

**ABSTRACT:** Continuous epidural stimulation of lumbar posterior root afferents can modify the activity of lumbar cord networks and motoneurons, resulting in suppression of spasticity or elicitation of locomotor-like movements in spinal cord-injured people. The aim of the present study was to demonstrate that posterior root afferents can also be depolarized by transcutaneous stimulation with moderate stimulus intensities. In healthy subjects, single stimuli applied through surface electrodes placed over the T11–T12 vertebrae with a mean intensity of 28.6 V elicited simultaneous, bilateral monosynaptic reflexes in quadriceps, hamstrings, tibialis anterior, and triceps surae by depolarization of lumbosacral posterior root fibers. The nature of these posterior root–muscle reflexes was demonstrated by the duration of the refractory period, and by modifying the responses with vibration and active and passive movements. Stimulation over the L4–L5 vertebrae selectively depolarized posterior root fibers or additionally activated anterior root fibers within the cauda equina depending on stimulus intensity. Transcutaneous posterior root stimulation with single pulses allows neurophysiological studies of state- and task-dependent modulations of monosynaptic reflexes at multiple segmental levels. Continuous transcutaneous posterior root stimulation represents a novel, non-invasive, neuro-modulative approach for individuals with different neurological disorders.

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## POSTERIOR ROOT–MUSCLE REFLEXES ELICITED BY TRANSCUTANEOUS STIMULATION OF THE HUMAN LUMBOSACRAL CORD

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**S**pinal reflex studies have led to a greater understanding of the monosynaptic reflex.<sup>2,7,22</sup> Hoffmann in 1918 reported that electrical stimulation of the posterior tibial nerve in the popliteal fossa evoked long-latency responses of motor units of the triceps surae in humans.<sup>9</sup> These reflex responses were termed the H reflex<sup>17</sup> and further physiologically examined by Magladery and colleagues.<sup>18</sup> The demonstration that such reflex activity could be recorded in humans rapidly advanced the means of assessing

supraspinal and sensorimotor control in healthy individuals and those with neurological diseases.<sup>11,25</sup>

Lloyd in 1943 reported the elicitation of “dorsal root–ventral root reflex discharges” in a cat model. He recorded a reflex discharge from an anterior root after single-shock stimulation of the posterior root of the same spinal cord segment. The reflex discharge displayed a prominent initial peak thought to be transmitted through a two-neuron reflex arc.<sup>14</sup> In humans, non-invasive detection of dorsal root–ventral root reflex discharges can be accomplished by electromyographic recording from the muscle to which the motoneuron discharge is directed as a monosynaptic reflex. Such posterior root–muscle reflexes (PRM reflexes)<sup>12,20,21</sup> are the basic components of the lower-limb muscle responses that are elicited by epidural stimulation of posterior lumbar cord structures. Monosynaptic PRM reflexes involve the same type of neurons as the stretch reflex or H reflex of the corresponding mus-

**Abbreviations:** CMAP, compound muscle action potential; EMG, electromyography; H, hamstrings; PRM, posterior root–muscle; Q, quadriceps; TA, tibialis anterior; TENS, transcutaneous electrical neural stimulation; TS, triceps surae

**Key words:** cauda equina; electrophysiology; H reflex; lumbosacral cord; posterior roots; transcutaneous stimulation

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cles.<sup>20</sup> Whereas the H reflex is evoked by stimulation of large-diameter afferents in the peripheral nerves, PRM reflexes are elicited in the same sensory axons at proximal sites adjacent to the spinal cord.

Recent studies have shown that PRM reflexes of the soleus can be elicited non-invasively in humans by high-voltage transcutaneous electrical stimulation or by magnetic stimulation of nerve roots at the cauda equina.<sup>16,27,30</sup> However, PRM reflexes evoked by these methods were detected only in the soleus; the responses to the same stimulation in other muscles studied were M waves.<sup>16,27</sup>

The purpose of the present study is to describe a novel approach to elicit short-latency reflexes in muscles innervated by motoneurons from multiple segmental levels. We describe the electrophysiological characteristics of simultaneously evoked bilateral PRM reflexes in quadriceps, hamstrings, tibialis anterior, and triceps surae by transcutaneous stimulation of the posterior roots at lumbosacral cord levels. We also show that, at a more caudal site, stimulation of the cauda equina can give rise to PRM reflexes as well as to direct motor responses that are initiated in the anterior roots. Our non-invasive technique promises to open a new avenue for studies of the peripheral and central mechanisms involved in reflexes and their interaction. Preliminary results of this work have been reported elsewhere.<sup>6</sup>

## MATERIALS AND METHODS

**Subjects.** This study was conducted on eight men, five members of our laboratory staff and three volunteers, aged 20–32 (mean, 27.6) years, with a mean height of 181 cm. Subjects were numbered according to their height, with subject 1 being the tallest. All subjects signed written informed consent to participate, and the study was approved by the local ethics committee.

