# THE EFFECTS OF INTENSIVE TRAINING ON MOTOR RECOVERY

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**Summary**: Intensive training and exercise may enhance motor recovery or even restore motor function in people who have been long paralyzed due to spinal cord injury or stroke. These training effects may be due to reversal of "learned non-use", a theoretical shutdown of neuronal circuitry that results from non-use of motor systems. Recent data suggest that the training effects may be due to the ability of the spinal cord to learn and adapt to motor activities, even in the absence of supraspinal influences. A substantial body of evidence indicates that weight-supported ambulation training on treadmills can remarkably restore overground locomotor performance of people with chronic spinal cord injury. The data provides strong bases for greater use of intensive exercise therapy, particularly use of weight-supported treadmill training for people with spinal cord injury and stroke.

## Learned Non-Use

Recent studies have reported beneficial effects of intensive training or exercise on motor recovery in people who have been paralyzed due to spinal cord injury or stroke. In 1993, Taub, et al. described a method called "constraint-induced" (CI) movement therapy to restore function in people with long-term paralysis after stroke and other central nervous system (CNS) lesions. By constraining the good side and forcing hemiplegic patients to utilize their paralyzed limbs, they were able to reverse "learned non-use", proposed by Taub, et al. (1994) to explain the excess motor disability that occurs after central nervous system (CNS) injuries. In 1997, Liepert, et al. reported that constraint-induced movement therapy not only improved motor function but enlarged motor cortex representation of the hand, indicative of large-scale neuroplasticity of the human brain (Kopp, et al., 1999). In Germany, Kunkel, et al. (1999) showed that 14 days of contraint-induced therapy with 6 hours of daily training substantially improved arm function in five patients with chronic stroke. Miltner, et al. (1999) replicated these results with 15 patients with chronic stroke in the United States. Taub, et al. (1999) pointed out that the common therapeutic factor appears to be inducing concentrated

repetitive use of the affected limb, producing a massive use-dependent cortical reorganization.

Despite the abundance of evidence supporting the beneficial effects of CI therapy, many patients and therapists expressed skepticism about the therapy. Page, et al. (2002) polled 208 patients in northeastern U.S. and 85 physical and occupational therapists for their opinions of CI therapy. A majority (68%) of the patients said that they were not interested in participating in such therapy, citing concerns with the practice schedule. Therapists cited concerns about patient adherence and safety, and speculated that facilities may not have the clinical resources to provide such therapies. One author (van der Lee, 2001) opined that the beneficial effects off CI therapy is not new and merely reflects the long-known correlation between with exercise intensity and duration with motor recovery. Certainly, many other methods can be used to encourage repeated motor practice, including electromy0gram-initiated neuromuscular stimulation, motor imagery, and music therapy (Hummelsheim 1999). Likewise, biofeedback therapy (Fernando & Basmajian, 1978) has long been used to restore function and systematic exercise such as Tai Chi that systematic exercises many parts of the body could have similar beneficial effects (Wolf, 2001). In fact, Klose, et al. (1990) compared the effects of physical exercise, neuromuscular stimulation, and electromyographic biofeedback therapies on functional recovery and showed no significant difference between the three therapies. All the studies show that repeated motor activation is associated with motor recovery. Many methods can be used to initiate the movements, as long as the training occurs daily and over several months.

**Laufband Training**

Perhaps the most dramatic demonstration of reversing "learned non-use" has come from the results of training people with spinal cord injury. In 1992, Wernig & Muller reported that treadmill (laufband) locomotion with body weight support improved walking in people after severe spinal cord injuries. They trained 8 people with "incomplete" spinal cord injury for 1.5 to 7 months (5 days a week, 30-60 minutes per day) starting 5-20 months after injury. This training significantly improved locomotion capabilities, including ability to walk 100-200 meter unsupported on a flat surface. Five of the people had complete loss of motor and sensory function in one leg. Over the training period, the amount of partial weight support was reduced from 40% to 0%, the distance of unsupported walking increased significantly from 0-104 meters in the first week to 200-410 meters in the last week of training, and the walking speed increased from 0-10 meters/minute to 13-23 meters/minute.

In a subsequent study, Wernig, et al. (1995) trained 89 people with incomplete paralysis after spinal cord injury to walk, comparing them against 62 patients that were treated conventionally. The training program consisted of daily upright walking on a treadmill with body weight support and assisted limb movements by therapists. Of 44 patients that trained for 3-20 weeks, 33 were wheelchair bound (unable to stand or walk without help) and only 6 were able to do stair stepping. Of the 33 patients that were unable to walk at the beginning of training, 25 (76%) developed the ability to walk independently, 7 patients had improved ambulation but still required help, and one patient did not

improve. Likewise, only 6 of the 44 (14%) patients were able to do stair climbing whereas 34 of 44 (77%) were able to do stair climbing.

Wernig, et al. (1998) followed 35 of these patients for 0.5-6.5 years and found that the walking capabilities were maintained in 31 patients, improved in 3 patients, and reduced in only one patient. Of 20 of 25 patients who were wheelchair bound before training became independent walkers. Interestingly, most of these patients showed only small improvements in voluntary muscle activity, suggesting that most of the improvement in locomotion resulted from improvements in reflexes, automatic muscle activation associated with ambulation, and better recruitment or utilization of muscles. Thus, these results suggest that the beneficial effects of the training can be maintained without further intensive training. The maintenance of these walking results was documented by electromyographic recordings (Wernig, et al. 1999). Thus, this study suggests that supported ambulation training can restore locomotor function in a majority of people after spinal cord injury, as long as 6.5 years after injury (Wernig, et al., 2000).

**Effects of Daily Ambulatory Training**

Other European centers have adopted the weight-supported treadmill ambulatory training with similar results. Dietz, et al. (1998a) at the Balgrist Rehabilitation Center in Zurich Switzerland examined clinical and electrophysiological changes in people after spinal cord injury, showing that spinal locomotor activity improves spontaneously in people with "complete" spinal cord injury, reaching a plateau in about 5 weeks. Daily ambulatory training produced a linear increase in the ability of the legs to support weight over 12 weeks. This, however, is not associated with any improvement in voluntary movements of the legs (Dietz, et al. 1998b). Wirz, et al. (2001) followed the patients for more than 3 years after training and showed that the patients with "incomplete" spinal cord injury who regularly did locomotor activity after the training maintained their level of leg extensor activation whereas patients with "complete" spinal cord injury and who did not maintain their locomotor training did not. Dietz (2001) pointed out that two forms of adaptations occur after injury that may contribute to improved locomotor function: development of spastic muscle tone and activation of spinal locomotor centers induced by treadmill training. He points out that use of antispastic drugs may interfere with locomotor training (Dietz, 2000). Locomotor training increases the amplitude of appropriate muscle activation and decreases the amplitude of inappropriate or spastic muscle activation. Due to the labor-intensive nature of the weight-supported treadmill training, several groups have attempted to design devices that can mechanically move the legs during such training (Colombo, et al. 2001).

Many U.S. centers have carried out preliminary studies that seem to be confirming the European experience. Gardner, et al. (1998) studied one subject with a C5 injury, showing that 6-week training with weight-supported ambulation on treadmill improved gait, speed, and energy consumption. Berman & Harkema (2000) at the University of Florida in Gainesville (UFG) assessed four subjects with chronic incomplete spinal cord injury and showed significant improvements in stepping and one person recovering independent overground locomotion. Trimble, et al. (2001) also at UFG assessed the

effects of a single bout of weight-supported ambulatory treadmill training on overground walking speed and H-reflex modulation. In four subjects who had classified as ASIA D (useful lower limb function), a single training session increased overground walking speed by 25% and reduced H-reflexes during overground walking. This suggests that even a single bout of locomotor training can produce immediate improvements in walking velocity and acute neurophysiological changes in individuals with incomplete spinal cord injury. Protas, et al. (2001) trained three subjects with incomplete chronic thoracic injuries, classified as ASIA D or C. The training started with 40% body weight support, 0.16 kilometer per hour, 1 hour per day, and 5 days per week for 3 months with treadmill walking for 20 minutes during sessions. All three subjects increased gait from 0.118 to 0.318 meters per second, endurance from 20.3 m per 5 minutes to 63.5 meters per 4 minutes. In addition, they showed a 34% reduction in oxygen costs of walking from 1.96 to 1.33 ml/kg. At the Miami Project, Field-Fote (2001) assessed the effects of combined weight-supported ambulation and functional electrical stimulation on 19 subjects who were classified as ASIA C and were at least one year after injury. The subjects trained for 1.5 hours per day, 3 days per week, and for 3 months. Electrical muscle stimulation was applied to the peroneal nerve in one leg. The training significantly increased overground walking speed from 0.12 to 0.21 meters per second, treadmill talking speed from 0.23 to 0.49 meters per second, treadmill walking distance from 93 to 243 meter. All the subjects showed significant improvement of overground, treadmill, and over all lower extremity strength.

Several European centers are now beginning to institute treadmill training of patients as soon as possible after spinal cord injury, to prevent learned non-use. Abel, et al. (2002) at Heidelberg, Germany, recently reported the results of training 7 patients soon after injury. They performed gait analyses as soon as the patients were stable enough to walk without manual aid from therapists and enough endurance to allow measurements of gait. The treadmill training began with 25% weight reduction (0-35 kg), a maximum walking speed of 0.28 (0.15-0.7) meters per second, and maximum walking duration of 4.7 (3-7) minutes. By the end of training, weight support decreased to an average of 9.3 (0-20) kg, maximum walking speed increased to 0.67 (0.23-1.1) meters per second, and maximum walking duration increased to 11 (8-15) minutes. The patients did not have walking orthoses and did not develop significant complications.

## Effects of Ambulatory Training on Complete Spinal Cord Injury

Although most of the studies on human locomotor recovery focused on “incomplete” spinal cord injury, many studies (Barbeau & Rossignol, 1987) have shown that ambulation training improve walking in animals and people with “complete” injuries. The spinal cord can engage in locomotor patterns in response to non-specific (Pearson & Rossignol, 1991) and pharmacological stimuli (Barbeau, et al., 1993). Rossignol, et al. (1996) reviewed the locomotor capacities of several animal species, including cats and primates, as well as human after complete transections of the spinal cord. They showed that animals with transected spinal cords can perform well-coordinated walking movements of the hindlimbs when they are placed on treadmills and that the locomotion can adapt to both speed and perturbations of gait. Several drugs, such as clonidine (an alpha-adrenergic receptor blocker) can enhance locomotion recovery in

cats with transected spinal cords (Chau, et al., 1998). Transplants of embryonic cells can also enhance locomotor recovery in spinalized rats (Ribotta, et al., 2000). Combinations of pharmacological, locomotor training, and functional electrical stimulation improve locomotor function.

Edgerton, et al. (Botterman & Edgerton, 1975; Gardiner, et al. 1982) had earlier shown that treadmill training of animals with transected spinal cords improve both electromyographic and histological appearance of hindlimb muscles, as well as net work performed by the muscles during locomotion (Whiting, et al., 1984) and changes in muscles reflecting the functional improvement (Roy, et al, 1984; Baldwin, et al. 1984; Shimamura, et al. 1987; Gregor, et al., 1988; Hauschka, et al., 1988; Hutchison, et al. 1989a; Pierotti, et al., 1989; Graham, et al. 1989; Roy, et al., 1998). The muscles not only show better coordination (Hutchison, et al. 1989b; Roy, et al. 1991; de Guzman, et al., 1991; de Leon, et al., 1994) but also have greater strength (Pierotti, et al., 1990). Adult cats with transected spinal cords can learn to engage in weight-supported locomotion (Loveley, et al. 1990; Edgerton, et al., 1992). Contrary to expectation, animals that were spinalized at a young age do not seem to recover short latency muscle activation as well as animals that were spinalized as adults (Smith, et al., 1993).

During treadmill locomotion, sensory input from the walking induced leg muscle activity that synchronized with the step cycle, in people with both complete and incomplete spinal cord injuries (Dobkin, et al. 1995). Even in the absence of supraspinal influences, the spinal cord is capable of remarkable plasticity and ability to learn from experience (Hodgson, et al., 1994; Dobkin, 2000). For example, Harkema, et al. (1997) showed that the human lumbosacral spinal cord interprets loading during stepping in complex strategies that are similar to what animal studies suggest. De Leon, et al. (1998) compared the effects of training versus spontaneous recovery in cats with transected cords, showing that step training significantly facilitates or reinforced the locomotor function, increasing the probability that the appropriate neurons are activated during locomotion and suggesting that the training facilitated or reinforced the function of extant sensorimotor pathways rather than promoting the generation of additional pathways. De Leon, et al. (1999) showed that the training effects are maintained in cats.

## Driving Brain and Spinal Cord Reorganization

The effects of motor training appear to be more than just exercise mediated. Exercise and improvement of muscle performance alone is unlikely to account for several aspects of constraint-induced therapy and weight-supported ambulation training. Several observations strongly support the theory that motor training is driving reorganization in the spinal cord and brain.

First, motor training effects depend on specific training parameters. For example, weight-supported ambulation training enhances locomotor recovery in people after stroke but best at certain treadmill frequencies. Sullivan, et al. (2002) trained 24 individuals with chronic hemiparesis after stroke. All the subjects had walking speeds that were 50% below normal. They were assigned to slow, fast, or variable speed

treadmill training with 20 minutes of walking per session, 12 sessions over 4 weeks. All the subjects showed significant improvement in overground walking velocity and maintained these improvements up to 3 months after training. The greatest improvements, however, occurred at fast treadmill speeds. Since the training periods of all the subjects were similar, the observation that the higher treadmill speeds are more effective suggest that the training effects are not just due to muscle changes but are neurally mediated.

Second, the training effects are not generalizable from function to function. For example, standing and stepping training have effects that are not generalizable to each other. De Leon, et al. (1999b) studied cats that were trained to stand or to step. Cats that were trained to stand after spinalizations were not able to step and administration of strychnine (a glycine receptor blocker) induced full weight-bearing stepping recovery in 30-45 minutes. However, cats that were trained to step, they not only had better stepping but the stepping behavior was not affected by strychnine. Standing and stepping training also produces different neural and muscle adaptations in cats (Roy, et al. 1999a). Spinalization resulted in a decrease in the mass and maximum activatable tension of the gastrocnemius muscle. Standing training ameliorated these changes but stepping training did not. Likewise, functional electrical stimulation does not produce the same favorable effects on locomotor performance as treadmill training does. For example, Kern et al. (1999) used functional electrical stimulation to activate tetanic contractions in atrophic muscles (using very high intensity and long duration pulses), combined with ankle weights and other exercises. They found that they were able to train and reverse atrophy in the denervated muscles. However, the patients do not show the same kinds of locomotor capability as those patients who received weight-supported treadmill training.

Third, the training effects are specific to muscles and neuronal circuits involved in the training and are unlikely to be mediated by general mechanisms such as exercise-induced hormonal changes. For example, the ambulatory training effects are present in both quadriplegic and paraplegics and hence are unlikely to be signaled by catecholamine rises which should be more prominent in paraplegics (Klokker, et al., 1998) or growth factor increases which should affect other muscle groups (Bigbee, et al. 2000). Training has the potential to drive brain and spinal cord reorganization to optimize functional performance (Shepard, 2001).

