HIGHLIGHTED TOPIC | Neural Changes Associated with Training

Training-induced adaptive plasticity in human somatosensory reflex pathways

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Zehr, E. Paul. Training-induced adaptive plasticity in human somatosensory reflex pathways. J Appl Physiol 101: 1783–1794, 2006. First published June 29, 2006; doi:10.1152/japplphysiol.00540.2006.—This paper reviews evidence supporting adaptive plasticity in muscle and cutaneous afferent reflex pathways induced by training and rehabilitative interventions. The perspective is advanced that the behavioral and functional relevance of any intervention and the reflex pathway under study should be considered when evaluating both adaptation and transfer. A cornerstone of this concept can be found in acute task-dependent reflex modulation. Because the nervous system allows the expression of a given reflex according to the motor task, an attempt to evaluate the training adaptation should also be evoked under the same conditions as training bearing in mind the functional role of the pathway under study. Within this framework, considerable evidence supports extensive adaptive plasticity in human muscle afferent pathways in the form of operant conditioning, strength training, skill training, and locomotor training or retraining. Directly comparable evidence for chronic adaptation in cutaneous reflex pathways is lacking. However, activity-dependent plasticity in cutaneous pathways is documented particularly in approaches to neurological rehabilitation. Overall, the adaptive range for human muscle afferent reflexes appears bidirectional (that is, increased or reduced amplitudes) and on the order of 25–50%. The adaptive range for cutaneous pathways is currently uncertain.

ACTIVITY-DEPENDENT PLASTICITY of neural function is a topic of increasing interest in applied physiology and rehabilitation. In both rehabilitation and exercise training the objective is often to cause a long-standing change in function (e.g., movement pattern) by applying some intervention (e.g., specialized exercise or therapy). To have a principled basis for an intervention requires an understanding of the extent to which the nervous system can accommodate to increased or decreased use before a long-standing change in control and function occurs. This is not a trivial issue because function in the nervous system is dynamically regulated. That is, adaptive plasticity is commonplace either in the form of rapid and short-term change (i.e., “acute adjustments”) or as longer-standing and persistent change (i.e., “chronic plasticity”). The use of this terminology borrows from the concepts described by Enoka (31) to differentiate temporary adjustments from persistent change.

In this review the focus is on adaptive plasticity in human reflex pathways induced by physical activity. The scope is delimited to alterations in reflex function in muscle and cutaneous afferent pathways. A central issue is the conceptual framework in which the induction of adaptive plasticity can be best understood. This relates to considering training and reflexes in a certain context. Table 1 illustrates the general concept where training can be considered as direct or indirect. Direct training refers to training aimed specifically at modifying the reflex under study. That is, the reflex itself is “targeted.” Operant conditioning is the best example of this. The indirect context refers to training in which modification of the reflex is not itself the objective of training but rather occurs “en passant” (in passing; to borrow from chess) as part of the broader context of the training. Strength training or locomotor retraining can be considered the simplest and most complex forms of training in this context. The last thing that is contained in Table 1 relates to a rough approximation of how strongly a given reflex pathway is related to the behavioral and functional relevance of the training context.

This review is organized into sections related to the concepts of acute and chronic plasticity in the different training contexts highlighted in Table 1. The main emphasis is on muscle afferent reflexes (stretch and Hoffmann). That is, those arising from activation of afferents innervating the muscle spindle.
Invited Review

ADAPTIVE PLASTICITY OF MUSCLE AND CUTANEOUS AFFERENT REFLEXES

Table 1. Type of training and relevance of somatosensory afferent reflex pathway to the training stimulus

<table>
<thead>
<tr>
<th>Training Context</th>
<th>Behavioral relevance</th>
<th>Functional relevance</th>
<th>Behavioral relevance</th>
<th>Functional relevance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct (“targeted”)</td>
<td>Operant</td>
<td>+ + +</td>
<td>+/-</td>
<td>+?</td>
</tr>
<tr>
<td>Indirect (“en passant”)</td>
<td>Strength</td>
<td>+ +</td>
<td>+</td>
<td>+?</td>
</tr>
<tr>
<td></td>
<td>Skill</td>
<td>+?</td>
<td>+?</td>
<td>+?</td>
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<tr>
<td></td>
<td>Locomotor</td>
<td>+ + +</td>
<td>+ + +</td>
<td>+ + +</td>
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</table>

The + signs represent arbitrary scaling of relevance from low (+) to high (+++). “?” indicates uncertainty about the extent of relevance.