**Electrode and Stimulation Set-Up.** Electrical stimulation was performed using commercially available self-adhesive transcutaneous electrical neural stimulation (TENS) electrodes (Schwa-medico GmbH, Ehringshausen, Germany). A pair of round electrodes with a diameter of 5 cm was placed over the paravertebral skin 1 cm apart on each side of the spine. This paravertebral electrode pair was positioned between two adjacent spinal processes at the designated rostrocaudal level. A pair of rectangular electrodes (8 cm × 13 cm each) was placed longitudinally over the abdomen, one on either side of the umbilicus. The two electrodes of each pair were connected to function as a single electrode.

A constant-voltage stimulator was used to deliver symmetric, biphasic rectangular pulses. Single stimuli with pulse widths of 2 ms and pairs of stimuli with an interstimulus interval of 50 ms were applied with intensities up to 50 V. The electrodes were connected to the stimulator such that the paravertebral electrodes acted as the anode during the first phase of the stimulus pulse, with the abdominal electrodes as cathode.

**Recording Procedure.** The electromyographic (EMG) activity of stimulus-evoked compound muscle action potentials (CMAPs) of left and right quadriceps, hamstrings, tibialis anterior, and triceps surae was recorded with pairs of silver–silver chloride surface electrodes. Each electrode pair was placed centrally over the corresponding muscle belly with an interelectrode distance of 3 cm, and oriented along the long axis of the muscles. The skin was slightly abraded to obtain electrode impedance below 5 k $\Omega$ . The EMG signals were amplified using Phoenix amplifiers (EMS-Handels GmbH, Korneuburg, Austria) with a gain of 502 over a bandwidth of 10–1000 Hz and digitized at 2048 Hz per channel. The data were analyzed off-line using WinDaq Waveform Browser playback software (Dataq Instruments, Akron, Ohio), and Microsoft Excel (Microsoft, Redmond, Washington) was used for calculations and graphs.

**Study Protocol.** The stimulation protocol was conducted with subjects in a relaxed, supine position. Muscle responses elicited by stimulation over the lumbosacral cord were studied by paravertebral electrodes at the T11–T12 interspinous space. Responses to cauda equina stimulation were tested by paravertebral electrodes at the L4–L5 interspinous space.

For a given stimulation site and intensity, three individual stimuli were triggered at 5-second intervals. Stimulation voltage was gradually increased in 1-V increments. Stimulus-evoked muscle responses were tested to determine whether they were the result of direct efferent stimulation or of reflex origin (see below).

Triceps surae H reflexes were elicited by peripheral nerve stimulation, using the same stimulator as above, adjusted to deliver biphasic rectangular stimuli with pulse widths of 2 ms to the posterior tibial nerve in the popliteal fossa through a round electrode (3-cm diameter), with a reference electrode (8 cm × 13 cm) over the patella.

**Analysis of EMG Responses.** Preliminary studies demonstrated that neural elements were stimulated (i.e., action potentials were elicited) at the transition

from the first to second phase of the biphasic stimulus, when the function of the paravertebral electrodes abruptly changed from anode to cathode. Therefore, response latencies were measured from the onset of the second phase of the biphasic stimulus pulse. The onset of a CMAP was defined as the first deflection from baseline that was larger than 5% of the peak-to-peak amplitude of the EMG. Pearson's correlation coefficients comparing subject height with the latency of the responses to lumbosacral cord stimulation were calculated. We also measured the CMAP width of triceps surae responses to lumbosacral cord stimulation and to tibial nerve stimulation. The CMAP width was defined as the time between the onset of the CMAP and the moment of its last deflection from baseline larger than 5% of the peak-to-peak amplitude.

To describe the order of muscle recruitment, by transcutaneous lumbosacral cord stimulation, we identified response thresholds and calculated recruitment curves. Thresholds were defined for each muscle as the lowest-intensity stimulus for eliciting EMG responses with peak-to-peak amplitudes larger than 100  $\mu$ V. A common threshold intensity was defined as the stimulus intensity needed to elicit EMG responses that were larger than 100  $\mu$ V simultaneously in all of the recorded muscles in both lower limbs.

Standard recruitment curves were calculated from the data of all subjects except subject 2 (see Results) for each muscle group. The peak-to-peak EMG response amplitudes of each muscle were normalized to that at the maximal stimulus intensity. The response amplitudes from the left and right sides were averaged individually and grouped into intervals of 5% of the common threshold intensity. Within each interval, an average amplitude was calculated from the seven subjects for each muscle pair. The maximal stimulus intensity was restricted to 140% of the common threshold intensity. Stimulus intensity was never increased beyond the level that started to cause moderate discomfort to the subject (due to local contraction of the paravertebral muscles). To consider interside differences in muscle recruitment, the response asymmetry of each muscle was defined as the difference of left/right response amplitude to the mean of both sides and expressed as percentage of the mean value.

**Identification of the Nature of Muscle Responses.** In all subjects, pairs of stimuli with interstimulus intervals of 50 ms were applied to test the occurrence of depression of the conditioned second response.

The effect of unilateral Achilles tendon vibration on the responses to transcutaneous lumbosacral spi-

nal cord stimulation was studied. The examined lower limb was positioned with the Achilles tendon resting on the vibrator. A pillow was put between the vibrator and the examination table to reduce mechanical propagation of the vibration. In this position, five control responses were elicited with constant stimulus intensity. The control responses were compared with five conditioned responses evoked while vibration was applied.