## Other Effects of Exercise

Exercise reverses muscle atrophy and increases muscle bulk, strength, and other characteristics. Roy, et al. (1999b) overloaded the plantaris muscle by removing the soleus and gastrocnemius muscles. In both trained and untrained rats, the plantaris increased. However, rats subjected to stepping training had significantly larger plantaris muscle. The plantaris muscle showed an increase in myonuclear numbers that was proportional to the increase in muscle size (Roy, et al. 1999c). This increase occurred without changes in motoneuronal sizes or numbers in the spinal cord. The increase in muscle bulk should be accompanied by proportional increases in muscle capillaries (Chilibeck, et al. 1999).

Exercise increases yet-to-be identified pituitary growth hormones. McCall, et al. (2001) proposed a novel muscle-neuro-endocrine pathway that modulates the secretion of an unidentified pituitary growth factor that is stimulated by proprioceptive input from skeletal muscle afferents. Exercise stimulates the release of this growth factor whereas chronic unloading of muscles associated with bedrest or spaceflight abrogates this exercise-induced effect. Bigbee, et al. (2000) and Gosselink, et al. (1998) had earlier showed that muscle activity stimulated growth factor is not immunoassayable growth hormone. Gosselink, et al. (2000) further showed that afferent input from low-threshold fast muscle afferents increased this factor but activation of slow skeletal muscle inhibits the release of this factor.

Intensive exercise preserves bone mass of upper limbs in men with spinal cord injury but does not retard demineralization of the lower body (Jones, et al. 2002). Frey-Rindova, et al. (2000) evaluated the loss of trabecular and cortical bone mineral density in the radius, ulna, and tibia of spinal cord injured persons at 6, 12, and 24 months after injury. The bone loss in the tibia occurred in both paraplegics and quadriplegics and did not correlate with physical activity or degree of spasticity. Needham-Shropshire, et al. (1997) likewise showed using the Parastep 1 ambulation system, a device that uses functional electrical stimulation during walking exercises, did not alter bone mineral density. Bloomfield, et al. (1996) also reported no significant increase in bone mineral density of the lower limbs after intensive 6-9 month exercise training but found increases in hormonal levels of osteocalcin. On the other hand, Mohr, et al. (1997) reported the prolonged electrically induced cycle training of paralyzed limbs can increase bone mineral density but only after 12 months of training. Furthermore, these effects disappeared after 6 months of reduced training.

Exercise has complex effects on the metabolism of people with spinal cord injury. For example, exercise improves oral glucose tolerance tests (Jeon, et al., 2002) in people with spinal cord injury. However, Kjaer, et al. (2001) showed that plasma free fatty acid levels fell during exercise in people with spinal cord injury but not as much in uninjured controls. Likewise, muscle glycogen breakdown, leg glucose uptake, carbohydrate oxidation, and lactate release were significantly greater in people with spinal cord injury than uninjured controls. The data suggests that the sympathoadrenergic signals (Stallknecht, et al. 2001) are not sufficient to elicit a normal increase in fatty acid mobilization during exercise in people with spinal cord injury.

## Conclusions

1. A new theory of neural dysfunction is attracting a great deal of attention. The theory posits that “learned non-use” plays a major role in the functional deficits that occur after central nervous system injury. Much evidence suggests that intensive repetitive motor activity can reverse such “learned non-use”, leading to a new class of therapies called “constraint-induced therapy” or “forced-use” therapies that encourages motor activities involving the paralyzed limbs. Several groups have now reported that “forced-use” therapy can restore function to people who have been paralyzed for many years. There is skepticism about this

theory, however. Some people believe that the beneficial effects of constraint-induced therapy are just a manifestation of increased exercise and motor activity.

2. Intensive motor training can restore function in a majority of people with spinal cord injury. In the past decade, many European and U.S. rehabilitation centers have reported that intensive weight-supported ambulation on treadmills can restore locomotor function in people with chronic spinal cord injury. The improvement in locomotor function is not associated with better voluntary activation of muscles but seems to be due to improved reflexive coordination and the ability of the spinal cord to learn to walk. Several centers are now beginning to apply weight-supported ambulation early after injury to prevent "learned non-use" and to facilitate locomotor recovery.
3. Ambulatory training may be beneficial for people with "complete" spinal cord injury. Both animal and human studies indicate that the spinal cord can engage in locomotor patterns in response to non-specific and pharmacological stimuli. Training will reactivate or induce walking patterns that do not require supraspinal control. For example, animal studies indicate that treadmill training of animals with transected spinal cords will improve coordination and efficiency of hindlimb walking, as well as reverse atrophy and other changes in muscles.
4. Motor training appears to have effects that exceed those produced by exercise or functional electrical stimulation alone. Specifically, motor training effects depend on specific training parameters, are not generalizable from function to function, and produce specific changes in muscles and neuronal circuits that cannot be explained by general mechanisms such as exercise-induced hormonal changes or other general effects of exercise.
5. Exercise has complex effects, many of which are still not well understood. Many studies have shown the exercise can reverse muscle atrophy and increase muscle bulk, strength, and other characteristics. Some of these exercise effects may involve yet-to-be-identified pituitary growth factors that appear to be signaled by activation of low threshold fast muscle sensory signals. Although exercise has been claimed to improve other characteristics such as bone mineral density, glucose tolerance, and fat mobilization, some studies suggest that people with cervical spinal cord injury may not show such responses.

## References

• Abel R, Schablowski M, Rupp R and Gerner HJ (2002). Gait analysis on the treadmill - monitoring exercise in the treatment of paraplegia. Spinal Cord. **40** (1): 17-22.
**Summary:** STUDY DESIGN: A prospective study was performed to evaluate the gait training of seven consecutive spinal cord injured patients and 10 controls on a treadmill using instrumented gait analysis and video documentation. OBJECTIVES: To determine whether it is possible to maintain gait motion within physiological limits during treadmill training. SETTING: Primary and secondary care unit for spinal cord injury, Heidelberg, Germany. METHODS: Treadmill training was instituted as early as possible. Gait analysis was performed when the patients were stable enough to walk without manual aid from therapists and enough endurance to allow measurements. A control group of healthy volunteers were examined as well. Video documentation and a

camera system using passive markers were employed. RESULTS: Treadmill training started with weight reduction of 25% of bodyweight (18 (0-35) kg), maximum walking speed 0.28 (0.15-0.7) m/s and maximum walking duration 4.7 (3-7) min. At the end of the training, weight reduction decreased to 9.3 (0-20) kg, maximum walking speed increased to 0.67 (0.23-1.1) ms with a maximum walking duration of 11 (8-15) min. 3-D motion analysis of hip, knee and ankle demonstrated joint excursions almost entirely within the limits of normal gait. Exceptions were due to fixed contractures. CONCLUSIONS: Our data suggests that it is possible to perform early gait training on a treadmill with no supportive orthoses within the physiologic range of joint motion. The risk for repetitive stress injuries or other negative effects is low. DOI: 10.1038/sj/sc/3101239. Stiftung Orthopadische Universitatsklinik Heidelberg, Heidelberg, Germany.

• Baldwin KM, Roy RR, Sacks RD, Blanco C and Edgerton VR (1984). Relative independence of metabolic enzymes and neuromuscular activity. J Appl Physiol. **56** (6): 1602-7. **Summary:** Effects of spinal cord transection in 2-wk-old cats on the metabolic, histochemical, and fatigue properties of a fast- and a slow-twitch muscle were determined. Chronic (6-12 mo) spinalization (Sp) resulted in an increased ratio of fast-twitch, oxidative-glycolytic (FOG) to slow-twitch, oxidative (SO) fibers in soleus (SOL). In medial gastrocnemius (MG), Sp produced a histochemical profile suggesting that fast fibers were increased at the expense of slow fibers. Changes in biochemical markers for oxidative (citrate synthase) and glycolytic (GPD) potential were consistent with the histochemical findings. The fatigue index of Sp MG and SOL remained normal and was consistent with the type and degree of fiber type change. Daily treadmill exercise did not markedly alter any of the adaptations. The metabolic and fatigue properties of skeletal muscle of Sp cats are consistent with the view that as some fibers develop "faster-like" characteristics, the oxidative and the glycolytic potential is also enhanced. As was true of the contractile properties and related biochemical data, the changes observed suggest that significant changes occurred within as well as across fiber types. These data, in conjunction with that of chronic EMG recordings, provide evidence that there is a relative independence of both the oxidative potential and the fatigability of a muscle relative to its quantity of activation.

• Barbeau H, Chau C and Rossignol S (1993). Noradrenergic agonists and locomotor training affect locomotor recovery after cord transection in adult cats. Brain Res Bull. **30** (3-4): 387-93. **Summary:** In one series of experiments, the effects of noradrenergic, serotonergic, and dopaminergic precursors and agonists on the initiation of locomotion were investigated within the first week after complete spinalization at +13 in five adult cats. In addition, the effects of clonidine and daily locomotor training were investigated during the first week after transection in another cat. The electromyographic (EMG) activity of vastus lateralis (VL) and semitendinosus (St) was recorded bilaterally through percutaneously implanted copper wires in all cats. The movement of the hindlimbs on the treadmill was also simultaneously videorecorded before and after the injection of drugs. Without drug injection, strong and sustained perineal or abdominal stimulation did not induce any prolonged episodes of coordinated stepping on the treadmill during the first week after spinalization. St often had sustained activity, in contrast to VL, in which minimal or no activity was present. Injection of apomorphine (0.3 to 0.5 mg/kg, n

= 3), a dopaminergic agonist, or DL-5-HTP (50 mg/kg, n = 2), a serotonergic precursor, failed to induce locomotion at such an early stage after spinalization. In contrast, injection of either L-dopa (50-60 mg/kg, n = 2), a noradrenergic precursor, or clonidine (150 micrograms/kg, n = 2), a noradrenergic agonist, induced locomotion on the treadmill. The animal demonstrated bilateral foot placement on the soles and complete weight support of the hindquarters. The spinal cat could follow the treadmill speed up to 0.80 ms-1. However, these effects disappeared when the NA drugs were tapered off.(ABSTRACT TRUNCATED AT 250 WORDS). Departement de Physiologie, Universite de Montreal, Canada.

• Barbeau H and Rossignol S (1987). Recovery of locomotion after chronic spinalization in the adult cat. Brain Res. **412** (1): 84-95. **Summary:** Cats were spinalized (T13) as adults and were trained to walk with the hindlimbs on a treadmill. After 3 weeks to 3 months and up to 1 year depending on the animal, all were capable of walking on the plantar surface of the feet and support the weight of the hindquarters. Interactive training appeared to accelerate the recovery of locomotion and maintain smooth locomotor movements. Despite the obvious loss of voluntary control and equilibrium which the experimenter partially compensated for by maintaining the thorax and/or the tail, the cats could walk with a regular rhythm and a well-coordinated hindlimb alternation at speeds of 0.1-1.2 m/s. Cycle duration as well as stance and swing duration resembled those of normal cats at comparable speeds. The range of angular motion was also similar to that observed in intact cats as was the coupling between different joints. The EMG activity of the hindlimb and lumbar axial muscles also retained the characteristics observed in the intact animal. Some deficits such as a dragging of the foot in early swing and diminution of the angular excursion in the knee were seen at later stages. Thus, the adult spinal cat preparation is considered as a useful model to study the influence of different types of training and of different drugs or other treatments in the process of locomotor recovery after injury to the spinal cord.

• Bauman WA and Spungen AM (2000). Metabolic changes in persons after spinal cord injury. Phys Med Rehabil Clin N Am. **11** (1): 109-40. **Summary:** Persons with chronic SCI have several metabolic disturbances. As a consequence of inactivity and the body compositional changes of decreased skeletal muscle with a relative increase in adiposity, a state of insulin resistance and hyperinsulinemia has been demonstrated to exist, associated with abnormalities in oral carbohydrate handling. Elevated plasma insulin levels in persons with SCI probably contribute to the cause of frequent dyslipidemia and hypertension. This constellation of metabolic changes represents an atherogenic pattern of CHD risk factors with many of the distinctive features of a cardiovascular dysmetabolic syndrome that is called syndrome X. Reduction in modifiable risk factors for CHD should decrease the occurrence of catastrophic cardiovascular events. There is evidence to suggest that endogenous anabolic hormone levels are depressed in a proportion of individuals with SCI. Depression of serum testosterone and growth hormone/IGF-I levels may exacerbate the adverse lipid and body compositional changes, reduce exercise tolerance, and have deleterious effects on quality of life. Because of immobilization, individuals with paraplegia have osteoporosis of the pelvis and lower extremities, and those with tetraplegia also have osteoporosis of the upper extremities. In addition, there is evidence to suggest that bone loss progresses with time

in persons with chronic SCI. This may be caused by chronic immobilization per se or may be a consequence of adverse hormonal changes, including deficiency of anabolic hormones or deficiency of vitamin D and calcium with secondary hyperparathyroidism. Serum thyroid function abnormalities resembling the euthyroid sick "low T3 syndrome" have been reported in those with acute and chronic spinal cord injury. Depressed serum T3 and elevated rT3 in chronic SCI may be caused by associated illness. Current practice has been hesitant to treat abnormal serum thyroid chemistries associated with nonthyroidal illness. Recognition of metabolic abnormalities in individuals with SCI is vital as a first step in improving clinical care. The application of appropriate interventions to correct or ameliorate these abnormalities promises to improve longevity and quality of life in persons with SCI. Department of Medicine, Mount Sinai Medical Center, New York, USA. Bauman.W@Bronx.VA.GOV.

• Behrman AL and Harkema SJ (2000). Locomotor training after human spinal cord injury: a series of case studies. Phys Ther. **80** (7): 688-700. **Summary:** Many individuals with spinal cord injury (SCI) do not regain their ability to walk, even though it is a primary goal of rehabilitation. Mammals with thoracic spinal cord transection can relearn to step with their hind limbs on a treadmill when trained with sensory input associated with stepping. If humans have similar neural mechanisms for locomotion, then providing comparable training may promote locomotor recovery after SCI. We used locomotor training designed to provide sensory information associated with locomotion to improve stepping and walking in adults after SCI. Four adults with SCIs, with a mean postinjury time of 6 months, received locomotor training. Based on the American Spinal Injury Association (ASIA) Impairment Scale and neurological classification standards, subject 1 had a T5 injury classified as ASIA A, subject 2 had a T5 injury classified as ASIA C, subject 3 had a C6 injury classified as ASIA D, and subject 4 had a T9 injury classified as ASIA D. All subjects improved their stepping on a treadmill. One subject achieved overground walking, and 2 subjects improved their overground walking. Locomotor training using the response of the human spinal cord to sensory information related to locomotion may improve the potential recovery of walking after SCI. Department of Physical Therapy and University of Florida Brain Institute, University of Florida, Gainesville 32510-0154, USA. abehrman@hp.ufl.edu.