The H-reflex is considered the electrical equivalent of a stretch reflex and is predominantly characterized by the monosynaptic and oligosynaptic projections of group Ia afferents onto homonymous motoneurons (16, 33). Unfortunately, the H-reflex has often been misused as a direct measure of motoneuronal excitability (for issues related to methodology, please see Refs. 51, 60, 64, 77, 91).

The amplitudes of both muscle and cutaneous afferent reflexes are modulated between motor tasks using both the arms and legs (for reviews, see Refs. 7, 10, 11, 91–93, 95, 97). Although the H-reflex is used as an example here, cutaneous reflexes are also extensively modulated (acutely adjusted) in a similar fashion, but via different mechanisms (for reviews, see Refs. 28, 29, 92, 95, 97). In the case of the soleus H-reflex this modulation has been observed across tasks such as standing and walking as well as within a motor task, such as swing vs. stance phases of walking (for reviews see Refs. 10, 71, 97). A major control mechanism involved in the fine-tuning of afferent feedback is the modulation of Ia presynaptic inhibition (PSI), particularly during locomotor tasks for the leg (10, 13, 22) and in the wrist during arm movements (3–5, 63). Significant modulation (inhibition) of the soleus H-reflex amplitude occurs when changing posture from lying, to sitting, to standing (6, 36, 44, 45, 54, 56). The schematic in Fig. 1 represents the effect of changing motor task on PSI of the H-reflex. This example is specifically related to amplitude modulation of H-reflexes in leg muscles during postural orientation and walking. Ia PSI is steadily increased when moving from lying, to standing, to walking, and then to running (see posture changes indicated by the cartoon mannequin). H-reflex amplitude is shown to steadily decrease in correspondence with the increase in Ia PSI. The asterisks by the interneuron exciting the Ia PSI inhibitory interneuron (filled in black) are meant to match the extent of suppression of H-reflex amplitude shown at figure bottom.

Acute and rapid changes in PSI thus play a strong role in H-reflex modulation during movement. It is also probable that chronic alterations in the level of segmental Ia PSI may also serve as a significant mechanism responsible for chronic training-induced adaptations in H-reflex amplitude described in the next section (79).

DIRECT TARGETED TRAINING: OPERANT CONDITIONING OF REFLEXES

One way to address neural plasticity using task-dependent control of reflexes during movement is by working example of acute adjustments because this may well provide the backdrop on which chronic adaptations are laid. This is essentially the same concept as state-dependent modulation articulated by Burke (12). Largely because of the ease with which it can be elicited in various muscles the most widely studied reflex pathway is probably the Hoffmann or H-reflex. The H-reflex is considered the electrical equivalent of a stretch reflex and is predominantly characterized by the monosynaptic and oligosynaptic projections of group Ia afferents onto homonymous motoneurons (16, 33). Unfortunately, the H-reflex has often been misused as a direct measure of motoneuronal excitability (for issues related to methodology, please see Refs. 51, 60, 64, 77, 91).

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CHRONIC PLASTICITY IN MUSCLE AFFERENT REFLEXES INDUCED BY LONG-TERM TRAINING

Direct targeted training: operant conditioning of reflexes. Seminal work in direct training was conducted in an elegant series of studies in the monkey and rat by Wolpaw and...
colleagues (for review, see Ref. 90). The primate stretch reflex was investigated initially to study the adaptive plasticity of a “simple” spinal reflex (83, 85, 87, 89). Operant conditioning with a juice reward for correct modification of stretch reflex amplitudes in biceps brachii could lead to both increased (“uptrained”) or decreased (“downtrained”) responses (85). These changes occurred typically in a two-phase process that included an initial adaptive phase (initiated within 6 h) on the order of ~8% and a second phase (that could span months) and was ~1–2% per day (88). This up- and downregulation of behavioral conditioning was later extended to the H-reflex in primate triceps surae (84). Subsequent investigations made precise measurement of the underlying mechanisms involved in the adaptation. Alterations in motoneuronal properties (including rheobase, input resistance, and axonal conduction velocity) (14, 15; see also 34a) and morphological changes in the terminals of sensory afferents (33) occurred as a result of the conditioning used to alter H-reflex amplitudes. It has also been determined that these adaptations require the interaction of multiple supraspinal sites, which may differ for up- and down-training, including cortex (17, 18) and cerebellum (86). In sum, these studies demonstrated clearly that adaptive plasticity could be induced in the primate and rodent spinal cord and that it could be examined by using the stretch and H-reflexes.