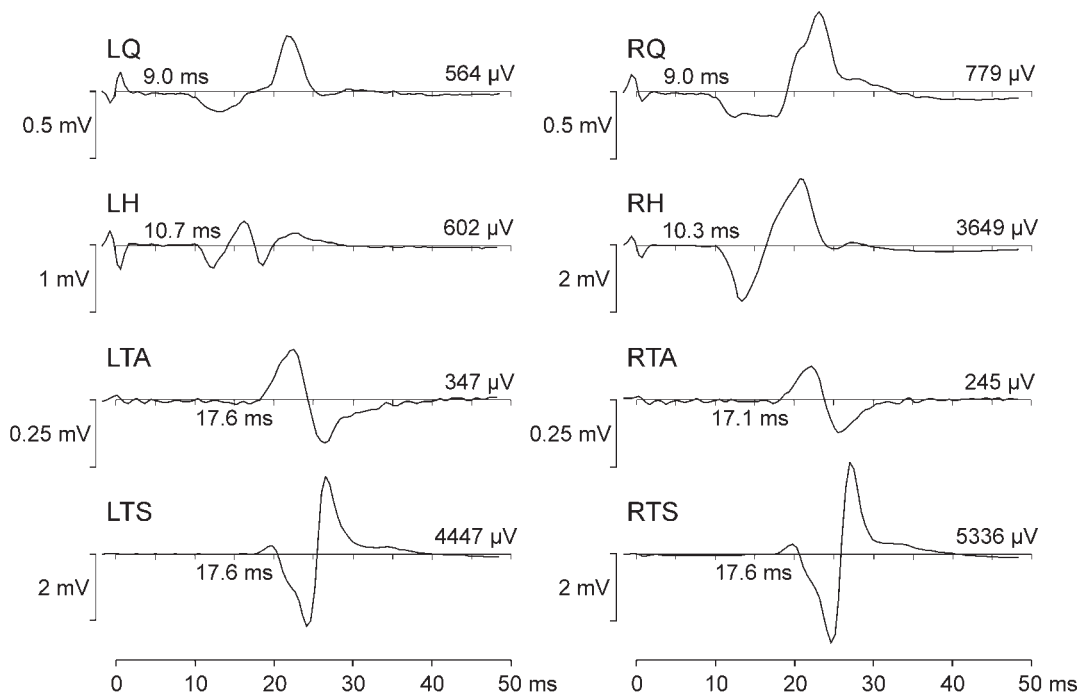
Passive, unilateral hip and knee flexion-extension movements were imposed by a therapist to study conditioning effects on the stimulus-evoked muscle responses. The cycle duration was approximately 2 seconds. Goniometers (Penny & Giles Biometrics, Ltd., Gwent, UK) were applied to assess the movements. Minimum hip and knee angles at the end of the flexion phase were approximately 135° and 90°, respectively. Five control responses were elicited while the therapist held the lower limb in an extended position. Then, passive movements were performed and stimulation at constant intensity was applied at 5-second intervals. The EMG amplitudes of the control and responses elicited during arbitrary segments of the flexion and extension phases were compared.

Finally, the subjects performed slight unilateral volitional contraction of the tibialis anterior (dorsiflexion) and, in separate trials, the triceps surae (plantar flexion) during electrical stimulation. Five control and conditioned responses were compared.

**Statistical Analysis of the Conditioning-Test Paradigms.** All unilateral conditioning-test paradigms were conducted on both sides in separate trials. Peak-to-peak amplitudes of left and right muscle responses were arranged into ipsilateral and contralateral groups (with respect to the conditioned side). For each subject and maneuver, five control and five conditioned response amplitudes were measured and averaged for each muscle. The mean conditioned response was then normalized to the control value. The normalized conditioned ipsilateral and contralateral responses resulting from the tests of both sides were averaged individually. Finally, the group results were calculated. To test the statistical significance of the differences between average conditioned and control response amplitudes, the Wilcoxon test was used, with significance set at  $P < 0.05$ .

## RESULTS

**PRM Reflexes to Transcutaneous Lumbosacral Cord Stimulation.** PRM reflexes were evoked in all recorded muscles by transcutaneous electrical stimulation of the lumbosacral cord in seven of the eight



**FIGURE 1.** PRM reflexes simultaneously recorded from the left (L) and right (R) quadriceps (Q), hamstrings (H), tibialis anterior (TA), and triceps surae (TS). Stimulation site: T11–T12 interspinous space; stimulus intensity: 30 V (subject 6). Inserted values are onset latencies and peak-to-peak amplitudes of the EMG responses.

subjects. Figure 1 shows representative CMAPs in the left and right quadriceps (Q), hamstrings (H), tibialis anterior (TA), and triceps surae (TS) elicited by a single pulse. Responses to a second pulse applied after 50 ms were depressed in all muscles. In one participant (subject 2), only direct motor responses were detected in Q, whereas bilateral PRM reflexes were elicited in the other muscles. Group average values reported here were calculated only from the seven subjects in whom PRM reflexes were recorded in all muscles.