• Bigbee AJ, Gosselink KL, Roy RR, Grindeland RE and Edgerton VR (2000). Bioassayable growth hormone release in rats in response to a single bout of treadmill exercise. J Appl Physiol. **89** (6): 2174-8. **Summary:** Plasma growth hormone (GH) measured by immunoassay [immunoassayable GH (IGH)] and by tibial bioassay [bioassayable GH (BGH)] increases in humans in response to exercise. In rats, however, IGH does not change in response to exercise. The objective of this study was to determine the BGH response to an acute exercise bout in rats. The rats ran on a treadmill at a rate of 27 m/min for 15 min, after which plasma and pituitary hormones, including IGH and BGH, and plasma metabolites were measured. Plasma and pituitary IGH were unchanged from control groups after the acute exercise bout, whereas plasma BGH was increased by 300% and pituitary BGH was decreased by 50%. Plasma thyroxine and corticosterone levels were significantly increased after a single exercise bout, but plasma testosterone, 3,5, 3'-triiodothyronine, glucose, lactate, and triglyceride concentrations were unchanged. Given previous results from in situ nerve stimulation

studies (Gosselink KL, Grindeland RE, Roy RR, Zhong H, Bigbee AJ, Grossman EJ, and Edgerton VR. J Appl Physiol 84: 1425-1430, 1998), these in vivo results are consistent with the rapid BGH response during exercise being induced by the activation of muscle afferents. Department of Neurobiology, University of California, Los Angeles 90095, California.

• Bloomfield SA, Mysiw WJ and Jackson RD (1996). Bone mass and endocrine adaptations to training in spinal cord injured individuals. Bone. **19** (1): 61-8. **Summary:** To investigate whether exercise training can produce increases in bone mass in spinal cord-injured (SCI) individuals with established disuse osteopenia, nine subjects (age 28.2 years, time since injury 6.0 years, level of injury C5-T7) were recruited for a 9-month training program using functional electrical stimulation cycle ergometry (FES-CE), which produces active muscle contractions in the paralyzed limb. After training, bone mineral density (BMD, by X-ray absorptiometry) increased by 0.047 +/- 0.010 g/cm2 at the lumbar spine; changes in BMD at the femoral neck, distal femur, and proximal tibia were not significant for the group as a whole. In a subset of subjects training at > or = 18 W for at least 3 months (n = 4), BMD increased by 0.095 +/- 0.026 g/cm2 (+18%) at the distal femur. By 6 months of training, a 78% increase in serum osteocalcin was observed, indicating an increase in bone turnover. Urinary calcium and hydroxyproline, indicators of resorptive activity, did not change over the same period. Serum PTH increased 75% over baseline values (from 2.98 +/- 0.15 to 5.22 +/- 0.62 pmol/L) after 6 months' training, with several individual values in hyperparathyroid range; PTH declined toward baseline values by 9 months. These data establish the feasibility of stimulating site-specific increases in bone mass in severely osteopenic bone with muscle contractions independent of weight-bearing for those subjects able to achieve a threshold power output of 18 W with FES-CE. Calcium supplementation from the outset of training in osteopenic individuals may be advisable to prevent training-induced increases in PTH. Department of Health & Kinesiology, Texas A&M University, College Station 77843-4243, USA. sbloom@acs.tamu.edu.

• Botterman BR and Edgerton VR (1975). Histochemical profiles of rat soleus intrafusal fibres after chronic exercise. Histochem J. **7** (2): 151-64. **Summary:** Intrafusal fibres from the rat soleus were investigated for representative histochemical profiles in sedentary animals and animals chronically exercised for 17 weeks on a treadmill. The pattern of myosin adenosine triphosphatase (ATPase) activity in the polar region revealed three intrafusal fibre types: (1) myosin ATPase-dark (MD) fibres, alkali- and acid-stabile; (2) myosin ATPase-light (ML) fibres, alkali- and acid-labile; and (3) myosin ATPase-reversible (MR) fibres, alkali-stabile and acid-labile. The three fibre types were correlated with the level of reduced NADH diaphorase activity, with MR, ML and MD fibres staining dark, moderate and light, respectively. In the equatorial region the morphological features of representative ML and MD fibres revealed that they were nuclear bag fibres, while representative MR fibres were identified as nuclear chain fibres. The MR fibres in the exercised animals had higher levels of myosin ATPase alkaline stability and acid lability than MR fibres in the sedentary animals, suggesting the MR fibre profiles are selectively influenced by chronic exercise. The mean cross-sectional area of MR fibres from the exercised animals was significantly less than the MR fibres from the sedentary animals. In contrast to the effect of endurance training on

NADH diaphorase activity in extrafusal muscle fibres, there was evidence of less activity in the MD fibres of the exercised animals.

• Chau C, Barbeau H and Rossignol S (1998). Early locomotor training with clonidine in spinal cats. J Neurophysiol. **79** (1): 392-409. **Summary:** Clonidine, a noradrenergic alpha-2 agonist, can initiate locomotion early after spinalization in cats. Because this effect lasts 4-6 h, we have injected clonidine daily, intraperitoneally or intrathecally, and intensively trained five spinal cats to perform hindlimb walking on a treadmill starting at day 3 and continuing until 10 days posttransection. Each day, clonidine was injected to induce locomotor activity and cats were trained to walk with as much weight support as possible and at different speeds during multiple (1-5) locomotor training sessions, each lasting from 10 to 20 min, until the effects of clonidine wore off. Electromyographic (EMG) activity synchronized to video images of the hindlimbs were recorded before and after each clonidine injection. The results showed, first, a day-to-day change of the locomotor pattern induced by clonidine from the 3rd to the 11th day including an increase in the duration of the step cycle, an increase in the duration of extensor EMG activity, and an increase in total angular excursion of the hip, knee, and ankle joints. Second, after 6-11 days of this regimen, there was an emergence of a coordinated locomotor pattern with weight support of the hindquarters that was visible even before that day's clonidine injection. The results suggested that daily injection of clonidine followed by early and daily interactive locomotor training can enhance the recovery of locomotion in spinal cats. Centre de Recherche en Sciences Neurologiques, Faculte de Medecine, Universit-e de Montr-eal, Montreal, Quebec, Canada.

• Chilibeck PD, Jeon J, Weiss C, Bell G and Burnham R (1999). Histochemical changes in muscle of individuals with spinal cord injury following functional electrical stimulated exercise training. Spinal Cord. **37** (4): 264-8. **Summary:** STUDY DESIGN: Longitudinal training. OBJECTIVES: To determine the effects of functional electrical stimulated (FES) leg cycle ergometer training on muscle histochemical characteristics in individuals with motor-complete spinal cord injury (SCI). SETTING: University of Alberta, Edmonton, Alberta, Canada. METHODS: Six individuals with motor-complete SCI (age 31-50 years; 3-25 years post-injury) trained using FES leg cycle ergometry for 30 min, 3 days per week for 8 weeks. Biopsies of the vastus lateralis muscle were obtained pre- and post-training and analyzed for fibre composition, fibre size and capillarization. RESULTS: The majority of muscle fibres were classified as type 2 pre- and post-training. Average fibre area increased 23% ($P<0.05$) and capillary number increased 39% ($P<0.05$) with training. As a result of these proportional increases, capillarization expressed relative to fibre area was unchanged with training. CONCLUSIONS: FES leg cycle ergometer training results in proportional increases in fibre area and capillary number in individuals with SCI. The Faculty of Physical Education and Recreation, University of Alberta, Edmonton, Canada.

• Colombo G, Wirz M and Dietz V (2001). Driven gait orthosis for improvement of locomotor training in paraplegic patients. Spinal Cord. **39** (5): 252-5. **Summary:** DESIGN: Single cases. OBJECTIVE: To compare the effects of manually assisted locomotor training in paraplegic patients with the automated training by a driven gait orthosis. SETTING: ParaCare, University Hospital Balgrist in Zurich, Switzerland.

METHODS: Treadmill training with manual assistance and by a driven gait orthosis was applied to two spinal cord injured patients. The first patient had an incomplete lesion at C3, the second a complete lesion at C5. They were selected by convenience sample. The EMG activity of the leg muscles rectus femoris, biceps femoris, gastrocnemius medials (GM) and tibialis anterior (TA) was visually compared for the two training methods. GM and TA activity was also quantified by calculating the variation ratio between the EMG of the patients and a set of healthy subjects. RESULTS: No significant difference between the two training methods was found according to the leg muscle EMG activity. CONCLUSION: Neuronal centers in the spinal cord become activated in a similar way by the manually assisted and the automated locomotor training. With the driven gait orthosis training sessions can be prolonged and workload of therapists can be reduced, and therefore, the automated training represents an alternative to the conventional therapy. Rehabilitation and Research Institute ParaCare, University Hospital Balgrist, Zurich, Switzerland.

• de Guzman CP, Roy RR, Hodgson JA and Edgerton VR (1991). Coordination of motor pools controlling the ankle musculature in adult spinal cats during treadmill walking. Brain Res. **555** (2): 202-14. **Summary:** The coordination of the motor pools of two ankle plantar-flexor, i.e. the soleus (Sol) and medial gastrocnemius (MG), and an ankle dorsiflexor, i.e. the tibialis anterior (TA) was quantified by comparing the EMG amplitude relationships in muscle pairs in normal and trained adult spinalized cats during treadmill walking across a range of relatively slow speeds (0.1 to 1.0 m/s). The effects of increased tactile stimulation or loading on locomotor performance were also studied in the spinal cats. Joint probability density distributions in the spinalized cats showed a low level of MG activation relative to Sol which did not change as speed increased. In general, the coordination between Sol and MG was similar in normal and spinal cats. However, towards the final phase of the extensor burst, the MG EMG amplitude decayed prematurely in spinal cats, particularly at higher speeds. Preferential elevation of MG relative to Sol activity was seen as a result of tactile stimulation. An elevated load resulted in a higher level of MG activation relative to Sol, prolonged MG activity at the end of the extensor burst, and the reduction in the clonic pattern of EMG typical of spinal cats. Spinalized cats showed an increased incidence of Sol-TA coactivation, especially at the higher speeds, due in part to the tonic activity in the TA. However, the overall reciprocal relationship between these antagonists was maintained. This reciprocity was preserved, but the high level of coactivation was unaffected by tactile stimulation. An elevated load, however, resulted in less Sol-TA coactivation. These results suggest that the coordination between synergists (Sol-MG) and between antagonists (Sol-TA and MG-TA), as well as the level of activation are modulated in the adult spinal cat similar to that observed in the normal cat. Further, there are specific types of proprioceptive-cutaneous information that can affect selected phases of the step cycle such that full weight-supporting stepping is significantly improved. Neuromuscular Research Laboratory, Department of Kinesiology, Los Angeles, CA 90024.

• de Leon R, Hodgson JA, Roy RR and Edgerton VR (1994). Extensor- and flexor-like modulation within motor pools of the rat hindlimb during treadmill locomotion and swimming. Brain Res. **654** (2): 241-50. **Summary:** EMG activity was recorded from

the vastus lateralis (VL, knee extensor), rectus femoris (RF, hip flexor and knee extensor), tibialis anterior (TA, ankle flexor and digit extensor) and either the lateral or medial gastrocnemius (LG, MG, knee flexors and ankle extensors) muscles of 7 adult rats during treadmill locomotion and swimming. Most flexors and extensors are activated as a single burst but each is known to be modulated differently during locomotion. For example, the extensor EMG bursts are shortened and amplitude elevated as speed increases, whereas little change occurs in the EMG duration and amplitude in flexors. The RF and VL displayed a double burst of EMG activity per cycle during treadmill locomotion and a single burst during swimming. Kinematic and EMG analyses showed that during running, one of these EMG bursts occurred primarily during swing while the other burst occurred primarily during stance. Modulation of the burst occurring during swing approximated a flexor pattern, while the second burst was modulated like a typical extensor when running over a range of speeds and grades on a treadmill. These data suggest that motoneurons within a motor pool of a uniarticular (VL) as well as a biarticular (RF) muscle can be modulated by more than one cyclical input, probably of central origin, and that under some conditions several motor pools may share the same central commands. Brain Research Institute, University of California, Los Angeles 90024-1761.

• de Leon RD, Hodgson JA, Roy RR and Edgerton VR (1998). Locomotor capacity attributable to step training versus spontaneous recovery after spinalization in adult cats. J Neurophysiol. **79** (3): 1329-40. **Summary:** Locomotor performance, hindlimb muscle activity and gait patterns during stepping were studied in step-trained and non-trained female, adult spinal cats. Changes in locomotor characteristics relative to prespinalization bipedal and quadrupedal stepping patterns were used to evaluate the effects of step training on the capacity to execute full weight-bearing stepping after spinalization. Step training consisted of full weight-bearing stepping of the hindlimbs at the greatest range of treadmill speeds possible at any given stage of locomotor recovery. In the initial stages of training the limbs were assisted as needed to execute successful steps. On the basis of two behavioral criteria, the maximum speed of treadmill stepping and the number of successful steps per unit time, the ability to step was at least 3 times greater in animals trained to step versus those allowed to recover spontaneously, i.e., the non-trained. The greater success in stepping was reflected in several physiological and kinematic properties. For example, the amplitude of electromyograph (EMG) bursts in the tibialis anterior (an ankle dorsiflexor), the amount of extension at the end of both the stance (E3) and swing (E1) phases of the step cycle, and the amount of lift of the hindlimb during swing were greater in step-trained than in non-trained spinal cats. The changes that occurred in response to training reflected functional adaptations at specific phases of the step cycle, e.g., enhanced flexor and extensor function. The improved stepping capacity attributable to step training is interpreted as a change in the probability of the appropriate neurons being activated in a temporally appropriate manner. This interpretation, in turn, suggests that step training facilitated or reinforced the function of extant sensorimotor pathways rather than promoting the generation of additional pathways. These results show that the capacity of the adult lumbar spinal cord to generate full weight-bearing stepping over a range of speeds is defined, in large part, by the functional experience of the spinal cord after supraspinal connectivity has been eliminated. These results have obvious implications with regards to 1) the

possibility of motor learning occurring in the spinal cord; 2) the importance of considering "motor experience" in assessing the effect of any postspinalization intervention; and 3) the utilization of use-dependent interventions in facilitating and enhancing motor recovery. Department of Physiological Science, UCLA, Los Angeles, California 90095, USA.

• De Leon RD, Hodgson JA, Roy RR and Edgerton VR (1999). Retention of hindlimb stepping ability in adult spinal cats after the cessation of step training. J Neurophysiol. **81** (1): 85-94. **Summary:** Adult spinal cats were trained to perform bipedal hindlimb locomotion on a treadmill for 6-12 wk. After each animal acquired the ability to step, locomotor training was withheld, and stepping was reexamined 6 and 12 wk after training ended. The performance characteristics, hindlimb muscle electromyographic activity patterns, and kinematic characteristics of the step cycle that were acquired with training were largely maintained when training was withheld for 6 wk. However, after 12 wk without training, locomotor performance declined, i.e., stumbling was more frequent, and the ability to consistently execute full weight-bearing steps at any treadmill speed decreased. In addition, the height that the paw was lifted during the swing phase decreased, and a smaller range of extension in the hindlimbs occurred during the E3 phase of stance. When three of the spinal cats underwent 1 wk of retraining, stepping ability was regained more rapidly than when trained initially. The finding that stepping ability in trained adult spinal cats can persist for 6 wk without training provides further evidence that training-induced enhancement of stepping is learned in the spinal cats and that a memory of the enhanced stepping is stored in the spinal networks. However, it appears that the spinal cord can forget how to consistently execute stepping if that task is not practiced for 12 wk. The more rapid learning that occurred with retraining is also consistent with a learning phenomenon. These results in conjunction with our earlier findings suggest that the efficacy of the neural pathways that execute a motor task is highly dependent on the periodic activation of those pathways in a sequence compatible with that motor task. Department of Physiological Science, University of California at Los Angeles, Los Angeles, California 90095, USA.