This general procedure has also been examined in human subjects both with and without neurotraumatic injury. The first demonstration that volitional training could modify stretch reflexes was in a clinical population. Using online biofeedback of elbow flexor muscle activity and tonic stretch reflex activity paired with a “reward” of favorite music playback, Neilson and McCaughey (57) were able to downtrain hyperactivity in stretch reflexes about the elbow joint in four participants with spasticity arising from cerebral palsy. In the initial evaluation of operant conditioning of human stretch reflexes in neurologically intact subjects, Evatt and colleagues (32) trained subjects with a juice reward for correct modification of stretch reflex magnitudes (24–25%), which could lead to both increased (“uptrained”) and decreased (“downtrained”) responses (85). These changes occurred typically in a two-phase process that included an initial adaptive phase (initiated within 6 h) on the order of ~8% and a second phase (that could span months) and was ~1–2% per day (88). This up- and downregulation of behavioral conditioning was later extended to the H-reflex in primate triceps surae (84). Subsequent investigations made precise measurement of the underlying mechanisms involved in the adaptation. Alterations in motoneuronal properties (including rheobase, input resistance, and axonal conduction velocity) (14, 15; see also 34a) and morphological changes in the terminals of sensory afferents (33) occurred as a result of the conditioning used to alter H-reflex amplitudes. It has also been determined that these adaptations require the interaction of multiple supraspinal sites, which may differ for up- and down-training, including cortex (17, 18) and cerebellum (86). In sum, these studies demonstrated clearly that adaptive plasticity could be induced in the primate and rodent spinal cord and that it could be examined by using the stretch and H-reflexes.

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brachii stretch reflex activity was shown with an average reduction in amplitude of \(\approx 36\%\). Although gaps remain in our understanding of the mechanistic underpinnings of these adaptations, it is clear that the potential for directly targeted chronic adaptive plasticity in human muscle afferent pathways mirrors other species.

En passant adaptive plasticity in muscle afferent reflex pathways: plasticity as an indirect by-product of training. The majority of studies on adaptive plasticity in human somatosensory reflex pathways fall under this category. The indirect context refers to the fact that modification of any aspect of the reflex pathway under study is not the explicit outcome that is trained but rather occurs indirectly as a “by-product” of the training whether it be strength, skill training, or locomotor training and retraining.

Initial forays into this area were cross-sectional studies that identified differences in H-reflex excitability across groups with different training histories. It was shown that participants trained for explosive movements in so-called anaerobic sports such as sprinting could have lower ratios of the maximum H-reflex to maximal M wave (Hmax:Mmax) than endurance-trained participants had larger ratios (62). Casabona et al. (16) also found a smaller Hmax:Mmax in athletes who trained for explosive movements (track sprinters and volleyball players) than in participants with no training. This has recently been confirmed as well for the mechanical output of the reflex (e.g., twitch force arising during contraction) in endurance- and power-trained participants (48). For skill acquisition, it was found by Nielsen and colleagues (58) that H-reflexes were smaller in elite ballet dancers than in other athletes trained for gross physiological power (runners, swimmers, cyclists). This observation paralleled an earlier study with stretch reflexes also conducted in dancers (42). These results were suggestive that something related to the skill training was involved in shaping the observed change in reflex amplitude in concert with other observations in trained populations (30, 48).

However, the specific benefit of a given training stimulus is difficult to sort out from a cross-sectional design as it is not possible to fully dissociate intrinsic genetic endowment from actual training adaptations. More recent work has focused on longitudinal attempts to induced adaptive plasticity by training (see also reviews in Refs. 1 and 43). Work in this area has really been dominated by strength-training interventions with more recent attempts to evaluate skill acquisition and locomotor retraining.