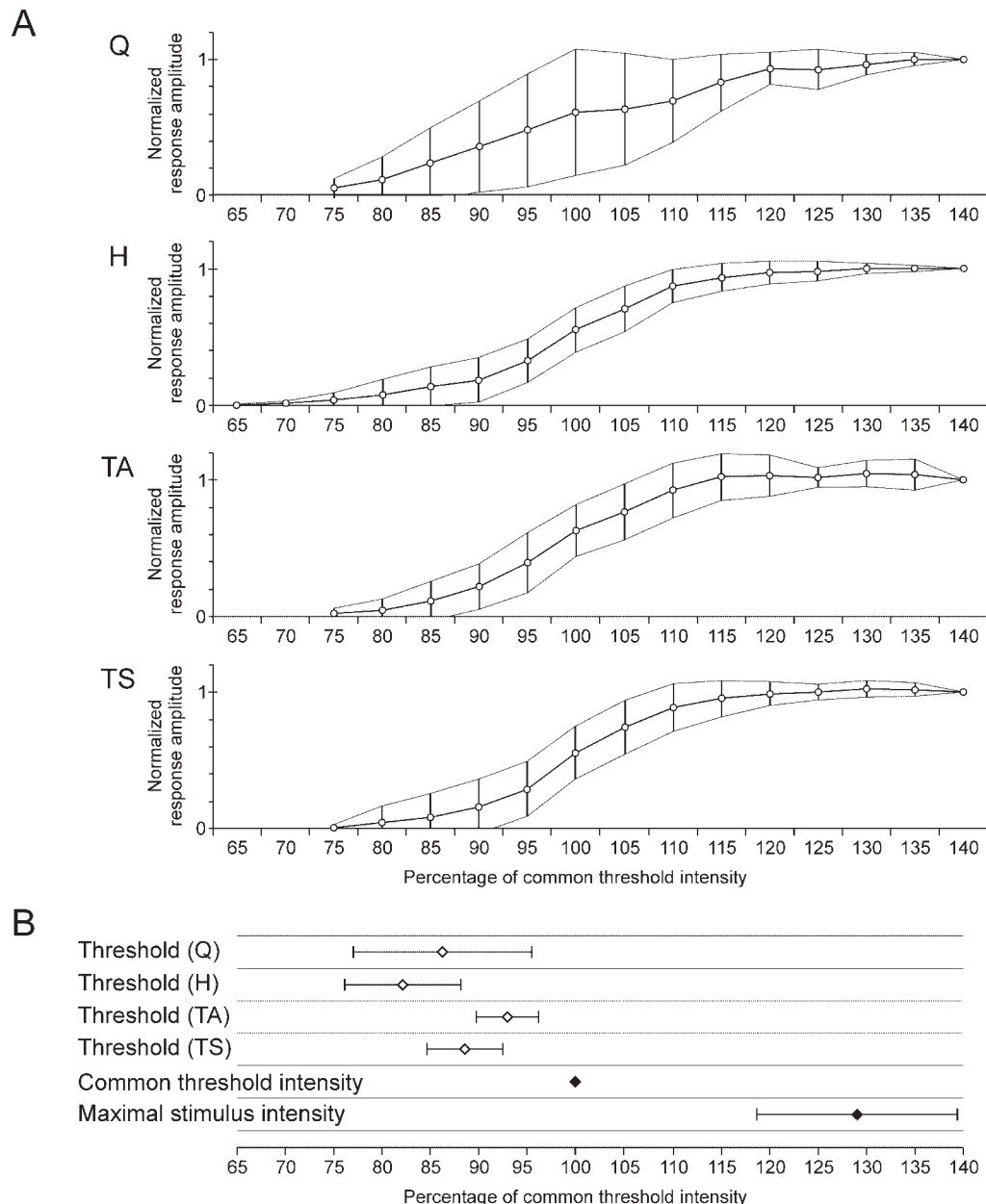
Standard recruitment curves calculated from the seven-subject group data are shown in Figure 2A, with supplementary information on relative thresholds given in Figure 2B. Graded lumbosacral cord stimulation resulted in recruitment curves for H, TA, and TS muscles that were of similar shapes (Fig. 2A). The stimulus–response relationships for these muscles followed a sigmoid curve initially with moderate slopes, growing more steeply with increasing stimulus strengths above 90% of the common threshold intensity until a plateau was reached. The Q recruitment curve demonstrated broad variations due to interindividual differences. Two characteristic curve types could be distinguished. One type, seen in three subjects, had a sigmoid shape and showed higher relative thresholds. The other type started with a steep initial slope at lower relative thresholds. The

large standard deviation seen in the Q thresholds (Fig. 2B) further added to the variation across individual Q recruitment curves from the average.

