: 222–227. [Medline] [CrossRef]
15) Gassel MM, Ott KH: Local sign and late effects on motoneuron excitability of cutaneous stimulation in man. Brain, 1970, 93: 95–106. [Medline] [CrossRef]
16) Yona M: Effects of cold stimulation of human skin on motor unit activity. Jpn J Physiol, 1997, 47: 341–348. [Medline] [CrossRef]
17) Clendenin MA, Szumski AJ: Influence of cutaneous ice application on single motor units in humans. Phys Ther, 1971, 51: 166–175. [Medline]
18) Grimby L, Hannerz J: Disturbances in voluntary recruitment order of low and high frequency motor units on blockades of proprioceptive afferent activity. Acta Physiol Scand, 1976, 96: 207–216. [Medline] [CrossRef]
19) Stephens JA, Garnett R, Buller NP: Reversal of recruitment order of signal

motor units produced by cutaneous stimulation during voluntary muscle contraction in man. Nature, 1978, 272: 362–364. [Medline] [CrossRef]
20) Garnett R, Stephens JA: Changes in the recruitment threshold of motor units produced by cutaneous stimulation in man. J Physiol, 1981, 311: 463–473. [Medline]
21) Masakado Y, Kamen G, De Luca CJ: Effects of percutaneous stimulation on motor unit firing behavior in man. Exp Brain Res, 1991, 86: 426–432. [Medline] [CrossRef]
22) Nielsen J, Kagamihara Y: Differential projection of the sural nerve to early and late recruited human tibialis anterior motor units change of recruitment gain. Acta Physiol Scand, 1993, 147: 385–401. [Medline] [CrossRef]
23) Malek MH, Housh TJ, Coburn JW, et al.: The effects of interelectrode distance on electromyographic amplitude and mean power frequency during incremental cycle ergometry. J Neurosci Methods, 2006, 151: 139–147. [Medline] [CrossRef]
24) Zipp P: Recommendations for the Standardization of Lead Positions in Surface Electromyography. Eur J Appl Physiol. 1982, 50: 41–54.
25) Keegan JJ, Garrnett FD: The segmental distribution of the cutaneous nerves in the limbs of man. Anat Rec, 1948, 102: 409–437. [Medline] [CrossRef]
26) Landgren S: Excitatory and inhibitory skin areas for flexor and extensor motoneurones. Acta Physiol Scand, 1952, 26: 1–34. [Medline]
27) Kobayashi K, Fukuoka T, Obata K, et al.: Distinct expression of TRPM8, TRPA1, and TRPV1 mRNAs in rat primary afferent neurons with adelta/c-fibers and colocalization with trk receptors. J Comp Neurol, 2005, 493: 596–606. [Medline] [CrossRef]
28) Karlsson S, Gerdle B: Mean frequency and signal amplitude of the surface EMG of the quadriceps muscles increase with increasing torque -a study using the continuous wavelet transform-. J Electromyogr Kinesiol, 2001, 11: 131–140. [Medline] [CrossRef]
29) Wakeling JM, Rozitis AI: Spectral properties of myoelectric signals from different motor units in the leg extensor muscles. J Exp Biol, 2004, 207: 2519–2528. [Medline] [CrossRef]
30) Phillips LH, Park TS: Electrophysiological mapping of the segmental innervation of the saphenous and sural nerves. Muscle Nerve, 1993, 16: 827–831. [Medline] [CrossRef]
31) Farina D: Interpretation of the surface electromyogram in dynamic contractions. Exerc Sport Sci Rev, 2006, 34: 121–127. [Medline] [CrossRef]
32) Johnson MA, Polgar J, Weightman D, et al.: Data on the distribution of fibre types in thirty-six human muscles. An autopsy study. J Neurol Sci, 1973, 18: 111–129. [Medline] [CrossRef]
33) Gerdle B, Henriksson-Larsén K, Lorentzon R, et al.: Dependence of the mean power frequency of the electromyogram on muscle force and fibre type. Acta Physiol Scand, 1991, 142: 457–465. [Medline] [CrossRef]
34) Farahmand F, Senavongse W, Amis AA: Quantitative study of the quadriceps muscles and trochlear groove geometry related to instability of the patellofemoral joint. J Orthop Res, 1998, 16: 136–143. [Medline] [CrossRef]
35) Pincivero DM, Coelho AJ: Activation linearity and parallelism of the superficial quadriceps across the isometric intensity spectrum. Muscle Nerve, 2000, 23: 393–398. [Medline] [CrossRef]