Strength training. Several exercise studies have examined the effect of long-term strength training on H-reflex amplitude (1, 2). In a recent study, Aagaard and colleagues (2) comprehensively evaluated of neural adaptation arising from 14 wk of heavy resistance training of the ankle extensor muscles. They reported a significant increase in soleus H-reflex amplitude of \(\approx 20\%\). Interestingly, this potentiation was seen exclusively when the reflex was evoked during maximum muscle contraction and not at rest. Recently we employed a cross-education (see for review Ref. 15a) strength training paradigm and examined H-reflex amplitude in soleus before and after 5 wk of training using maximal isometric contractions (46). Data for H-reflexes in trained and untrained legs can be found at the bottom of Fig. 2. Across all subjects a 35% increase in H-reflex amplitude was found only in the trained leg; no significant change in H-reflex amplitude was seen in the untrained leg despite comparable gains in strength. This increase in H-reflex amplitude reflects chronic plastic adaptations in the Ia spinal reflex pathway leading to increased reflex excitability. It is interesting that neural plasticity associated with the adaptation of the H-reflex was only seen in the trained leg. Failure to demonstrate plasticity in the untrained leg (despite a comparable increase in force production due to cross-education) could arise if there are different loci for the adaptations in the trained and untrained leg. Likely spinal and supraspinal contributions occurred for the trained leg, whereas the untrained leg would have experienced only supraspinal adaptation (see also Ref. 2 for evidence of supraspinal contributions). This is what is intended by the schematic cartoon representation in Fig. 2. We speculated that this specific change in the trained limb was indicative of Hebbian plasticity in spinal reflex pathways requiring the combination of somatosensory feedback (only experienced in the trained limb) and descending drive (possibly experienced by both limbs) for full expression. Interestingly, this suggestion is reinforced by the observations that functional electrical stimulation (FES)-induced strength training (which bypasses the descending drive) of triceps surae potentiates strength without a corresponding change in H-reflex amplitude (35, 49). However, this form of training also significantly activates cutaneous afferents innervating tactile mechanoreceptors in the skin. The contributions of these inputs to the overall adaptation in the muscle afferent pathways must therefore also be considered (see ACUTE AND CHRONIC ADAPTATIONS IN CUTANEOUS AFFERENT REFLEX PATHWAYS).

Skill learning. One of the initial skill-training studies that examined H-reflex plasticity induced by voluntary activity was conducted by Trimble and Koceja (74). A paradigm was used in which subjects were instructed to intentionally suppress the soleus H-reflex response to minimize the perturbation of the reflex contraction to their standing balance (74). That is, subjects were placed in a precarious posture such that the plantarflexion torque generated by the H-reflex would lead to postural instability. Subjects could, over the course of a single day of “training” to suppress reflex responses, reduce the soleus H-reflex amplitude by \(\approx 26\%\). Interestingly, this H-reflex suppression persisted while standing normally. The effects were only examined “acutely” within the training day and persistence across other days is unknown. However, a subsequent study used a similar paradigm to examine the effect of 2 h of training for 3 days across a single week (75). There was a trend toward increased suppression of the Hmax amplitude across the 3 days of training suggesting that the H-reflex amplitude could be adapted “downward” in a chronic and persistent manner. This is reminiscent of the operant conditioning discussed above. However, a key difference is that participants were not given explicit feedback about the reflex per se (e.g., did not monitor reflex amplitude). Rather, the behavioral and functional destabilizing outcome of the reflex response was noted indirectly by the subjects and adjusted accordingly through training. Subsequent work has shown that implementing a similar paradigm in elderly participants can yield similar adaptive changes across several training days (55). The implications of this outcome are important for possible rehabilitation of balance and postural sway decrements that occur with aging.
In another early study aimed at examining chronic plasticity, Voigt et al. (79) had subjects perform hopping training for 4 wk. Before training, during hopping subjects showed a ~40% inhibition in soleus H-reflex amplitude relative to that recorded while standing. After training this suppression disappeared (that is, H-reflex excitability increased). Furthermore, stretch reflex amplitude in soleus increased ~28% as a result of the training. This longitudinal training adaptation was suggested to arise because of a reduction in a preexisting inhibition of the soleus H-reflex. Voigt et al. suggested that acute suppressive modulation of H-reflex amplitude (such as occurs when going from standing to walking, see Fig. 1) may dissipate with prolonged training because of the need for increased reflex excitability to contribute functionally to the task at hand.