Mean thresholds for PRM reflexes were: Q, 24.6 V; H, 23.4 V; TA, 26.6 V; and TS, 25.3 V. Relative values with respect to the common threshold intensity are displayed in Figure 2B. The mean common threshold intensity needed to elicit PRM reflexes bilaterally in all muscles was  $28.6 \pm 6.3$  V in the seven-subject group. At this stimulus intensity, mean EMG amplitudes of the responses were: Q,  $848.0 \pm 735.9$  μV; H,  $1683.4 \pm 986.7$  μV; TA,  $449.4 \pm 356.9$  μV; and TS,  $2686.0 \pm 2060.2$  μV. The asymmetries amounted to: Q,  $21.0 \pm 26.9\%$ ; H,  $18.5 \pm 13.5\%$ ; TA,  $43.6 \pm 20.1\%$ ; and TS,  $25.5 \pm 23.8\%$ .

When pairs of stimuli were applied to the lumbosacral cord at the common threshold intensity with an interstimulus interval of 50 ms, the second pulse evoked either no response or low-amplitude responses. This prolonged refractory period excluded direct electrical stimulation of efferent structures as a probable mechanism. For up to 107.8% of the common threshold intensity, all responses to the second stimulus in the pair were less than 20% of the response to the first pulse.

In one participant (subject 8), an increase of stimulus intensity to 120% of the common threshold intensity was accompanied by a discrete shortening



**FIGURE 2.** (A) Standard recruitment curves for quadriceps (Q), hamstrings (H), tibialis anterior (TA), and triceps surae (TS) responses to lumbosacral cord stimulation. Circles represent group averages of the response amplitudes individually normalized to those at the maximal stimulus intensity and grouped into intervals of 5% of the common threshold intensity. Vertical bars are standard deviations. (B) Mean response thresholds of muscles (white diamonds) as percentage of the common threshold intensity and two characteristic stimulus intensities (black diamonds).

of response latencies by 1.4 ms. Furthermore, when a pair of stimuli was applied with 50-ms interstimulus interval, the amplitudes of the second responses were 32%–90% of the first. The shorter latencies and the absence of depression of the second response indicated direct activation of  $\alpha$ -motoneurons in addition to the recruitment of afferent structures in this case.

Mean PRM reflex latencies at the common threshold intensity of subjects 1 and 3–8 (mean

height 180.3 cm) were: Q,  $10.3 \pm 1.1$  ms; H,  $11.2 \pm 0.4$  ms; TA,  $19.1 \pm 0.9$  ms; and TS,  $19.7 \pm 1.1$  ms. Pearson's correlation coefficients comparing latency with subject height were: Q,  $r = 0.95$ ; H,  $r = 0.61$ ; TA,  $r = 0.91$ ; and TS,  $r = 0.90$ .

The mean latency of the triceps surae H reflex elicited by tibial nerve stimulation in the popliteal fossa was  $31.3 \pm 1.6$  ms in the original eight subjects. The mean latency of lumbosacral spinal cord stimu-



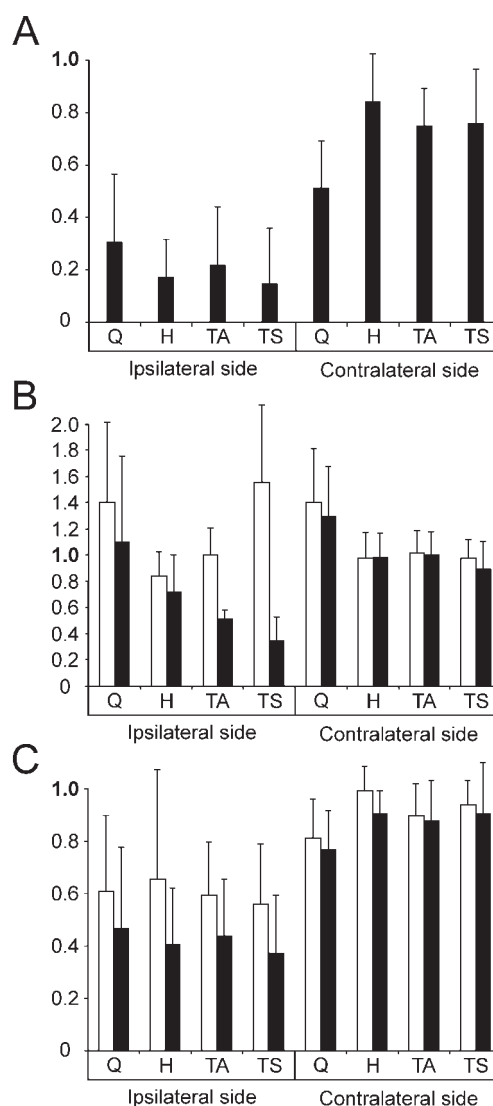
lation-evoked TS responses was  $19.8 \pm 1.0$  ms, thus being  $63.2 \pm 1.2\%$  of the H-reflex delay, in the same subject group. The shapes of the CMAPs elicited by stimulation at the two different sites were identical and invariably had a triphasic waveform with a small initial negativity, followed by dominating positive and negative peaks. The CMAP widths of the H reflexes were  $11.5 \pm 2.1$  ms and  $13.5 \pm 1.9$  ms of the TS responses to spinal cord stimulation, respectively.