• de Leon RD, Tamaki H, Hodgson JA, Roy RR and Edgerton VR (1999b). Hindlimb locomotor and postural training modulates glycinergic inhibition in the spinal cord of the adult spinal cat. J Neurophysiol. **82** (1): 359-69. **Summary:** Adult spinal cats were trained initially to perform either bipedal hindlimb locomotion on a treadmill or full-weight-bearing hindlimb standing. After 12 wk of training, stepping ability was tested before and after the administration (intraperitoneal) of the glycinergic receptor antagonist, strychnine. Spinal cats that were trained to stand after spinalization had poor locomotor ability as reported previously, but strychnine administration induced full-weight-bearing stepping in their hindlimbs within 30-45 min. In the cats that were trained to step after spinalization, full-weight-bearing stepping occurred and was unaffected by strychnine. Each cat then was retrained to perform the other task for 12 wk and locomotor ability was retested. The spinal cats that were trained initially to stand recovered the ability to step after they received 12 wk of treadmill training and strychnine was no longer effective in facilitating their locomotion. Locomotor ability declined in the spinal cats that were retrained to stand and strychnine restored the ability to step to the levels that were acquired after the step-training period. Based on

analyses of hindlimb muscle electromyographic activity patterns and kinematic characteristics, strychnine improved the consistency of the stepping and enhanced the execution of hindlimb flexion during full-weight-bearing step cycles in the spinal cats when they were trained to stand but not when they were trained to step. The present findings provide evidence that 1) the neural circuits that generate full-weight-bearing hindlimb stepping are present in the spinal cord of chronic spinal cats that can and cannot step; however, the ability of these circuits to interpret sensory input to drive stepping is mediated at least in part by glycinergic inhibition; and 2) these spinal circuits adapt to the specific motor task imposed, and that these adaptations may include modifications in the glycinergic pathways that provide inhibition. Department of Physiological Science, University of California, Los Angeles, California 90095, USA.

• Dietz V (2000). [Focus on current research: improving the mobility of paraplegic patients]. Schweiz Med Wochenschr. **130** (22): 829-36. **Summary:** Since the first paraplegic centre was established in 1945, life expectancy and life quality of paraplegics have considerably improved. However, endeavours to enhance the mobility of these patients have been less successful. The most promising approach, functional electric stimulation of paralysed muscles, is poorly accepted by patients at present because of technical problems. This study describes current approaches which may help to improve patients' mobility. A central motor lesion is perceived by the patient as a movement disorder of the legs, e.g. a gait disorder. Neurological investigation indicates, on the basis of exaggerated tendon reflexes and increased resistance of the non-activated leg muscles to stretching, that spastic paresis underlies the movement disorder. This combination of symptoms and clinical (physical) signs suggests that the exaggerated tendon tap reflexes are responsible for muscle hypertonia and the latter causes the movement disorder. However, electromyography during movement shows that the exaggerated short latency reflexes are associated with loss or attenuation of the functionally essential polysynaptic spinal reflexes. In the event of impaired supraspinal control there is loss of monosynaptic stretch reflex inhibition combined with reduced facilitation of polysynaptic spinal reflexes. Development of tension in tonically active calf muscles in patients with spastic paresis during gait occurs independently of spinal reflex activity. From electrophysiological and histological observations it can be assumed that transformation of motor units resulting in simple and less well adapted regulation of muscle tone allows movements such as gait. The reduction of muscle tone obtained with antispastic drugs is usually associated with paresis and may therefore hamper locomotion. Locomotor training represents a new attempt to improve the mobility of patients with incomplete paraplegia. It includes activation of neuronal circuits within the spinal cord below the level of the lesion. In incomplete paraplegics a coordinated leg muscle activation pattern and corresponding leg movements can be triggered and trained in patients standing on a treadmill with partial weight support. Improvement of training of the spinal cord locomotor centre can be expected from triggering of spinal cord reflexes and regeneration of spinal tract fibres, which is expected to be possible in the near future. Schweizerisches Paraplegikerzentrum, Universitatsklinik Balgrist, Zurich. dietz@balgrist.unizh.ch.

• Dietz V (2001). Spinal cord lesion: effects of and perspectives for treatment. Neural Plast. **8** (1-2): 83-90. **Summary:** Following central motor lesions, two forms of

adaptation can be observed which lead to improved mobility: (1) the development of spastic muscle tone, and (2) the activation of spinal locomotor centers induced by specific treadmill training. Tension development during spastic gait is different from that during normal gait and appears to be independent of exaggerated monosynaptic stretch reflexes. Exaggerated stretch reflexes are associated with an absence or reduction of functionally essential polysynaptic reflexes. When supraspinal control of spinal reflexes is impaired, the inhibition of monosynaptic reflexes is missing in addition to a reduced facilitation of polysynaptic reflexes. Therefore, overall leg muscle activity becomes reduced and less well modulated in patients with spasticity. Electrophysiological and histological studies have shown that a transformation of motor units takes place following central motor lesions with the consequence that regulation of muscle tone is achieved at a lower level of neuronal organization which in turn enables the patient to walk. Based on observations of the locomotor capacity of the spinal cat, recent studies have indicated that spinal locomotor centers can be activated and trained in patients with complete or incomplete paraplegia when the body is partially unloaded. However, the level of electromyographic activity in the gastrocnemius (the main antigravity muscle during gait) is considerably lower in the patients compared to healthy subjects. During the course of a daily locomotor training program, the amplitude of gastrocnemius, electromyographic activity increases significantly during the stance phase, while inappropriate tibialis anterior activation decreases. Patients with incomplete paraplegia benefit from such training programs such that their walking ability on a stationary surface improves. The pathophysiology and functional significance of spastic muscle tone and the effects of treadmill training on the locomotor pattern underlying new attempts to improve the mobility of patients with paraplegia are reviewed. ParaCare, Paraplegic Centre, University Hospital Balgrist, Zurich, Switzerland. dietz@balgrist.unizh.ch.

• Dietz V, Wirz M, Colombo G and Curt A (1998). Locomotor capacity and recovery of spinal cord function in paraplegic patients: a clinical and electrophysiological evaluation. Electroencephalogr Clin Neurophysiol. **109** (2): 140-53. **Summary:** Recent studies have shown that a locomotor pattern can be induced and trained into paraplegic patients under conditions of body unloading using a moving treadmill. The present study investigated the behaviour of the locomotor pattern and also the relationship of its development to the spontaneous recovery of spinal cord function assessed by clinical and electrophysiological (tibial nerve somatosensory evoked potentials and motor evoked potentials) examinations. The earliest time that spinal locomotor activity could be induced was when signs of spinal shock had disappeared. This activity was distinct from spinal stretch reflex activity. In complete and incomplete paraplegic patients an increase of gastrocnemius electromyographic activity occurred during the stance phase of a step cycle with daily locomotor training over the whole training period of 12 weeks. This was coincident with a significant decrease in body unloading. In contrast to this, neither clinical nor electrophysiological examination scores improved after the onset of training in both patient groups. Only in incomplete paraplegic patients was there an insignificant increase in sensory and motor scores obtained in the neurological examination during the time period before onset of training. An improvement of locomotor function by training was also seen in patients with paraplegia due to a cauda lesion. Therefore, in patients with a spinal cord lesion training effects on muscles and

tendons are present in addition to those on the spinal locomotor centres. The findings of this study may be relevant for future clinical treatment of paraplegic patients. Swiss Paraplegic Centre, University Hospital Balgrist, Zurich, Switzerland. dietz@balgrist.unizh.ch.

• Dietz V, Wirz M, Curt A and Colombo G (1998). Locomotor pattern in paraplegic patients: training effects and recovery of spinal cord function. Spinal Cord. **36** (6): 380-90. **Summary:** Recent studies have shown that a locomotor pattern can be induced and utilized by paraplegic patients under conditions of body unloading using a moving treadmill. The present study investigated the behaviour of the locomotor pattern and also the relationship of its development to the spontaneous recovery of spinal cord function assessed by clinical and electrophysiological (tibial nerve somatosensory evoked potentials and motor evoked potentials) examinations. The earliest time that spinal locomotor activity could be induced was when signs of spinal shock had disappeared. This activity was distinct from spinal stretch reflex activity. In complete paraplegic patients the locomotor pattern improved spontaneously without training. This was coincident with both an increase of gastrocnemius electromyographic activity during the stance phase of gait and a decrease of body unloading. These effects reached a plateau after about 5 weeks. In complete and incomplete paraplegic patients a near linear increase of gastrocnemius electromyographic activity occurred during the stance phase of a step cycle with daily locomotor training over the whole training period of 12 weeks. This was also coincident with a significant decrease of body unloading. In contrast to this, neither clinical nor electrophysiological examination scores improved after the onset of training in both patient groups. Only in incomplete paraplegic patients was there recovery, albeit statistically insignificant, of spinal cord function according to the sensory and motor scores obtained in the neurological examination during the time period before onset of training. An improvement of locomotor function by training was also seen in patients with paraplegia due to a cauda lesion. Such training effects on muscles and tendons could be separated from those on the spinal locomotor centres. The findings of this study may be relevant for the future clinical treatment of paraplegic patients. Paraplegic Centre, University Hospital Balgrist, Zurich, Switzerland.

• Dobkin BH (2000). Spinal and supraspinal plasticity after incomplete spinal cord injury: correlations between functional magnetic resonance imaging and engaged locomotor networks. Prog Brain Res. **128**: 99-111. **Summary:** Department of Neurology, University of California, Los Angeles 90095, USA. bdobkin@ucla.edu.

• Dobkin BH, Harkema S, Requejo P and Edgerton VR (1995). Modulation of locomotor-like EMG activity in subjects with complete and incomplete spinal cord injury. J Neurol Rehabil. **9** (4): 183-90. **Summary:** Treadmill training with partial body weight support (BWS) is being advocated as a strategy to enhance walking in patients with spinal cord injury (SCI). Clinical reports have not examined the range of sensory inputs that might modulate electromyographic (EMG) output in the legs during training. During passive, manually assisted stepping on a treadmill with partial BWS, we found similar rhythmical EMG activity in the flexor and extensor muscles of the lower extremities in subjects who had chronic, complete thoracic spinal cord injuries and in subject who had incomplete lesions that resulted in minimal motor control and an

inability to ambulate. The EMG bursts were temporally synchronized to specific phases of the step cycle, and their amplitudes and durations were modulated by varying the treadmill speed and the level of limb loading. Hip extension at the end of stance often induced involuntary hip flexion that initiated the swing phase. When the incomplete SCI subjects attempted volitional stepping, the EMG bursts in some muscles had a similar waveform but greater amplitude and duration compared to that observed during passive, assisted stepping. This suggests that, as in the model of the cat after a thoracic spinal transection, peripheral sensory inputs that are associated with rhythmical locomotion can enhance the output of lumbosacral neural circuits that contribute to step-like EMG activity, even in the absence of supraspinal descending influences. Attention should be given to optimizing the manipulation of sensory inputs during rehabilitation efforts with body weight supported treadmill training. School of Medicine, University of California Los Angeles 90095-6975, USA.

• Edgerton VR, Roy RR, Hodgson JA, Prober RJ, de Guzman CP and de Leon R (1992). Potential of adult mammalian lumbosacral spinal cord to execute and acquire improved locomotion in the absence of supraspinal input. J Neurotrauma. **9 Suppl 1**: S119-28. **Summary:** The neural circuitry of the lumbar spinal cord can generate alternating extension and flexion of the hindlimbs. The hindlimbs of adult cats with complete transection of the spinal cord at a low thoracic level (T12-T13) can perform full weight-supporting locomotion on a treadmill belt moving at a range of speeds. Some limitations in the locomotor capacity can be associated with a deficit in the recruitment level of the fast extensors during the stance phase and the flexors during the swing phase of a step cycle. The level of locomotor performance, however, can be enhanced by daily training on a treadmill while emphasizing full weight-support stepping and by providing appropriately timed sensory stimulation, loading, and/or pharmacologic stimulation of the hindlimb neuromuscular apparatus. Furthermore, there appears to be an interactive effect of these interventions. For example, the maximum treadmill speed that a spinal adult cat can attain and maintain is significantly improved with daily full weight-supporting treadmill training, but progressive recruitment of fast extensors becomes apparent only when the hindlimbs are loaded by gently pulling down on the tail during the stepping. Stimulation of the sural nerve at the initiation of the flexion phase of the step cycle can likewise markedly improve the locomotor capability. Administration of clonidine, in particular in combination with an elevated load, resulted in the most distinct and consistent alternating bursts of electromyographic activity during spinal stepping. These data indicate that the spinal cord has the ability to execute alternating activation of the extensor and flexor musculature of the hindlimbs (stepping) and that this ability can be improved by several interventions such as training, sensory stimulation, and use of some pharmacologic agents. Thus, it appears that the spinal cord, without supraspinal input, is highly plastic and has the potential to "learn," that is, to acquire and improve its ability to execute full weight-supporting locomotion on a treadmill belt. Brain Research Institute, University of California at Los Angeles.

• Edgerton VR, Roy RR, Hodgson JA, Day MK, Weiss J, Harkema SJ, Dobkin B, Garfinkel A, Konigsberg E and Koslovskaya I (2000). How the science and engineering of spaceflight contribute to understanding the plasticity of spinal cord injury. Acta Astronaut. **47** (1): 51-62. **Summary:** Space programs support experimental

investigations related to the unique environment of space and to the technological developments from many disciplines of both science and engineering that contribute to space studies. Furthermore, interactions between scientists, engineers and administrators, that are necessary for the success of any science mission in space, promote interdiscipline communication, understanding and interests which extend well beyond a specific mission. NASA-catalyzed collaborations have benefited the spinal cord rehabilitation program at UCLA in fundamental science and in the application of expertise and technologies originally developed for the space program. Examples of these benefits include: (1) better understanding of the role of load in maintaining healthy muscle and motor function, resulting in a spinal cord injury (SCI) rehabilitation program based on muscle/limb loading; (2) investigation of a potentially novel growth factor affected by spaceflight which may help regulate muscle mass; (3) development of implantable sensors, electronics and software to monitor and analyze long-term muscle activity in unrestrained subjects; (4) development of hardware to assist therapies applied to SCI patients; and (5) development of computer models to simulate stepping which will be used to investigate the effects of neurological deficits (muscle weakness or inappropriate activation) and to evaluate therapies to correct these deficiencies. Brain Research Institute, University of California, Los Angeles,USA.

• Fernando CK and Basmajian JV (1978). Biofeedback in physical medicine and rehabilitation. Biofeedback Self Regul. **3** (4): 435-55. **Summary:**

• Field-Fote EC (2001). Combined use of body weight support, functional electric stimulation, and treadmill training to improve walking ability in individuals with chronic incomplete spinal cord injury. Arch Phys Med Rehabil. **82** (6): 818-24. **Summary:** OBJECTIVE: To assess the effect of an intervention combining body weight support (BWS), functional electric stimulation (FES), and treadmill training on overground walking speed (OGWS), treadmill walking speed, speed and distance, and lower extremity motor scores (LEMS). DESIGN: Before and after comparison. SETTING: Miami Project to Cure Paralysis. PARTICIPANTS: Nineteen subjects with American Spinal Injury Association class C injury who were at least 1 year postinjury and had asymmetrical lower extremity function. INTERVENTION: Subjects trained 1.5 hours per day, 3 days per week, for 3 months. The training consisted of body weight-supported treadmill walking assisted by electric stimulation. Stimulation was applied to common peroneal nerve of the weaker lower extremity (LE) and timed to assist with the swing phase of the step cycle. MAIN OUTCOME MEASURES: OGWS in the absence of both BWS and FES; LEMS, and treadmill training parameters of speed and distance. RESULTS: Over the course of training, there was a significant increase in OGWS (from.12 +/- 0.8m/s to .21 +/- .15m/s, p = .0008), treadmill walking speed (from .23 +/- .12m/s to.49 +/- .20m/s, p = .00003), and treadmill walking distance (from 93 +/- 84m to 243 +/- 139m, p = .000001). The median LEMS increased significantly for both the stimulated and nonstimulated leg (from 8 to 11 in the FES-assisted leg, from 15 to 18 in the nonassisted leg, p < .005 for each). CONCLUSIONS: All subjects showed improvement in OGWS and overall LE strength. Further research is required to delineate the essential elements of these particular training strategies. Division of Physical Therapy and the Miami Project to Cure Paralysis, University of Miami School of Medicine, Miami, FL, USA. edee@miami.edu.