**Locomotor retraining.** Somatosensory reflexes are specifically sculpted to assist with the regulation of human locomotion (for reviews, see Refs. 95, 97). Despite that, chronic adaptive plasticity of reflexes during human walking has been little studied. The most elegant approach to this issue is the study of Schneider and Capaday (65), who took the novel approach of evaluating whether undergoing a training program of backward walking would result in any effect on the pattern of soleus H-reflex modulation. Recall that the soleus H-reflex amplitude is dynamically modulated as an acute adjustment across phases of the walking cycle (see above). This “phase-dependent” reflex modulation is linked to function because it ensures that the reflex excitability of triceps surae muscles is high during stance where afferent feedback can assist with force production during plantar flexion but low during swing where a stretch (or H-) reflex could actually interfere with the ankle dorsiflexion (97). Schneider and Capaday noticed that during backward walking there was a large H-reflex amplitude in soleus even during swing. Excitability in the muscle afferent pathway from ankle extensors was now not functionally useful at the same relative part of the step cycle because it occurred during swing phase (this can be seen as the large amplitude on the day 1 trace in Fig. 3). Participants were then trained at walking backward for 15 min each day for 10 days. When the reflex patterns were again studied the peak of the abnormal H-reflex pattern progressively shifted to a more functionally relevant part of the step cycle (see traces with rightward shift indicated by the gray arrow for days 4, 7, and 10 on Fig. 3) and with a decreased amplitude. Interestingly, elements of this chronically adapted H-reflex pattern were maintained for up to 5 mo after the training period. When monthly experiments were conducted, after training, the H-reflex pattern was intermediate between that on day 1 and the fully adapted pattern, but within 20 min of walking the pattern reverted back to that observed in the fully adapted subjects. A more recent experiment excludes a strong role for corticospinal projections in this adaptation with the suggestion of modulation of Ia presynaptic inhibition by other supraspinal descending tracts (78).
tional spinally mediated effects could also be presumed to contribute (92, 95). At any rate, regardless of source of adaptation, it is difficult to overstate the implications of this experiment for adaptive retraining of locomotor plasticity in rehabilitation and in exercise training.

Currently there are no specific data on this form of adaptive plasticity in a rehabilitative or training context. However, there are some earlier data on shorter term adaptive plasticity in spinal cord injured and stroke participants with spasticity (i.e., hyperactive stretch reflexes). In this context two studies by Trimble and colleagues are also relevant. Using an acute and chronic intervention of treadmill locomotor retraining (for details, see Refs. 9, 26), they showed that the H-reflex–to–M-wave ratio could be significantly suppressed in four participants with incomplete SCI during both swing and stance (73). The suppression pushed the H-reflex amplitudes closer to the values obtained in participants without neurological damage. This suggested that access to spinal circuitry could alter H-reflex properties even after SCI. It had also been shown earlier that 10 days of 30 min/day treadmill retraining could significantly improve access to inhibition of normally hyperactive H-reflexes in one person with SCI (76). However, both of these studies involved very small samples sizes, and further confirmation is warranted. Indeed, most of the available data in this area involve very small piloting of approaches in clinical populations. Another recent case study (n = 1) has also shown that 12 wk (5 days/wk, 1 h each session) of cycle training could assist in “normalizing” the H-reflex amplitude and pattern and reduce spasticity in a man with an incomplete C7 spinal cord injury (41). Cycle training can likely be considered functionally equivalent to walking retraining in this context (see Ref. 92), but the result needs replication in a larger sample.