#### Nature of the Stimulus-Evoked Muscle Responses.

Figure 3A illustrates the conditioning effect of additional afferent input to the spinal cord produced by unilateral Achilles tendon vibration on the PRM reflexes. The responses in all ipsilateral muscles were markedly suppressed during vibration. Responses in the contralateral muscles were also reduced, although the depression was less distinct than on the ipsilateral side. These findings signify that the transcutaneous lumbosacral spinal cord stimulation-evoked muscle responses are of reflex origin.

The reflex nature of these responses was also supported by the effect of a slight volitional contraction of the leg muscles on the PRM reflex amplitudes (Fig. 3B). Slight plantar flexion significantly increased peak-to-peak amplitudes of TS responses ipsilateral to the volitional activation. Triceps surae responses elicited during voluntary contraction of the antagonistic TA were suppressed. This volitional motor task also reduced the EMG amplitudes recorded in the ipsilateral TA and H. Both volitional conditioning-test paradigms had no significant influence on the responses from contralateral H, TA, and TS, but those from the contralateral Q were facilitated.

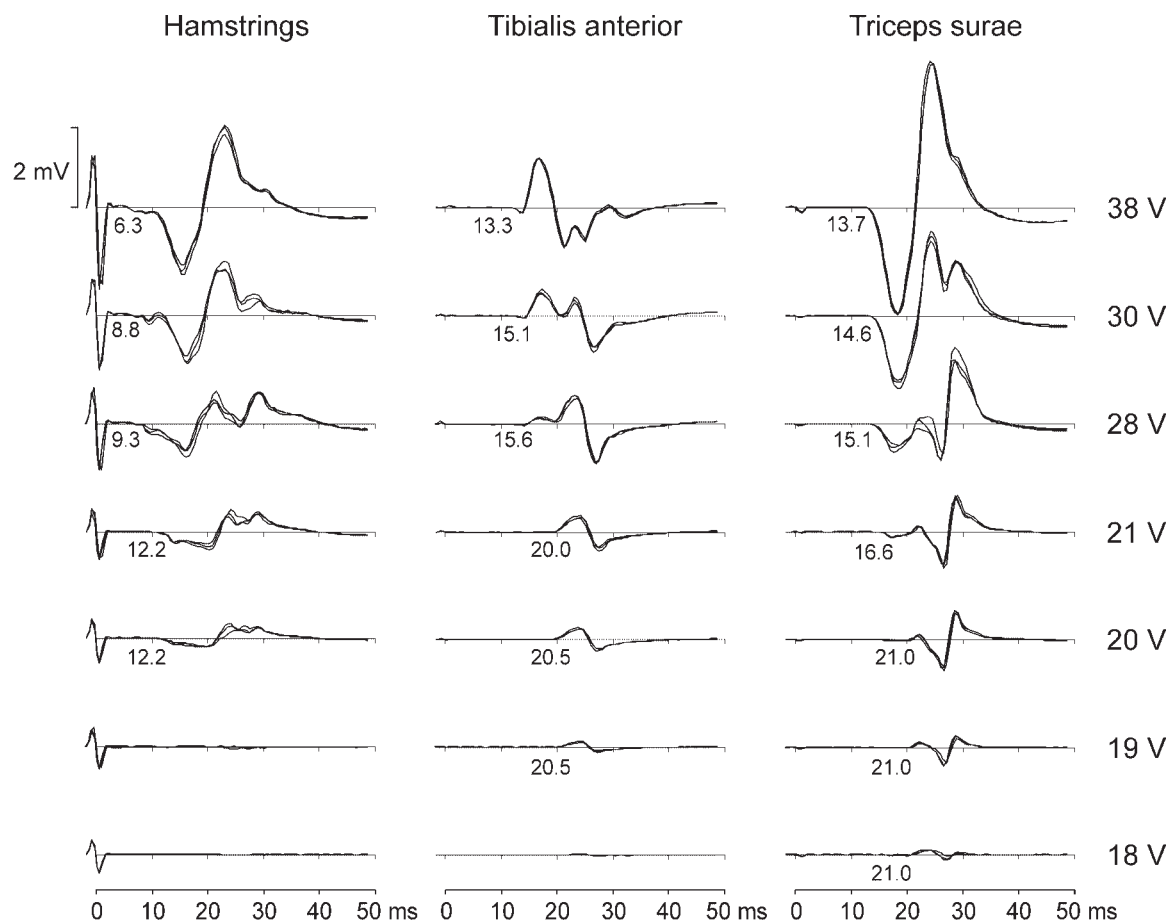
Unilateral passive hip and knee movements significantly reduced the response amplitudes of the ipsilateral muscles during both extension and flexion phases, with the exception of the responses of the H muscle during the extension phase (Fig. 3C). In all subjects and studied muscles, the mean amplitudes of responses elicited during the flexion phase were smaller than those from the extension phase. Responses of H, TA, and TS in the contralateral lower limb that was resting in an extended position during the unilateral conditioning-test paradigm did not demonstrate significant modulations, with the exception of a reduction in the H muscle during passive flexion of the other limb. Responses in the contralateral Q were reduced throughout the passive movement of the other limb.