• Frey-Rindova P, de Bruin ED, Stussi E, Dambacher MA and Dietz V (2000). Bone mineral density in upper and lower extremities during 12 months after spinal cord injury measured by peripheral quantitative computed tomography. Spinal Cord. **38** (1): 26-32. **Summary:** OBJECTIVE: To evaluate the loss of trabecular and cortical bone mineral density in radius, ulna and tibia of spinal cord injured persons with different levels of neurologic lesion after 6, 12 and 24 months of spinal cord injury (SCI). DESIGN: Prospective study in a Paraplegic Centre of the University Hospital Balgrist, Zurich. SUBJECTS AND METHODS: Twenty-nine patients (27 males, two females) were examined by the highly precise peripheral quantitative computed tomography (pQCT) soon after injury and subsequently at 6, 12 and in some cases 24 months after SCI. Using analysis of the bone mineral density (BMD), various degrees of trabecular and cortical bone loss were recognised. A rehabilitation program was started as soon as possible (1-4 weeks) after SCI. The influence of the level of neurological lesion was determined by analysis of variance (ANOVA). Spasticity was assessed by the Ashworth Scale. RESULTS: The trabecular bone mineral density of radius and ulna was significantly reduced in subjects with tetraplegia 6 months (radius 19% less, $P<0.01$; ulna 6% less, $P>0.05$) and 12 months after SCI (radius 28% less, $P<0.01$; ulna 15% less, $P<0.05$). The cortical bone density was significantly reduced 12 months after SCI (radius 3% less, $P<0.05$; ulna 4% less, $P<0.05$). No changes in BMD of trabecular or cortical bone of radius and ulna were detected in subjects with paraplegia. The trabecular BMD of tibia was significantly reduced 6 months (5% less, $P<0.05$) and 12 months after SCI (15% less, $P<0.05$) in all subjects with SCI. The cortical bone density of the tibia only was decreased after a year following SCI (7% less, $P<0.05$). No significant difference between both groups, subjects with paraplegia and subjects with tetraplegia was found for tibia cortical or trabecular BMD. There was no significant influence for the physical activity level or the degree of spasticity on bone mineral density in all subjects with SCI. CONCLUSIONS: Twelve months after SCI a significant decrease of BMD was found in trabecular bone in radius and in tibia of subjects with tetraplegia. In subjects paraplegia, a decrease only in tibia BMD occurred. Intensity of physical activity did not significantly influence the loss of BMD in all subjects with para- and tetraplegia. However, in some subjects regular intensive loading exercise activity in early rehabilitation (tilt table, standing) can possibly attenuate the decrease of BMD of tibia. No influence was found for the degree of spasticity on the bone loss in all subjects with SCI. Paraplegic Centre, University Hospital Balgrist, Zurich, Switzerland.

• Gardiner KR, Gardiner PF and Edgerton VR (1982). Guinea pig soleus and gastrocnemius electromyograms at varying speeds, grades, and loads. J Appl Physiol. **52** (2): 451-7. **Summary:** The purpose of the study was to describe changes that occur in the usage of fast-twitch and slow-twitch guinea pig hindlimb muscles, as estimated using chronically implanted electromyogram (EMG) electrodes, during voluntary locomotion under various conditions. Guinea pigs, in which fine wire electrodes were implanted in soleus (SOL) and lateral gastrocnemius (LG) muscles, were exercised at various speeds (13.4, 26.8, 40.2 m/min), grades (0-30%) and in some conditions loads (50-150 g) on a motor-driven treadmill. Bipolar EMG signals were rectified-averaged (RA-EMG) and analyzed for burst duration, amplitude, and the integral of each burst (IEMG). For each condition and muscle, total IEMG/min (IEMG/step x steps/min) was

calculated and expressed as a percent of the maximum IEMG recorded. With increasing speed at 0% grade, the ratio of LG to SOL IEMG, each expressed as percent of maximum, remained constant at about 0.82. An increased stepping rate of 150 (at 13.4 m/min) to 225 (at 40.2 m/min) steps/min was accompanied by a 37% decrease in burst duration in LG and SOL. When the treadmill belt speed was increased from 13.4 to 4.02 m/min at 30% grade, the LG/SOL ratio increased from 0.83 to 1.03, whereas burst duration decreased by 49% (SOL) and 51% (LG). Soleus IEMG did not change significantly with increases in speed or grade; LG IEMG increased significantly with speed at 10% grade and with grade increase at the highest speed (40.2 m/min). These data provide some insight into how modifications of work load on a treadmill affect overall muscle activity and may assist in the interpretation of training-induced muscle biochemical alterations previously noted by other investigators.

• Gardner MB, Holden MK, Leikauskas JM and Richard RL (1998). Partial body weight support with treadmill locomotion to improve gait after incomplete spinal cord injury: a single-subject experimental design. Phys Ther. **78** (4): 361-74. **Summary:** BACKGROUND AND PURPOSE: Gait training with partial body weight support has been used to improve gait. In this study, changes in gait relative to speed, cadence, stride length, and percentages of stance and swing for both lower extremities (LEs) during comfortable walking, fast walking, and running were studied in a subject with an incomplete C-5 on C-6 spinal cord injury. SUBJECT AND METHODS: A single-subject experimental design was used. Following a 6-week period of baseline measurements taken at various intervals (phase AI), the subject ambulated on a treadmill three times a week for 6 weeks with 32% of his body weight supported (phase B). Phase B was followed by a 3-week period without treatment during which measurements were taken at various intervals (phase AII). Gait variables were measured once a week during comfortable walking, fast walking, and running. Heart rate was monitored during treadmill training. RESULTS: During comfortable walking, fast walking, and running, improvements were seen in gait speed. During running, improvements also were seen in stride length and percentages of stance and swing for the right LE. The largest changes were recorded during running. Smaller changes were recorded during comfortable walking and fast walking. CONCLUSION AND DISCUSSION: These results justify testing the efficacy of this technique with larger groups of subjects with neurological impairments. MGH Institute of Health Professions, Boston, Mass, USA. kgard1@aol.com.

• Gosselink KL, Grindeland RE, Roy RR, Zhong H, Bigbee AJ and Edgerton VR (2000). Afferent input from rat slow skeletal muscle inhibits bioassayable growth hormone release. J Appl Physiol. **88** (1): 142-8. **Summary:** The release of a bioassayable form of growth hormone (BGH), distinct from growth hormone as measured by immunoassay (IGH), from the rat pituitary into the blood is differentially regulated by afferent input from fast and slow skeletal muscles. Specifically, activation of low-threshold fast muscle afferents for 15 min increased plasma BGH by 217 and 295% and decreased pituitary BGH by 68 and 45% in male and female rats, respectively. In contrast, activation of slow muscle afferents inhibited BGH release, decreasing plasma BGH by approximately 60% and increasing pituitary BGH by 30-50% in male rats. Female rats from which food had been withheld for approximately 12 h had elevated basal plasma BGH levels, which then

were decreased by 81% after slow muscle nerve stimulation. Plasma IGH concentrations were unchanged after any nerve stimulation condition. These results demonstrate that regulation of BGH release can be differentially mediated through low-threshold afferent inputs from fast or slow skeletal muscle. Furthermore, the results indicate that BGH responses are independent of gender or feeding status. Department of Physiological Science, University of California, Los Angeles 90095, USA.

• Gosselink KL, Grindeland RE, Roy RR, Zhong H, Bigbee AJ, Grossman EJ and Edgerton VR (1998). Skeletal muscle afferent regulation of bioassayable growth hormone in the rat pituitary. J Appl Physiol. **84** (4): 1425-30. **Summary:** There are forms of growth hormone (GH) in the plasma and pituitary of the rat and in the plasma of humans that are undetected by presently available immunoassays (iGH) but can be measured by bioassay (bGH). Although the regulation of iGH release is well documented, the mechanism(s) of bGH release is unclear. On the basis of changes in bGH and iGH secretion in rats that had been exposed to microgravity conditions, we hypothesized that neural afferents play a role in regulating the release of these hormones. To examine whether bGH secretion can be modulated by afferent input from skeletal muscle, the proximal or distal ends of severed hindlimb fast muscle nerves were stimulated ( approximately 2 times threshold) in anesthetized rats. Plasma bGH increased approximately 250%, and pituitary bGH decreased approximately 60% after proximal nerve trunk stimulation. The bGH response was independent of muscle mass or whether the muscles were flexors or extensors. Distal nerve stimulation had little or no effect on plasma or pituitary bGH. Plasma iGH concentrations were unchanged after proximal nerve stimulation. Although there may be multiple regulatory mechanisms of bGH, the present results demonstrate that the activation of low-threshold afferents from fast skeletal muscles can play a regulatory role in the release of bGH, but not iGH, from the pituitary in anesthetized rats. Department of Physiological Science, California 94035, USA.

• Graham SC, Roy RR, Hauschka EO and Edgerton VR (1989). Effects of periodic weight support on medial gastrocnemius fibers of suspended rat. J Appl Physiol. **67** (3): 945-53. **Summary:** Based on the current view that muscle fiber types reflect, at least to some degree, the probability of excitation of motor units in most normal movements, it was hypothesized that brief moderate periods of weight support would have little effect on a muscle that consists predominantly of high-threshold motor units. To test this hypothesis, the effects of 7 days of hindlimb suspension (HS) and HS plus intermittent weight support activity on the size and metabolic properties of individual fibers in the medial gastrocnemius (MG) were studied. HS resulted in a 40% decrease in the mean cross-sectional area of fibers that stain either dark or light for myosin adenosinetriphosphatase (ATPase) at an alkaline preincubation and are located in the deep region (i.e., close to the bone) of the MG. Dark ATPase fibers located in the superficial region were 17% smaller than controls (P greater than 0.05). Although the mean succinate and alpha-glycerophosphate dehydrogenase activities (optical density/min) per muscle fiber were not significantly (P greater than 0.05) affected by HS, it appeared that selected fibers of the deep MG region of HS rats had elevated enzyme activities. HS plus walking on a treadmill for 10 min every 6 h at 5 m/min and at a 19 degrees incline (total of 40 min/day) resulted in mean fiber cross-sectional area

and enzyme activities nearer to control than the HS values. All adaptations were much less obvious in the fibers in a superficial (i.e., away from the bone) MG region.(ABSTRACT TRUNCATED AT 250 WORDS). Department of Kinesiology, Brain Research Institute, Los Angeles, California.

• Gregor RJ, Roy RR, Whiting WC, Lovely RG, Hodgson JA and Edgerton VR (1988). Mechanical output of the cat soleus during treadmill locomotion: in vivo vs in situ characteristics. J Biomech. **21** (9): 721-32. **Summary:** To study the mechanical output of skeletal muscle, four adult cats were trained to run on a treadmill and then implanted under sterile conditions and anesthesia with a force transducer on the soleus tendon and EMG electrodes in the muscle belly. After a two-week recovery period, five consecutive step cycles were filmed at treadmill speeds of 0.8, 1.3 and 2.2 m s-1. Locomotion data in vivo included individual muscle force, length and velocity changes and EMG during each step cycle. Data for an average step cycle at each speed were compared to the force-velocity properties obtained on the same muscle under maximal nerve stimulation and isotonic loading conditions in situ. Results indicate that the force and power generated at a given velocity of shortening during late stance in vivo were greater at the higher speeds of locomotion than the force and power generated at the same shortening velocity in situ. Strain energy stored in the muscle-tendon unit during the yield phase in early stance is felt to be a major contributor to the muscle's enhanced mechanical output during muscle shortening in late stance. Department of Kinesiology, University of California, Los Angeles 90024-1568.

• Harkema SJ, Hurley SL, Patel UK, Requejo PS, Dobkin BH and Edgerton VR (1997). Human lumbosacral spinal cord interprets loading during stepping. J Neurophysiol. **77** (2): 797-811. **Summary:** Studies suggest that the human lumbosacral spinal cord can generate steplike oscillating electromyographic (EMG) patterns, but it remains unclear to what degree these efferent patterns depend on the phasic peripheral sensory information associated with bilateral limb movements and loading. We examined the role of sensory information related to lower-extremity weight bearing in modulating the efferent motor patterns of spinal-cord-injured (SCI) subjects during manually assisted stepping on a treadmill. Four nonambulatory subjects, each with a chronic thoracic spinal cord injury, and two nondisabled subjects were studied. The level of loading, EMG patterns, and kinematics of the lower limbs were studied during manually assisted or unassisted stepping on a treadmill with body weight support. The relationships among lumbosacral motor pool activity [soleus (SOL), medial gastrocnemius (MG), and tibialis anterior (TA)], limb load, muscle-tendon length, and velocity of muscle-tendon length change were examined. The EMG mean amplitude of the SOL, MG, and TA was directly related to the peak load per step on the lower limb during locomotion. The effects on the EMG amplitude were qualitatively similar in subjects with normal, partial, or no detectable supraspinal input. Responses were most consistent in the SOL and MG at load levels of < 50% of a subject's body weight. The modulation of the EMG amplitude from the SOL and MG, both across steps and within a step, was more closely associated with limb peak load than muscle-tendon stretch or the velocity of muscle-tendon stretch. Thus stretch reflexes were not the sole source of the phasic EMG activity in flexors and extensors during manually assisted stepping in SCI subjects. The EMG amplitude within a step was highly dependent on the phase of the step cycle regardless

of level of load. These data suggest that level of loading on the lower limbs provides cues that enable the human lumbosacral spinal cord to modulate efferent output in a manner that may facilitate the generation of stepping. These data provide a rationale for gait rehabilitation strategies that utilize the level of load-bearing stepping to enhance the locomotor capability of SCI subjects. Department of Neurology, University of California, Los Angeles 90095, USA.

• Hauschka EO, Roy RR and Edgerton VR (1988). Periodic weight support effects on rat soleus fibers after hindlimb suspension. J Appl Physiol. **65** (3): 1231-7. **Summary:** The morphological and histochemical properties of the rat soleus were studied after 1 wk of hindlimb suspension, one model that removes the weight-bearing function of the hindlimbs. To examine the effectiveness of weight support activity in maintaining soleus mass, fiber size, and succinate dehydrogenase (SDH) activity, the hindlimbs of adult male Sprague-Dawley rats were suspended (HS) and half of these rats were walked on a treadmill for 40 min/day (10 min every 6 h) at 5 m/min and a 19 degree grade (HS-WS). Significant reductions in soleus mass and fiber size were found after 1 wk of HS. Weight support activity decreased the atrophic response by approximately 50%. In the alkaline myofibrillar adenosine triphosphatase (ATPase) dark-staining fibers, SDH activity was higher in the HS than control rats, whereas it was similar to control in the HS-WS rats. Total SDH activity (SDH activity X cross-sectional area) in fibers staining lightly for ATPase in HS and HS-WS rats was lower than in control rats, whereas in the darkly stained ATPase fibers it was similar among the three groups. No changes were observed in fiber type percentages after 1 wk of HS or HS-WS. The results suggest that short-duration, daily weight support activity can ameliorate, but not prevent, soleus atrophy induced by HS. Furthermore, fiber cross-sectional area is more responsive to periodic weight support in dark than light ATPase fibers. These results also demonstrate that muscle fiber atrophy need not be associated with a loss in SDH activity. Brain Research Institute, Los Angeles, California.