Acute bouts of using FES applied to the peroneal nerve (innervates ankle flexor tibialis anterior) during walking lead to a reduction in hyperactive stretch reflexes in triceps surae of stroke participants (80). This inhibition was shown to persist beyond the period of walking and FES suggesting it could be useful as a “retraining” stimulus. Later, Mirbagheri and colleagues (50) examined the effect of >16 mo of using FES of the ankle flexor muscles to assist with gait on the stretch reflexes (as well as intrinsic muscle stiffness) at the ankle of four incomplete SCI participants. It was shown that reflex stiffness (an index of alteration in stretch reflex excitability) decreased by >50% after the habitual use of FES and walking. A review of other data on this topic can be found in Ref. 8.

CHRONIC PLASTICITY IN THE SPINAL CORD: TRANSFER BETWEEN TASKS

A key element of training-induced plasticity of somatosensory reflex pathways is possible transfer from trained to untrained tasks. The extent of transfer from one task to another (such as from an isolated movement in a training environment to a complete skill) will depend on the nature of the functional relevance of the pathway that is involved in training. In humans this transfer is still an open question. However, recent work in using a rodent preparation is very encouraging. Using a combined operant conditioning and locomotor training intervention, Chen et al. (19) demonstrated transfer of plasticity acquired from a nonlocomotor training task to locomotion. They used operant conditioning to increase (HRup) or reduce (HRdown) H-reflex amplitude in rats. As seen at the top of Fig. 4, there was a clear effect of the operant conditioning to reduce H-reflex amplitude in HRdown rats (left) and to increase H-reflex amplitude in HRup rats (top right). This would in itself be simply more data supporting the previously established operant conditioning paradigm described above. The key and stunning new finding was that the operant conditioning of the H-reflex transferred to the functional task of walking (Fig. 4, middle and bottom). As mentioned above, soleus
H-reflex amplitude is normally large during stance and small during swing. Results showing significant conditioning of H-reflex amplitude in both up and down paradigms are shown in Fig. 4, middle for stance and bottom for swing. The observations to note are the dramatically reduced amplitudes of stance H-reflex shown in the HRdown rats (middle left, indicated by dotted oval) and the increased H-reflex amplitudes during swing phase in HRup rats (bottom right, indicated by dashed oval). This latter observation is striking because H-reflex amplitude can often be reduced to zero during swing because of powerful inhibition at this phase of walking. These observations represent the first clear and tangible evidence for significant transfer of training-induced reflex plasticity. Further exploration of this paradigm will yield important data on the functional use and transfer of chronic adaptive plasticity in reflex pathways for exercise training and rehabilitation.

**ACUTE AND CHRONIC ADAPTATIONS IN CUTANEOUS AFFERENT REFLEX PATHWAYS**

As mentioned earlier, cutaneous afferent pathways are well documented to undergo modulation (acute adjustments) related to motor task, movement context, and phase of movement as was described for H-reflexes (for reviews, see Refs. 10, 29, 92, 95, 97). In particular the most powerful effects for acute adjustment of cutaneous reflexes is during locomotion where there is an extensive literature (for reviews, see Refs. 29, 92, 95, 97). However, with respect to training-induced plasticity, there is currently a shortage of comparable data for cutaneous afferent reflexes that can be directly compared with the muscle afferent pathways described above. Partly this may be a result of the complexity of the pathways involved, which may have limited experimental study for this purpose. The cutaneous reflex pathway is a polysynaptic pathway that contains an unknown number of excitatory and inhibitory interneurons interposed between the first order afferent terminals and the motoneurons. Figure 5A, top is a simple illustration of parallel inhibitory and excitatory projections from cutaneous afferents yielding suppression and facilitation of EMG activity at early and middle latency, respectively. The resulting rectified and averaged EMG trace shown in Fig. 5B is typical of many cutaneous reflexes evoked in limb muscles by tactile stimulation. This form of stimulation is at an intensity to evoke tactile buzzing, fluttering, tingling sensations induced by activation of afferents innervating, for example Pacinian, Meissner's, and Ruffini corpuscles and Merkel discs, of the skin covering the hands and feet. Specific data on the modulation of these reflexes with training are lacking. Instead, the persistent modification of ongoing neural activity due to activation of afferents innervating, for example Pacinian, Meissner's, and Ruffini corpuscles and Merkel discs, of the skin covering the hands and feet. There is a body of literature on this topic that is primarily focused on functional...
recovery of movement after neurotrauma. These are addressed briefly below using the acute and chronic categories as applied previously.