**FIGURE 3.** Group results for the conditioning-test paradigms with the test responses normalized to the corresponding controls. Quadriceps (Q), hamstrings (H), tibialis anterior (TA), and triceps surae (TS) responses elicited during: (A) unilateral Achilles tendon vibration; (B) unilateral volitional contraction of TS (white bars) or TA (black bars); and (C) extension (white bars) and flexion (black bars) phases of passive unilateral hip and knee movements. The common threshold intensity was used throughout the trials.

#### Muscle Responses to Transcutaneous Cauda Equina Stimulation.

Applying graded stimulation to the cauda equina through paravertebral electrodes placed over the L4–L5 interspinous space resulted in a complex but characteristic sequence of indirect and direct responses in the lower limb muscles (Fig. 4). The average muscle recruitment order was TS first, TA second, and H third, with mean thresholds of 19.6 V, 21.0 V, and 21.2 V, respectively. At  $23.6 \pm 4.0$  V, responses were simultaneously and bilaterally



**FIGURE 4.** EMG responses to graded transcutaneous stimulation of the cauda equina (subject 8). Three responses are shown superimposed for every muscle and given stimulus intensity. Same scaling for all traces; inserted values are onset latencies (ms).

elicited in H, TA, and TS in all subjects, whereas no responses were evoked in Q at this stimulus intensity.

The mean latencies of responses to cauda equina stimulation elicited at threshold intensities were: H,  $13.3 \pm 1.0$  ms; TA,  $21.1 \pm 1.0$  ms; and TS,  $21.3 \pm 1.1$  ms, in the eight subjects. These latencies were longer than the latencies of responses to lumbosacral cord stimulation by 2.1 ms for H, 2.0 ms for TA, and 1.6 ms for TS. The longer latencies of threshold responses elicited by stimulation at the more caudal site suggests the excitation of afferent structures. The shapes of the CMAPs were identical for each muscle (except of Q) for both stimulation sites.

As the intensity of stimulation applied to the cauda equina was increased above threshold, there was initially a progressive increase in amplitudes of the H, TA, and TS responses without changes in the CMAP shapes or response latencies. Stronger stimulation produced additional, earlier EMG components that resulted in an abrupt shortening of the response latencies to: H,  $9.0 \pm 0.8$  ms; TA,  $16.4 \pm 1.0$  ms; and TS,  $17.2 \pm 1.6$  ms. The short-latency EMG

components increased in size with yet stronger stimulation along with a progressive decrease of the longer-latency EMG components. The mean latencies declined to: H,  $7.8 \pm 1.3$  ms; TA,  $15.5 \pm 1.3$  ms; and TS,  $16.6 \pm 2.2$  ms, at the maximal stimulation intensity, suggesting activation of efferent structures at rather distal sites. The aforementioned recruitment of H, TA, and TS responses to cauda equina stimulation resembled the H-reflex and M-wave recruitment known from mixed peripheral nerve stimulation. In the Q muscle, cauda equina stimulation produced only M waves that had short latencies (mean, 6.5 ms) and generally did not exceed EMG amplitudes of  $150 \mu V$ .

## DISCUSSION

The present study provides evidence that transcutaneous stimulation can depolarize lumbosacral posterior roots, eliciting bilateral short-latency reflexes at several segmental levels. Other investigators have shown that the soleus H reflex can be elicited by

high-voltage (300–750 V) transcutaneous electrical stimulation of spinal roots.<sup>16,27,30</sup> Responses recorded from Q, TA, extensor digitorum brevis,<sup>16</sup> and flexor hallucis brevis<sup>27</sup> muscles to root stimulation were reported to be M waves. This finding that a reflex response was only evoked in a single muscle may be explained by the stimulation techniques applied in the aforementioned studies. When the anatomy of the terminal spinal cord and lumbosacral roots is taken into account, there is no rational way to explain why PRM reflexes should not be evoked in several muscles by appropriate stimulation.<sup>20,21</sup>

#### **Electrical Phenomena and Spinal Cord Anatomy.**

Stimulating through surface electrodes as in the present study induces a current flow perpendicular to the spine<sup>27</sup> with a high current density near the paravertebral electrodes. Some current presumably flows through the ligaments between the spinal processes and laminae of adjacent vertebrae into the vertebral canal, where a high current density will be present in the well-conducting cerebrospinal fluid.<sup>10</sup> Such stimulation will favor spinal roots that are immersed in the cerebrospinal fluid, rather than neurons located in the spinal cord, which has a lower conductivity than the cerebrospinal fluid.<sup>10</sup> Group Ia afferents in the posterior roots will have the lowest thresholds. They have the largest fiber diameters and are closest to the paravertebral electrodes.<sup>23</sup> In addition, posterior root fibers have low thresholds at the sites entering the spinal cord due to their strong curvatures and the fact that they cross the interface of two media with different conductivities.<sup>15,24,26</sup>

The arrangement of the spinal roots characteristically changes from the lumbosacral cord<sup>28</sup> in the caudal direction.<sup>29</sup> At the lumbosacral cord, the posterior root fibers are separated from the anteriorly located motor fibers by the spinal cord. Therefore, stimulation over the lumbosacral cord can selectively depolarize the afferent fibers due to their anatomical isolation and posterior location. The elicitation of pure PRM reflexes in the Q, H, TA, and TS of both lower limbs can be explained by the activation of group Ia muscle spindle afferents within the proximal portion of the L2–S2 posterior roots.