• Hodgson JA, Roy RR, de Leon R, Dobkin B and Edgerton VR (1994). Can the mammalian lumbar spinal cord learn a motor task? Med Sci Sports Exerc. **26** (12): 1491-7. **Summary:** Progress toward restoring locomotor function in low thoracic spinal transected cats and the application of similar techniques to patients with spinal cord injury is reviewed. Complete spinal cord transection (T12-T13) in adult cats results in an immediate loss of locomotor function in the hindlimbs. Limited locomotor function returns after several months in cats that have not received specific therapies designed to restore hindlimb stepping. Training transected cats to step on a treadmill for 30 min.d-1 and 5 d.wk-1 greatly improves their stepping ability. The most successful outcome was in cats where training began early, i.e., 1 wk after spinal transection. Cats trained to stand instead of stepping had great difficulty using the hindlimbs for locomotion. These effects were reversible over a 20-month period such that cats unable to step as a result of standing training could be trained to step and, conversely, locomotion in stepping-trained cats could be abolished by standing training. These results indicate that the spinal cord is capable of learning specific motor tasks. It has not been possible to elicit locomotion in patients with clinically complete spinal injuries, but appropriately coordinated EMG activity has been demonstrated in musculature of the legs during assisted locomotion on a treadmill. Department of Physiological Science, University of

California at Los Angeles 90024-1527.

• Hummelsheim H (1999). Rationales for improving motor function. Curr Opin Neurol. **12** (6): 697-701. **Summary:** New findings in basic neuroscience, and the growing knowledge regarding neuroplasticity and motor learning have exerted influence and have provided stimuli for motor rehabilitation research. Repeated motor practice has been identified as crucial for motor recovery. Further novel and scientifically based therapeutic approaches have been developed: constraint-induced movement therapy, electromyogram-initiated neuromuscular stimulation, motor imagery and music therapy are all discussed in the present review. Neurologisches Rehabilitationszentrum Leipzig, University of Leipzig, Bennewitz, Germany. hhummelshe@aol.com.

• Hutchison DL, Roy RR, Bodine-Fowler S, Hodgson JA and Edgerton VR (1989). Electromyographic (EMG) amplitude patterns in the proximal and distal compartments of the cat semitendinosus during various motor tasks. Brain Res. **479** (1): 56-64. **Summary:** The electromyographic (EMG) signals recorded from the proximal (STp) and distal (STd) compartments of the cat semitendinosus muscle (ST) during treadmill running at various speeds, jumping and paw-shaking were quantified to assess the degree of independence of neural control of the two portions of the muscle. Five adult cats were implanted with intramuscular electrodes in the STp and STd. Raw EMG signals were sampled, rectified and a modified form of their running average was used to calculate the mean EMG every 20 ms. EMG amplitudes of each portion of the muscle were plotted and their relative density distributions were generated. The relative density distribution was used to represent a measure of the probability of any two amplitudes occurring simultaneously (i.e. joint probability density distribution). Based on the probability density distributions of the EMG signals from different movements, the patterns of recruitment from the STp and STd were similar. However, during jumping and paw shaking, two relatively vigorous tasks, some deviations in the pattern were apparent. These data, therefore, suggest that the two ends of the ST are subjected to similar, but not identical, control mechanisms during the motor tasks studied. Brain Research Institute, University of California, Los Angeles 90024.

• Hutchison DL, Roy RR, Hodgson JA and Edgerton VR (1989). EMG amplitude relationships between the rat soleus and medial gastrocnemius during various motor tasks. Brain Res. **502** (2): 233-44. **Summary:** The amplitude and temporal interrelationships of the EMG signals from the rat soleus (Sol) and medial gastrocnemius (MG) muscles during standing, locomoting on a treadmill at various speeds and inclines and swimming were studied. Joint probability density distributions demonstrated a high level of excitation of the Sol relative to the MG during standing. With increasing treadmill speed and/or incline, there was a greater probability of an enhancement in amplitude of the MG than the Sol. Further, there was a greater probability of higher EMG amplitudes of the deep, mixed fiber type region than the superficial, homogeneously fast fiber type region of the MG as speed and incline of locomotion increased. Based on the plotting of sequential points for the joint probability density distributions of EMG amplitudes of the two synergists, the data demonstrated a much greater amplitude modulation of the Sol than the MG during the initial phases of extensor activity. These plots also showed that the Sol activity terminated earlier than

that of the MG. Consequently, the recruitment and derecruitment patterns of these two synergists showed a hysteresis effect, indicating that the motor pools of these two muscles do not function as a single entity. Further, differences in the EMG amplitude relationships of these synergists during a non-weight-bearing activity, i.e. swimming, in comparison to weight-supporting treadmill locomotion suggest that there is a strong peripheral influence on the neural control mechanisms involved. Brain Research Institute, Department of Kinesiology, Los Angeles, CA 90024.

• Jeon JY, Weiss CB, Steadward RD, Ryan E, Burnham RS, Bell G, Chilibeck P and Wheeler GD (2002). Improved glucose tolerance and insulin sensitivity after electrical stimulation-assisted cycling in people with spinal cord injury. Spinal Cord. **40** (3): 110-7. **Summary:** DESIGN: Longitudinal training. OBJECTIVES: The purpose was to determine the effect of electrical stimulation (ES)-assisted cycling (30 min/day, 3 days/week for 8 weeks) on glucose tolerance and insulin sensitivity in people with spinal cord injury (SCI). SETTING: The Steadward Centre, Alberta, Canada. METHODS: Seven participants with motor complete SCI (five males and two females aged 30 to 53 years, injured 3-40 years, C5-T10) underwent 2-h oral glucose tolerance tests (OGTT, n=7) and hyperglycaemic clamp tests (n=3) before and after 8 weeks of training with ES-assisted cycling. RESULTS: Results indicated that subjects' glucose level were significantly lower at 2 h OGTT following 8 weeks of training (122.4+/-10 vs 139.9+/-16, P=0.014). Two-hour hyperglycaemic clamps tests showed improvement in all three people for glucose utilisation and in two of three people for insulin sensitivity. CONCLUSIONS: These results suggested that exercise with ES-assisted cycling is beneficial for the prevention and treatment of Type 2 diabetes mellitus in people with SCI. SPONSORSHIP: Supported by Alberta Paraplegic Foundation, Therapeutic Alliance. The Steadward Centre for Personal and Physical Achievement, University of Alberta, Edmonton, Alberta, Canada.

• Jones LM, Legge M and Goulding A (2002). Intensive exercise may preserve bone mass of the upper limbs in spinal cord injured males but does not retard demineralisation of the lower body. Spinal Cord. **40** (5): 230-5. **Summary:** STUDY DESIGN: Cross-sectional study comparing a group of active spinal cord injured (SCI) males carefully matched for age, height, and weight with active able-bodied male controls. OBJECTIVES: To compare bone mass of the total body, upper and lower limbs, hip, and spine regions in active SCI and able-bodied individuals. SETTING: Outpatient study undertaken in two centres in New Zealand. METHODS: Dual energy X-ray absorptiometry (DEXA) scanning was used to determine bone mass. Questionnaires were used to ascertain total time spent in weekly physical activity for each individual. The criterion for entry into the study was regular participation in physical activity of more than 60 min per week, over and above that required for rehabilitation. RESULTS: Seventeen SCI and their able-bodied controls met our required activity criterion. Bone mineral density (BMD) values of the total body and hip regions were significantly lower in the SCI group than in their controls (P=0.0001). Leg BMD and bone mineral content (BMC) were also significantly lower in the SCI group (P=0.0001). By contrast, lumbar spine BMD and arm BMD and BMC did not differ between the SCI and control groups. Arm BMD and BMC were greater (not significant) than the reference norms (LUNAR database) for both groups. CONCLUSION: Intensive

exercise regimens may contribute to preservation of arm bone mass in SCI males, but does not prevent demineralisation in the lower body. The School of Physical Education, University of Otago, Dunedin, New Zealand.

• Kern H, Hofer C, Strohhofer M, Mayr W, Richter W and Stohr H (1999). Standing up with denervated muscles in humans using functional electrical stimulation. Artif Organs. **23** (5): 447-52. **Summary:** The use of electrical stimulation for denervated muscles is still considered to be a controversial issue by many rehabilitation facilities and medical professionals because prior clinical experience has shown that treating denervated muscle tissue using exponential current over a long time period constitutes an impossible task. Despite this fact, we managed to evoke tetanic contractions in denervated muscle using a long duration stimulation with anatomically shaped electrodes and sufficiently high amplitudes. The pulse amplitudes, which were being used for this purpose, exceeded by far the MED-GV and EC regulations (300 mJ/impulse). For this reason, an application has recently been submitted to have the EC regulations changed accordingly. It takes a tetanic contraction to achieve the desired muscle fiber tension, constituting a hypertrophic stimulus. It is also an appropriate means of exercise, which is capable of creating the metabolic and structural conditions needed (e.g, increased mitochondrial volume and capillary density) to obtain satisfactory muscle performance. With patients suffering from a complete spinal cord injury at level D12/L1, having motor and sensory loss in both lower extremities, we were able to train denervated muscle using long-duration stimulation, evoking single muscle contractions at first, soon followed by tetanic contractions against gravity. To increase the efficacy of this functional electrical stimulation (FES) strengthening program, we used ankle weights. With daily FES training over a period of 1-2 years, denervated muscle was exercised until it produced torques between 16 and 38 Nm in the m. quadriceps. With that muscle force, it is possible to stand up from a sitting position in parallel bars. Our results show that denervated muscle in humans is indeed trainable and can perform functional activities with FES. Furthermore, this method of stimulation can assist in decubitus prevention and significantly improve the mobility of paraplegics. Department of Physical Medicine and Rehabilitation, Wilhelminenspital, Vienna, Austria.

• Kjaer M, Dela F, Sorensen FB, Secher NH, Bangsbo J, Mohr T and Galbo H (2001). Fatty acid kinetics and carbohydrate metabolism during electrical exercise in spinal cord-injured humans. Am J Physiol Regul Integr Comp Physiol. **281** (5): R1492-8. **Summary:** Motor center activity and reflexes from contracting muscle have been shown to be important for mobilization of free fatty acids (FFA) during exercise. We studied FFA metabolism in the absence of these mechanisms: during involuntary, electrically induced leg cycling in individuals with complete spinal cord injury (SCI). Healthy subjects performing voluntary cycling served as controls (C). Ten SCI (level of injury: C5-T7) and six C exercised for 30 min at comparable oxygen uptake rates (approximately 1 l/min), and [1-14C]palmitate was infused continuously to estimate FFA turnover. From femoral arteriovenous differences, blood flow, muscle biopsies, and indirect calorimetry, leg substrate balances as well as concentrations of intramuscular substrates were determined. Leg oxygen uptake was similar in the two groups during exercise. In SCI, but not in C, plasma FFA and FFA appearance rate fell during exercise,

and plasma glycerol increased less than in C (P < 0.05). Fractional uptake of FFA across the working legs decreased from rest to exercise in all individuals (P < 0.05) but was always lower in SCI than in C (P < 0.05). From rest to exercise, leg FFA uptake increased less in SCI than in C subjects (14 +/- 3 to 57 +/- 20 vs. 41 +/- 13 to 170 +/- 57 micromol x min(-1) x leg(-1); P < 0.05). Muscle glycogen breakdown, leg glucose uptake, carbohydrate oxidation, and lactate release were higher (P < 0.05) in SCI than in C during exercise. Counterregulatory hormonal changes were more pronounced in SCI vs. C, whereas insulin decreased only in C. In conclusion, FFA mobilization, delivery, and fractional uptake are lower and muscle glycogen breakdown and glucose uptake are higher in SCI patients during electrically induced leg exercise compared with healthy subjects performing voluntary exercise. Apparently, blood-borne mechanisms are not sufficient to elicit a normal increase in fatty acid mobilization during exercise. Furthermore, in exercising muscle, FFA delivery enhances FFA uptake and inhibits carbohydrate metabolism, while carbohydrate metabolism inhibits FFA uptake. The Copenhagen Muscle Research Centre, Copenhagen University Hospital, DK-2400 Copenhagen NV, Denmark. m.kjaer@mfi.ku.dk.

• Klokker M, Mohr T, Kjaer M, Galbo H and Pedersen BK (1998). The natural killer cell response to exercise in spinal cord injured individuals. Eur J Appl Physiol Occup Physiol. **79** (1): 106-9. **Summary:** In order to evaluate exercise-induced changes in natural killer (NK) and other immunocompetent cells in spinal cord injured individuals, immunological competent blood cells and stress hormones were followed in five paraplegic and six quadriplegic subjects in relation to 30 min electrically stimulated cycling exercise. The leukocyte and lymphocyte concentrations increased during exercise. In the recovery period, the concentration of neutrophils increased, whereas the lymphocytes decreased. The percentage and concentration of NK cells increased during exercise in the paraplegic group and returned to pre-exercise level 2 h after, whereas no changes were seen in these measures for the quadriplegic group. No changes in activated CD38+ NK cells appeared. Unstimulated and interferon-alpha or interleukin-2 stimulated NK cell activity increased during exercise and returned to pre-exercise level 2 h after with no distinction between paraplegics and quadriplegics. The concentrations of plasma growth hormone and catecholamines increased during exercise, with the rise in epinephrine being more pronounced in paraplegic than in quadriplegic subjects, indicating a difference between the groups in sympathetic nervous system integrity. The sympathoadrenal activity is concluded to be responsible for recruitment of NK cells to the blood during exercise. The Copenhagen Muscle Research Centre, Department of Infectious Diseases M 7641, Rigshospitalet, Denmark.

• Klose KJ, Schmidt DL, Needham BM, Brucker BS, Green BA and Ayyar DR (1990). Rehabilitation therapy for patients with long-term spinal cord injuries. Arch Phys Med Rehabil. **71** (9): 659-62. **Summary:** The functional effects of three types of therapy for subjects with long-term incomplete cervical spinal cord injuries were investigated. Men and women, aged 18 to 45 years, were assigned to one of four groups using a restricted randomization process. The training period was divided into two consecutive eight-week time blocks where subjects received either (1) supervised physical exercise therapy (PET), (2) neuromuscular stimulation (NMS), or (3) electromyographic (EMG) biofeedback. Group 1 received EMG biofeedback followed by PET; Group 2 received

EMG biofeedback followed by NMS; Group 3 received NMS followed by PET; and Group 4 received 16 weeks of PET. Dependent measures (manual muscle tests, self-care scores, mobility measures, and voluntary EMG activity) were assessed before training, at eight weeks, and after 16 weeks of training. A significant improvement (p less than .05) across time was found on all dependent measures except voluntary EMG. No difference was found on comparisons between groups. Department of Neurological Surgery, University of Miami School of Medicine, FL.