ACUTE EFFECTS OF CUTANEOUS STIMULATION AFTER NEUROTRAUMA

Studies that have addressed acute alterations in spinal cord excitability after cutaneous input have generally shown an inhibitory effect. That is, cutaneous input and cutaneous reflex activity typically lead to a reduction in ongoing motor output. The initial study that presaged subsequent research in this area was done by Dimitrijevic and Nathan (25). As part of a more complex and comprehensive project examining spasticity in humans, Dimitrijevic and Nathan applied cutaneous stimulation to the medial aspect of the plantar foot surface (most likely stimulating the skin as well as the medial plantar nerve) in patients with spasticity arising from spinal cord injury and in neurologically intact subjects. They found that repetitive cutaneous stimulation (for periods of many hours in some experiments) eventually lead to an overall reduction in spinoally mediated motor output even in spasticity. Levin and Chapman (47) stimulated the common peroneal (mixed) and superficial peroneal (cutaneous) nerves in people with SCI and spasticity and in neurologically intact participants and examined changes in soleus H-reflex amplitude. Superficial peroneal nerve stimulation typically results in facilitation of the H-reflex in intact humans but this was shown to be either blunted or switched to suppression in SCI. They suggested that the balance of excitability in the spinal cord is changed after the spinal lesion and that cutaneous afferents could access inhibitory pathways to extensor muscles. This could theoretically be used to modify spasticity. This idea has also been addressed by Seib et al. (68). They applied surface electrical stimulation over the tibialis anterior muscle in patients with traumatic brain injury and SCI, all of whom had evident spasticity. After treatment, viscoelastic stiffness at the ankle was reduced and could be maintained for up to 24 h. The effects were equivalent for spasticity arising from SCI or traumatic brain injury. Similar results were observed.

Fig. 5. A: speculative theoretical neuronal circuitry underlying a tactile cutaneous reflex. The chain of INs shown represents the suggested minimum. Actual number of INs is unknown. Pathway leading to inhibition is shown at bottom and that to excitation at top. This schematic is not meant to represent all cutaneous pathways, which can be either suppressive or facilitatory at different latencies dependent on the muscle examined and nerve stimulated. B: cutaneous reflexes observed in rectified and averaged sweeps of surface EMG. Early and middle latency responses are as indicated and could represent activation in the inhibitory and excitatory pathways, respectively, shown in A. Data in B are from anterior deltoid muscle after superficial radial nerve stimulation. Note that the sign of the response at each latency will depend upon the stimulated nerve and the muscle studied.
tained from the upper limb of hemiparetic stroke survivors by Dewald et al. (23). They applied low-intensity electrical stimulation to the skin overlying the biceps brachii muscle and examined reflex torque responses to ramp and hold angular perturbations at the elbow before and after stimulation. They noted that stimulation typically reduced peak torque and increased the reflex threshold for angular movement of both elbow extensor and flexor muscles that could persist for at least half an hour. This observation suggests that cutaneous stimulation of the skin in the arm has a similar effect to that shown in the leg by Seib et al.

There are fewer studies examining these questions during movement. However, observations of cutaneous reflex patterns evoked by nerve stimulation at the ankle during locomotion after stroke has revealed that some of the effects in leg muscles are similar to those seen in uninjured participants (96). This suggests that cutaneous stimulation might be usefully applied during gait recovery after stroke. Indeed after SCI this may also be the case. Stimulation of the cutaneous medial plantar nerve impaired H-reflex modulation during walking in spastic parietic subjects (34). However, Jones and Yang (39) found excessive excitation after cutaneous nerve stimulation in incomplete SCI whereas Duyssens and colleagues (27) found reduced amplitudes in hereditary spastic paraparesis and thus the picture remains unclear.