In the lower cauda equina, posterior root fibers associated with H, TA, and TS are close to the corresponding anterior motor bundles in the thecal sac.<sup>1</sup> Consequently, recruitment of afferents and efferents at this caudal site by graded stimulation was similar to the results of stimulation in mixed peripheral nerves.<sup>25</sup> By contrast, the L2–L4 spinal roots exit the thecal sac rostral to the stimulation site over the L4–L5 interspinous space. In the Q muscle, only

direct motor responses of low amplitude were evoked by the lower cauda equina stimulation and were probably elicited in the corresponding anterior roots or spinal nerves at the intervertebral foramen.<sup>15</sup>

**Evidence for the Reflex Nature of the Responses.** By stimulating the cauda equina, PRM reflexes could be distinguished from direct motor responses by their different latencies resulting from differences in length of the transmitting pathways.<sup>30</sup> In the case of lumbosacral spinal cord stimulation, identification of the nature of the responses based on their latencies might not be definitive,<sup>8,27</sup> but neurophysiological methods can be applied for this purpose.

Muscle responses elicited by transcutaneous lumbosacral cord stimulation at the common threshold intensity were depressed 50 ms after stimulation. This refractory period excluded the possibility that the responses were produced by direct activation of  $\alpha$ -motoneurons in the ventral horn or anterior roots.<sup>4,26</sup> When stimulus intensity was increased, responses of low amplitude could be evoked by the second of a pair of stimuli applied with a 50-ms interstimulus interval, presumably because the refractory period of PRM reflexes depends on the stimulus intensity.<sup>20</sup> Further increase of stimulus intensity could result in the activation of both afferents and efferents, as was observed in one subject.

Supporting evidence for the reflex nature of the responses to lumbosacral cord stimulation was provided by the effects of tendon vibration and active and passive maneuvers. Achilles tendon vibration suppressed the ipsilateral TS responses. Vibration characteristically suppresses monosynaptic reflex pathways of the homologous muscle but not longer-latency reflex pathways.<sup>19</sup> There was also a distinct reduction of responses in the other ipsilateral muscles, and modification of those from the contralateral side. This widespread effect of vibration could be due to a partial occlusion of input to the spinal cord carried via large afferents.

Slight voluntary contraction of TA inhibited the responses in the antagonistic TS just as voluntary dorsiflexion depresses the monosynaptic soleus H reflex to tibial nerve stimulation through the activation of group Ia inhibitory pathways.<sup>3</sup> Voluntary contraction of TS facilitated stimulus-evoked responses in the same muscle. Unexpected results were found in the conditioned responses of TA that require further study to understand the underlying mechanisms.

Unilateral passive hip and knee movements attenuated the responses of the ipsilateral muscles.



This was a consistent finding in all subjects. The extent to which this result depended on the biomechanics or the sensory conditioning of segmental reflexes is uncertain. Regardless, these modifications support the reflex nature of the responses. The absence of modifications of responses in the H, TA, and TS muscles of the non-moved contralateral lower limb confirmed constant stimulation conditions during the passive movements.

**PRM Reflexes and the H Reflex.** The PRM reflex appears to be the functional equivalent of the H reflex. Both are initiated in the same type of sensory axons, except that the PRM reflex results from excitation of sensory input at proximal sites adjacent to the spinal cord. This interpretation is supported by the similar CMAP shapes and widths of the PRM reflex and H reflex of the TS, with the PRM reflex shifted to shorter latencies.

There may also be differences between the PRM reflex and the H reflex. Simultaneously evoked PRM reflexes from several adjacent segments of the spinal cord and both sides may influence each other. Facilitation from close synergists, disynaptic inhibition from antagonists, or influence from the contralateral side can affect the PRM reflexes. Due to the synchronicity of the stimulus-evoked multisegmental afferent inputs, however, short-latency effects alone may modify the excitability of central components of the PRM reflex pathways, particularly when the PRM reflex is of a mono- or oligosynaptic nature.<sup>8,27</sup> This assumption only holds for single-pulse or low-frequency stimulation. When stimuli are applied in close succession, PRM reflexes will be conditioned by the effects of the preceding stimuli. Trains of stimuli can engage central spinal components, which influence and shape the generated motor output.<sup>5,12,13,20</sup>

**Significance of the Results.** Our transcutaneous approach of posterior root stimulation is non-invasive, involves simple electrode placement and moderate stimulus intensities, and delivers stimulation at a fixed site. The widespread nature of the stimulus-evoked sensory input can be significant when exploring how the nervous system simultaneously modulates reflexes across multiple segmental levels. A potential clinical application of this method is in the assessment of the functional condition of the lumbosacral cord and the cauda equina. Future work will show how far repetitive transcutaneous posterior root stimulation can modify the central state of excitability of lumbar cord networks, particularly in the

case of decreased descending drive from brain structures due to different neurological disorders.

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