• Kopp B, Kunkel A, Muhlnickel W, Villringer K, Taub E and Flor H (1999). Plasticity in the motor system related to therapy-induced improvement of movement after stroke. Neuroreport. **10** (4): 807-10. **Summary:** Neuroplasticity might play a beneficial role in the recovery of function after stroke but empirical evidence for this is lacking thus far. Constraint-induced (CI) therapy was used to increase the use of a paretic upper extremity in four hemiparetic stroke patients. Dipole modeling of steady-state movement-related cortical potentials was applied before and after training and 3 months later. The source locations associated with affected hand movement were unusual at follow-up because activation of the ipsilateral hemisphere was found in the absence of mirror movements of the unaffected hand. This long-term change may be considered as an initial demonstration of large-scale neuroplasticity associated with increased use of the paretic limb after application of CI therapy. Department of Psychology, Humboldt University, Clinical Psychology and Behavioral Neuroscience, Berlin, Germany.

• Kunkel A, Kopp B, Muller G, Villringer K, Villringer A, Taub E and Flor H (1999). Constraint-induced movement therapy for motor recovery in chronic stroke patients. Arch Phys Med Rehabil. **80** (6): 624-8. **Summary:** OBJECTIVE: Assessment of the effectiveness of constraint-induced (CI) movement therapy and quantitative evaluation of the effects of CI therapy. DESIGN: Intervention study; case series; pretreatment to posttreatment measures and follow-up 3 months after intervention. SETTING: An outpatient department. PATIENTS: Five chronic stroke patients with moderate motor deficit; convenience sample. INTERVENTIONS: CI therapy consisting of restraint of the unaffected upper extremity in a sling for 14 days combined with 6 hours of training per weekday of the affected upper extremity. MAIN OUTCOME MEASURES: Actual Amount of Use Test (AAUT), Motor Activity Log (MAL), Wolf Motor Function Test (WMFT), and Arm Motor Ability Test (AMAT) RESULTS: There was a substantial improvement in the performance times of the laboratory tests (AMAT, WMFT, p < or = .039) and in the quality of movement (AMAT, WMFT, p < or = .049; MAL, p = .049), particularly in the use of the extremity in "real world" environments (AAUT, p = .020), supported by results of quantitative evaluation. The effect sizes were large and comparable to those found in previous studies of CI therapy. CONCLUSIONS: CI therapy is an efficacious treatment for chronic stroke patients, especially in terms of real world outcome. Department of Psychology, Humboldt-University, Berlin, Germany.

• Liepert J, Miltner WH, Bauder H, Sommer M, Dettmers C, Taub E and Weiller C (1998). Motor cortex plasticity during constraint-induced movement therapy in stroke patients. Neurosci Lett. **250** (1): 5-8. **Summary:** Stroke patients in the chronic phase received constraint-induced (CI) movement therapy. The motor cortex was spatially

mapped using focal transcranial magnetic stimulation (TMS) before and after 2 weeks of treatment. Motor-output areas of the abductor pollicis brevis muscle, motor evoked potential (MEP) amplitudes and location of centre of gravity (CoG) of motor cortex output were studied. After CI therapy, motor performance improved substantially in all patients. There was also an increase of motor output area size and MEP amplitudes, indicating enhanced neuronal excitability in the damaged hemisphere for the target muscles. The mean centre of gravity of the motor output maps was shifted considerably after the rehabilitation, indicating the recruitment of motor areas adjacent to the original location. Thus, even in chronic stroke patients, reduced motor cortex representations of an affected body part can be enlarged and increased in level of excitability by an effective rehabilitation procedure. The data therefore demonstrate a CNS correlate of therapy-induced recovery of function after nervous system damage in humans. Department of Neurology, Friedrich-Schiller-University of Jena, Germany. liepert@neuro.uni-jena.de.

• Lovely RG, Gregor RJ, Roy RR and Edgerton VR (1990). Weight-bearing hindlimb stepping in treadmill-exercised adult spinal cats. Brain Res. **514** (2): 206-18. **Summary:** Hindlimb locomotion on a motor-driven treadmill was studied in 5 cats spinalized at a low thoracic level adults. Six months after surgery, the cats were anesthetized and implanted for electromyographic (EMG) and force recordings in hindlimb muscles. For the last 5 months of the spinalization period, the hindlimbs of each cat were exercised daily for 30 minutes on a treadmill. Data were collected during hindlimb locomotion on a treadmill across the entire range of speeds each cat could accommodate. All trials were filmed (100 frames/s) for kinematic analysis. EMG data were recorded from the soleus (Sol), medial gastrocnemius (MG), tibialis anterior (TA) and extensor digitorum longus (EDL). Forces were recorded in vivo from the Sol and MG tendons. All cats could sustain full weight-bearing stepping without the need for mechanical stimulation of the tail. Although the general stepping pattern of the spinal cats was remarkably similar to that of normal cats, several key differences were identified. Compared to normal cats, the adult spinal cats walked at a lower range of speeds and exhibited a longer swing phase duration. The Sol produced forces and displayed activation periods comparable to those observed in normal cats. The MG of adult spinal cats, however, produced lower forces and had a later onset of activation in comparison to normal cats. Each of the muscles in all spinal cats exhibited tremor during stepping. These results suggest that there were limitations in the activation levels of some hindlimb flexor and extensor muscles during treadmill locomotion. These data further suggest that, in normal cats, accommodation to treadmill speed is accomplished by modulating supraspinal input to the lumbar spinal cord while leaving many of the timing details to be regulated by lumbar spinal networks. Department of Kinesiology, University of California, Los Angeles 90024-1568.

• McCall GE, Gosselink KL, Bigbee AJ, Roy RR, Grindeland RE and Edgerton VR (2001). Muscle afferent-pituitary axis: a novel pathway for modulating the secretion of a pituitary growth factor. Exerc Sport Sci Rev. **29** (4): 164-9. **Summary:** Evidence is presented for a novel muscle-neuro-endocrine pathway for modulating the secretion of an unidentified pituitary growth factor by proprioceptive input from skeletal muscle afferents. Exercise stimulates the release of this growth factor, whereas chronic

unloading associated with bed rest or spaceflight abrogates the normal exercise stimulus. Department of Physiology and Biophysics, University of California, Irvine, USA.

• Miltner WH, Bauder H, Sommer M, Dettmers C and Taub E (1999). Effects of constraint-induced movement therapy on patients with chronic motor deficits after stroke: a replication. Stroke. **30** (3): 586-92. **Summary:** BACKGROUND AND PURPOSE: Constraint-induced movement therapy (CI therapy) has previously been shown to produce large improvements in actual amount of use of a more affected upper extremity in the "real-world" environment in patients with chronic stroke (ie, >1 year after the event). This work was carried out in an American laboratory. Our aim was to determine whether these results could be replicated in another laboratory located in Germany, operating within the context of a healthcare system in which administration of conventional types of physical therapy is generally more extensive than in the United States. METHODS: Fifteen chronic stroke patients were given CI therapy, involving restriction of movement of the intact upper extremity by placing it in a sling for 90% of waking hours for 12 days and training (by shaping) of the more affected extremity for 7 hours on the 8 weekdays during that period. RESULTS: Patients showed a significant and very large degree of improvement from before to after treatment on a laboratory motor test and on a test assessing amount of use of the affected extremity in activities of daily living in the life setting (effect sizes, 0.9 and 2.2, respectively), with no decrement in performance at 6-month follow-up. During a pretreatment control test-retest interval, there were no significant changes on these tests. CONCLUSIONS: Results replicate in Germany the findings with CI therapy in an American laboratory, suggesting that the intervention has general applicability. Department of Biological and Clinical Psychology, Friedrich-Schiller University of Jena, Germany. miltner@biopsy.uni-jena.de.

• Mohr T, Podenphant J, Biering-Sorensen F, Galbo H, Thamsborg G and Kjaer M (1997). Increased bone mineral density after prolonged electrically induced cycle training of paralyzed limbs in spinal cord injured man. Calcif Tissue Int. **61** (1): 22-5. **Summary:** Spinal cord injured (SCI) individuals have a substantial loss of bone mass in the lower limbs, equaling approximately 50% of normal values in the proximal tibia, and this has been associated with a high incidence of low impact fractures. To evaluate if this inactivity-associated condition in the SCI population can be reversed with prolonged physical training, ten SCI individuals [ages 35.3 +/- 2.3 years (mean +/- standard error [SE]); post injury time: 12.5 +/- 2.7 years, range 2-24 years; level of lesion: C6-Th4; weight: 78 +/- 3.8 kg] performed 12 months of Functional Electrical Stimulated (FES) upright cycling for 30 min per day, 3 days per week, followed by six months with only one weekly training session. Bone mineral density (BMD) was determined before training and 12 and 18 months later. BMD was measured in the lumbar spine, the femoral neck, and the proximal tibia by dual energy absorptiometry (DEXA, Nordland XR 26 MK1). Before training, BMD was in the proximal tibia (52%), as well as in the femoral neck, lower in SCI subjects than in controls of same age ($P < 0.05$). BMD of the lumbar spine did not differ between groups ($P > 0.05$). After 12 months of training, the BMD of the proximal tibia had increased 10%, from 0.49 +/- 0.04 to 0. 54 +/- 0.04 g/cm2 ($P < 0.05$). After a further 6 months with reduced training, the BMD in the proximal tibia no longer differed from the BMD before training ($P >$

0.05). No changes were observed in the lumbar spine or in the femoral neck in response to FES cycle training. It is concluded that in SCI, the loss of bone mass in the proximal tibia can be partially reversed by regular long-term FES cycle exercise. However, one exercise session per week is insufficient to maintain this increase. Department of Medical Physiology, Panum Institute, University of Copenhagen, Blegdamsvej 3, DK-2200 Copenhagen, Denmark.

• Needham-Shropshire BM, Broton JG, Klose KJ, Lebwohl N, Guest RS and Jacobs PL (1997). Evaluation of a training program for persons with SCI paraplegia using the Parastep 1 ambulation system: part 3. Lack of effect on bone mineral density. Arch Phys Med Rehabil. **78** (8): 799-803. **Summary:** OBJECTIVE: To determine if the bone mineral density loss seen after spinal cord injury (SCI) is reversed by a walking program using the Parastep 1 system. DESIGN: Before-after trial. SETTING: Human SCI applied research laboratory. PARTICIPANTS: Thirteen men and 3 women with thoracic motor- and sensory-complete SCI, mean age 28.8yrs, mean duration postinjury 3.8yrs. INTERVENTION: Thirty-two functional neuromuscular stimulation (FNS) ambulation training sessions using a commercially available system (Parastep 1). This system consists of a microprocessor-controlled stimulator and a modified walking frame with finger-operated switches that permit the user to control the stimulation parameters and activate the stepping. OUTCOME MEASURE: Bone mineral density at the femoral head, neck, and Ward's triangle measured using a Lunar DP3 dual-photon densitometer. RESULTS: No significant change in bone mineral density was found using repeated measures analyses of variance. CONCLUSIONS: Axial loading combined with muscle stimulation and resistive exercise does not result in significant changes in bone mineral density in persons with complete paraplegia. The Miami Project to Cure Paralysis, University of Miami School of Medicine, FL 33136, USA.

• Page SJ, Levine P, Sisto S, Bond Q and Johnston MV (2002). Stroke patients' and therapists' opinions of constraint-induced movement therapy. Clin Rehabil. **16** (1): 55-60. **Summary:** OBJECTIVE: To determine the opinions of patients with stroke and therapists about constraint-induced movement therapy (CIT). SUBJECTS AND INTERVENTION: Two hundred and eight patients with stroke in the northeastern USA responded to a self-report questionnaire administered through the mail and via telephone interviews. A similar questionnaire was administered to 85 physical and occupational therapists in the northeastern USA during their clinical staff meetings. The questionnaire described CIT to participants using excerpts from a recently published CIT study. Subjects then responded to various statements concerning their opinions of the protocol and supplied rationale for their opinions. RESULTS: Sixty-eight per cent of patients said they were not interested in participating in CIT, citing concerns with the practice schedule and the restrictive device schedule. Therapists cited concerns about patient adherence and safety, and speculated that facilities may not have the clinical resources to provide CIT. CONCLUSIONS: Patients with stroke and therapists in some environments may hold sceptical views about the utility of CIT. Although it has been shown to be effective in laboratory research, CIT may have low clinical practicality in some environments. Kessler Medical Rehabilitation Research and Education Corporation (KMRREC), West Orange NJ 07052, USA. spage@kmrrec.org.

• Pearson KG and Rossignol S (1991). Fictive motor patterns in chronic spinal cats. J Neurophysiol. **66** (6): 1874-87. **Summary:** 1. Fictive motor patterns were recorded in hind leg nerves of 10 adult chronic spinal cats (spinalized at T13). Four of these animals had been trained to step with their hind legs on a treadmill (late-spinal animals), whereas the remainder received no training and were examined a short time after spinalization (early-spinal animals). 2. A fictive pattern resembling the locomotor pattern for stepping was evoked in all animals in response to stimulation of the skin of the perineal region. (2-[2,6-Dichloroaniline]-2-imidazoline) hydrochloride (Clonidine) at doses ranging from 100 to 500 micrograms/kg iv facilitated the production of this pattern, particularly in early-spinal animals. 3. The fictive locomotor pattern in late-spinal animals was more complex than that occurring in early-spinal animals. In the latter the pattern consisted of an alternation of activity in flexor and extensor nerves, and changing leg position did not qualitatively alter the pattern, whereas in late-spinal animals the relative durations of the bursts in different flexors were usually not the same, and the pattern of flexor activity was dependent on leg position. 4. Moving the legs from extension to flexion progressively decreased the duration of flexor bursts, increased the cycle period, and decreased the ease with which the pattern could be evoked in both early- and late-spinal animals. 5. 1-beta-3,4-Dihydroxyphenylalanine (DOPA)/Isonocotinic acid 2-[(2-benzylcarbamoyl)ethyl]hydrazide (Nialamide) treatment following Clonidine in early-spinal animals increased the complexity of flexor burst activity. This, and other observations, indicates that DOPA and Clonidine do not have strictly identical actions on the locomotor pattern generator. 6. Stimulation of the paws in late-spinal animals produced two patterns of activity distinctly different from the locomotor pattern. of activity distinctly different from the locomotor pattern. One was a short sequence of high-frequency rhythmic activity (at approximately 8 c/s) in response to gently stimulating one paw with a water jet, and the other was a slow rhythm in flexor nerves in response to squeezing the paw. 7. The main conclusion of this investigation is that three distinctly different fictive motor patterns can be generated in chronic spinal cats depending on the method and site of stimulation. These patterns correspond to three different behaviors (locomotion, paw shake, and rhythmic leg flexion) that can be elicited in behaving chronic spinal cats in response to the same stimuli.(ABSTRACT TRUNCATED AT 400 WORDS). Department of Physiology, Universite de Montreal, Quebec, Canada.