**CHRONIC EFFECTS OF CUTANEOUS STIMULATION AFTER NEUROTROMA**

There is less detailed information about the issue of cutaneous contributions to adaptive recovery from neurotrauma in humans. However, several studies have examined the effect of cutaneous feedback on motor recovery after stroke. Transcutaneous electrical stimulation (TENS) was applied over the sural nerve of the paretic leg of subjects with spastic hemiparesis after stroke (61). Increased compliance was seen at the ankle joint and this effect was maintained for ~45 min post-stimulation. Dimitrijevic et al. (24) extended this approach in the upper limb to cutaneous stimulation of the whole hand using a mesh glove. Mesh glove stimulation was applied for 20–30 min to the more affected hand of chronic stroke patients with negligible immediate effects. However, when the mesh glove stimulation was applied daily (blocks of 20–30 min/day) over several months, significant improvements in range of wrist motion concomitant with a reduction in muscle coactivation could be seen. This result suggested that stimulation applied to the hand could have large functional effects on movement control of the wrist after neurotrauma. In another study, TENS was applied to the paretic hand of stroke patients for 1 h, 5 days/wk for 3 mo (69). Motor performance with the paretic hand was significantly improved with TENS. However, although some differences still existed, only a minor effect was seen when followed up after 3 yr (70), suggesting that perhaps long-term stimulation may have been required for maintenance of any functional gains. TENS application on the paretic hand was performed in a 3-wk inpatient program for chronic stroke survivors. Interestingly, in this study changes in clinical measures and motor performance were paralleled by significant increases in sensation in the hand as well as changes in the somatosensory evoked potentials (59).

Interestingly, some very compelling recent data has come from step retraining in the cat (21). After spinalization, cats were trained to perform locomotor stepping. Typically in these preparations the response to cutaneous afferent input is exaggerated and of much larger amplitude than in intact preparations. This can be detected with intracellular recordings from impaled motoneurons and measuring the responses arising from cutaneous stimulation. In Fig. 6 is a sample recording from a medial gastrocnemius motoneuron after stimulation of the cutaneous superficial peroneal nerve. Note that there are two traces shown superimposed. Untrained refers to data from a spinalized cat that was not step trained whereas trained indicates the step-trained cat. There was reduction in amplitude of exaggerated responses from intracellular motoneuron recordings in this preparation. The data suggest a normalization of transmission in cutaneous reflex pathways induced by the stepping locomotor retraining. Further work is needed, but this result represents direct support for the suggestion that cutaneous pathways can be functionally retrained at the spinal cord level in mammals. Indeed, it was also shown that enhanced cutaneous feedback significantly improved locomotor recovery in the hemispinal hatching chick model (52, 53).

In summary, the evidence suggests that cutaneous input could be a useful therapeutic adjunct to alteration of neural excitability after neurotrauma. However, the link to function during movement remains unproven and the range of adaptive plasticity experienced in neurologically intact subjects remains unknown. Further research in this area is needed.

**SUMMARY AND CONCLUSIONS**

The key point of this review was to point out the need to account for the behavioral and functional relevance of a train-
ing intervention and the reflex pathway under study. A cornerstone of this concept can be found in acute task-dependent modulation within muscle and cutaneous afferent pathways. Because the nervous system modulates the expression of a given reflex according to the motor task, an attempt to evaluate the training adaptation should also be evoked under the same conditions as training. Reflexes are also modulated according to function and alterations in that function will be best expressed when examined in a behaviorally relevant context.

Although reflexes can be recorded at rest or at various muscle activity levels, very little of the functional utility of any adaptive plasticity may be revealed. To paraphrase the quote by Sherrington found at the beginning of this review, we may study reflex pathways as though they are “simple” and attempt training interventions aimed at specific outcomes but must consider the context in which they are placed if we really want to understand function, plastic adaptation, and transfer. When considering this functional framework, a limitation of the available data is that few measures of actual changes in motor behavior (e.g., biomechanical measures) have been taken in parallel with the neurophysiological recordings. This is particularly so in the examination of adaptive plasticity in muscle afferent pathways. Combining these approaches in future work is highly recommended. Taken across all preparations, the approximate range of adaptive changes in muscle afferent pathways is bidirectional (i.e., increased or reduced amplitudes) and between 25 and 50%. It is interesting to note that this longitudinal adaptive range is similar to the range of amplitude modulation that occurs in acute adjustments of reflexes during behavior.

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