• Pierotti DJ, Roy RR, Flores V and Edgerton VR (1990). Influence of 7 days of hindlimb suspension and intermittent weight support on rat muscle mechanical properties. Aviat Space Environ Med. **61** (3): 205-10. **Summary:** Unloading the rat hindlimb results in a decrease in mass, especially in those muscles that normally have a load-bearing function. The present study was designed to evaluate the effect of intermittent periods of weight support in ameliorating this atrophic response. Adult male Sprague-Dawley rats were assigned to either a control (CON), a hindlimb suspended (HS), or a hindlimb suspended plus intermittent weight support (HS-WS) group. HS-WS rats were walked slowly on a treadmill at 0.2 m/s and a 19% incline for 10 min, every 6 h. After 7 d, the in situ mechanical properties of the soleus (Sol) and medial gastrocnemius (MG) were studied. Body weights of HS and HS-WS rats were 9 and 13% lower than CON. The SOl weight relative to body weight was 21 and 9% lower in HS and HS-WS than CON. Maximum tetanic tension relative to muscle mass was significantly lower in HS than

CON, whereas HS-WS had values similar to CON. The MG weight relative to body weight was significantly lower in both suspended groups. The maximum tetanic tension relative to muscle weight was significantly elevated in HS-WS compared to CON, suggesting that weight support may have preferentially maintained the contractile protein component of the muscle. Contraction times were 25% faster (p less than 0.05) in the Sol and unchanged in teh MG of HS rats. For each muscle, the fatigue properties were similar in all groups. These data indicate that a low-force, short-duration exercise regime results in a significant functional recovery in the "slow" Sol, whereas the "fast" MG is less affected.(ABSTRACT TRUNCATED AT 250 WORDS). Neuromuscular Research Laboratory, University of California, Los Angeles 90024-1568.

• Pierotti DJ, Roy RR, Gregor RJ and Edgerton VR (1989). Electromyographic activity of cat hindlimb flexors and extensors during locomotion at varying speeds and inclines. Brain Res. **481** (1): 57-66. **Summary:** Electromyographic activity (EMG) was used to determine how hindlimb muscle activation patterns are modified as speed and incline of locomotion are varied in treadmill-trained cats. EMG was recorded using chronically implanted i.m. electrodes from the soleus, medial gastrocnemius, gluteus medius, and tibialis anterior muscles of adult cats during treadmill locomotion at a range of speeds and inclines. The patterns of changes in EMG activity at varying speeds and inclines were similar in all cats. Across speeds, the integrated EMG per step decreased for the soleus but remained constant for the other muscles. The integrated EMG per step was elevated in all muscles at higher inclines. Generally, with increased speed or incline the mean EMG per step was elevated in the medial gastrocnemius, gluteus medius, and tibialis anterior, the largest increase seen in the medial gastrocnemius. Soleus mean EMG per step remained unchanged with increased speed, but showed an absolute increase at the higher inclines. The integrated EMG per minute was always highest for the soleus followed by the medial gastrocnemius, and always lowest for the tibialis anterior. At the faster speeds, the 'on-time' increased in the tibialis anterior and decreased in the other muscles. These data suggest that the number of motor units activated and/or their firing frequencies increased in the medial gastrocnemius and the gluteus medius during locomotion at faster speeds or larger inclines, while relatively little change occurred in the soleus and tibialis anterior. These data also suggest that while there is considerable modulation of the level and duration of excitation of the extensor motor pools there is relatively little modulation of the flexor motor pools to adjust for both the speed and the incline of locomotion. Neuromuscular Research Lab, University of California, Los Angeles 90024-1568.

• Protas EJ, Holmes SA, Qureshy H, Johnson A, Lee D and Sherwood AM (2001). Supported treadmill ambulation training after spinal cord injury: a pilot study. Arch Phys Med Rehabil. **82** (6): 825-31. **Summary:** OBJECTIVES: To conduct a pilot study of weight-supported ambulation training after incomplete spinal cord injury (SCI), and to assess its safety. DESIGN: Quasiexperimental, repeated measures, single group. SETTING: Veterans Affairs medical center. PATIENTS: Three subjects with incomplete, chronic, thoracic SCIs; 2 classified as D on the American Spinal Injury Association (ASIA) impairment scale and 1 as ASIA impairment scale C. INTERVENTION: Subjects participated in 12 weeks of training assisted by 2 physical therapists. The training consisted of walking on a treadmill while supported by a harness and a pneumatic

suspension device. Support started at 40% of body weight and a treadmill speed of.16kmph, and progressed by reducing support and increasing treadmill speed and continuous treadmill walking time up to 20 minutes. Training was conducted for 1 hour per day, 5 days per week for 3 months. Treadmill walking occurred for 20 minutes during the sessions. MAIN OUTCOME MEASURES: Gait function (speed, endurance, walking status, use of assistive device and orthotics); oxygen costs of walking; brain motor control assessment; self-report indices; ASIA classification; muscle function test; and safety. RESULTS: All 3 subjects increased gait speed (.118m/s initially to.318m/s after training 12wk), and gait endurance (20.3m/5min initially to 63.5m/5min). The oxygen costs decreased from 1.96 to 1.33mL x kg(-1) x m(-1) after 12 weeks of training. CONCLUSIONS: This pilot study suggests that supported treadmill ambulation training can improve gait for individuals with incomplete SCIs by using objective gait measures. The self-report indices used have promise as patient-centered outcome measures of this new form of gait training. A larger, controlled study of this technique is warranted. School of Physical Therapy, Texas Woman's University, Houston 77030-2897, USA. hf_protas@twu.edu.

• Ribotta MG, Provencher J, Feraboli-Lohnherr D, Rossignol S, Privat A and Orsal D (2000). Activation of locomotion in adult chronic spinal rats is achieved by transplantation of embryonic raphe cells reinnervating a precise lumbar level. J Neurosci. **20** (13): 5144-52. **Summary:** Traumatic lesions of the spinal cord yield a loss of supraspinal control of voluntary locomotor activity, although the spinal cord contains the necessary circuitry to generate the basic locomotor pattern. In spinal rats, this network, known as central pattern generator (CPG), was shown to be sensitive to serotonergic pharmacological stimulation. In previous works we have shown that embryonic raphe cells transplanted into the sublesional cord of adult rats can reinnervate specific targets, restore the lesion-induced increase in receptor densities of neurotransmitters, promote hindlimb weight support, and trigger a locomotor activity on a treadmill without any other pharmacological treatment or training. With the aim of discriminating whether the action of serotonin on CPG is associated to a specific level of the cord, we have transplanted embryonic raphe cells at two different levels of the sublesional cord (T9 and T11) and then performed analysis of the kinematic and EMG activity synchronously recorded during locomotion. Locomotor performances were correlated to the reinnervated level of the cord and compared to that of intact and transected nontransplanted animals. The movements expressed by T11 transplanted animals correspond to a well defined locomotor pattern comparable to that of the intact animals. On the contrary, T9 transplanted animals developed limited and disorganized movements as those of nontransplanted animals. The correlation of the locomotor performances with the level of reinnervation of the spinal cord suggests that serotonergic reinnervation of the L1-L2 level constitutes a key element in the genesis of this locomotor rhythmic activity. This is the first in vivo demonstration that transplanted embryonic raphe cells reinnervating a specific level of the cord activate a locomotor behavior. Institut National de la Sante et de la Recherche Medicale U336, Ecole Pratique des Hautes Etudes, Universite Montpellier II, F-34095 Montpellier, France. mgyr@univmontp2.fr.

• Rossignol S, Chau C, Brustein E, Belanger M, Barbeau H and Drew T (1996).

Locomotor capacities after complete and partial lesions of the spinal cord. Acta Neurobiol Exp (Warsz). **56** (1): 449-63. **Summary:** This paper first reviews some of the observations made on the locomotor capabilities of several animal species with a special emphasis on cats and including primates and man after complete spinal lesions. We show that animals can perform well-coordinated walking movements of the hindlimbs when they are placed on a treadmill belt and this locomotion is also adaptable to speed and perturbations. Cats with partial spinal lesions of the ventral and ventrolateral parts of the cord can perform voluntary quadrupedal locomotion overground or on the treadmill albeit with deficits in weight support and interlimb coordination. We also show that some drugs such as clonidine (an alpha-2 noradrenergic agonist) can be used to trigger locomotion in early-spinal cats and discuss the effects of various neurotransmitter systems on the expression of the locomotor pattern in both complete and partial spinal cats. It is concluded that a pharmacological approach could be used, in combination with other approaches, such as locomotor training and functional electrical stimulation, to improve locomotor functions after spinal cord injuries in humans. Centre de recherche en sciences neurologiques, Universite Montreal, Quebec, Canada.

• Roy RR, Hutchison DL, Pierotti DJ, Hodgson JA and Edgerton VR (1991). EMG patterns of rat ankle extensors and flexors during treadmill locomotion and swimming. J Appl Physiol. **70** (6): 2522-9. **Summary:** Intramuscular electromyography (EMG) was used to determine and compare the recruitment patterns of the rat soleus (Sol), tibialis anterior (TA), and a deep and a superficial portion of the medial gastrocnemius (MG) during treadmill locomotion at various speeds and inclines and during swimming. Raw EMG signals for 10-20 step or stroke cycles were rectified, averaged, and processed to determine cycle period (EMG onset of one cycle to EMG onset of the next cycle), EMG burst duration, and integrated area of the rectified burst (IEMG). Mean EMG per burst was calculated as IEMG/burst duration. IEMG/min was calculated as IEMG times the number of bursts (cycles) per minute. Cycle period and burst duration of the extensors decreased hyperbolically, while the TA burst duration was unchanged, with increased treadmill speed. With increased treadmill speed, IEMG was decreased in the Sol and unchanged in the MG and TA, whereas IEMG/min decreased in the Sol and increased in the MG and TA. An elevation in treadmill incline resulted in an increase in the activation levels of the MG but not in the Sol or TA. These data indicate that the additional power required at increased speeds and/or inclines of treadmill locomotion is derived from the recruitment of the fast extensors, e.g., the MG. The mean cycle period during swimming was similar to that observed during the fastest treadmill locomotion. EMG burst durations and amplitudes, however, were higher in the TA, relatively similar in the MG, and lower in the Sol during swimming than treadmill locomotion.(ABSTRACT TRUNCATED AT 250 WORDS). Brain Research Institute, University of California, Los Angeles 90024.

• Roy RR, Sacks RD, Baldwin KM, Short M and Edgerton VR (1984). Interrelationships of contraction time, Vmax, and myosin ATPase after spinal transection. J Appl Physiol. **56** (6): 1594-601. **Summary:** Interrelationships of selected mechanical and biochemical properties of hindlimb extensor muscles following low thoracic cord transection were studied. Kittens were spinalized (Sp) at 2 wk and maintained for 6-12

mo. Some Sp animals were exercised (Sp-E) on a treadmill 25-30 min/day, 5 days/wk. In situ contractile properties of the slow-twitch soleus (SOL) and fast-twitch medical gastrocnemius (MG) muscles of normal (N), Sp, and Sp-E cats were determined. Exercise did not affect most parameters; thus Sp and Sp-E groups are considered collectively. The cross-sectional areas (CSA) of the SOL and MG decreased by 43 and 32%, respectively. Specific tension (tension/CSA) was maintained in the SOL but decreased (P less than 0.05) in the MG. Contraction time (CT) and half-relaxation time were significantly shorter in the SOL but unchanged in the MG. Maximum shortening velocity (Vmax) and myosin ATPase (mumol X mg-1 X min-1) increased (P less than 0.05) in the SOL of both groups and the MG of Sp. Frequency-tension responses of both muscles shifted toward that resembling a "faster" muscle. These results substantiate the existence of relatively independent regulatory mechanisms for Vmax and CT and show that myosin ATPase levels are more closely related to Vmax than CT. Although the changes in the SOL were consistent with the hypothesis that slow fibers are converted to fast, the elevated Vmax and myosin ATPase of the MG suggest that significant changes also occur within a "fast" fiber-type category.

• Roy RR, Talmadge RJ, Hodgson JA, Zhong H, Baldwin KM and Edgerton VR (1998). Training effects on soleus of cats spinal cord transected (T12-13) as adults. Muscle Nerve. **21** (1): 63-71. **Summary:** Adult spinal cord transected (T12-13) cats were trained for 30 min/day, 5 days/week to either step on a treadmill (Stp-T) or stand (Std-T) for approximately 5 months. Training ameliorated soleus atrophy and enhanced maximum force capability compared to nontrained (N-T) spinal cats, with Stp-T being significantly different from N-T. Isometric twitch speed and maximum rate of shortening were unaffected by training; the soleus of all spinal groups was significantly faster than control. There was an elevation in myosin adenosine triphosphatase activity and a shift toward faster myosin heavy chain and fiber type compositions in N-T and Std-T, but not Stp-T cats. Thus, rhythmical activity involving muscle length and force changes (stepping) was more effective than a similar amount of a more static activity (standing). This specificity related to the type of training should be considered when developing rehabilitative strategies following spinal cord injury. Brain Research Institute, UCLA School of Medicine, Center for the Health Sciences, Los Angeles, California 90095-1761, USA.

• Roy RR, Talmadge RJ, Hodgson JA, Oishi Y, Baldwin KM and Edgerton VR (1999a). Differential response of fast hindlimb extensor and flexor muscles to exercise in adult spinalized cats. Muscle Nerve. **22** (2): 230-41. **Summary:** Adult cats were spinal transected (T12-13) and maintained for approximately 6 months. Spinal cats were either not trained (N-T) or trained for 30 min/day to either step on a treadmill (Stp-T) or stand (Std-T). Spinalization resulted in a decrease in the mass and maximum tension potential of the medial gastrocnemius (MG), a fast ankle extensor. These adaptations were ameliorated in Std-T but not Stp-T cats. The maximum rate of shortening was elevated by 18 (ns), 34, and 19 (ns)% in the N-T, Std-T, and Stp-T cats, respectively, a finding consistent with a shift in the percentage of fast fibers, a decrease in the percentage of fibers expressing only type I myosin heavy chain, and an increase in myofibrillar adenosine triphosphatase activity. The shift toward a faster fiber type profile in the tibialis anterior (TA), a fast ankle flexor, was of a lesser magnitude than in

the MG. There were no significant effects on the contractile properties of the TA in any group of spinal cats. The greater preservation of muscle mass, shift toward faster physiological and biochemical properties, and fatigability in the MG of Std-T than Stp-T cats suggest that factors other than the level of activation and force generation must play a role in muscle homeostasis. From a clinical perspective, the results indicate that muscles innervated by motor neurons below the level of a complete spinal cord lesion are affected differentially by specific neuromuscular activity patterns. Brain Research Institute, UCLA School of Medicine, Center for the Health Sciences, Los Angeles, California 90095-1761, USA.

• Roy RR, Ishihara A, Kim JA, Lee M, Fox K and Edgerton VR (1999b). Metabolic and morphological stability of motoneurons in response to chronically elevated neuromuscular activity. Neuroscience. **92** (1): 361-6. **Summary:** The purpose of this study was to determine the plasticity of spinal motoneuron size and succinate dehydrogenase activity in response to increased levels of neuromuscular activation and/or increased target size. The plantaris muscles of adult rats were functionally overloaded for one or 10 weeks via the removal of the soleus and gastrocnemius muscles bilaterally. In addition, one group of functionally overloaded rats at each time period was trained daily (1 h/day) on a treadmill. The plantaris muscle on one side in each rat was injected with the fluorescent tracer Nuclear Yellow two days prior to the end of the study to retrogradely label the associated motor pool. At one week, the plantaris weight was increased compared to control, whereas there was no change in motoneuron size. Succinate dehydrogenase activity was unaffected in either the muscle or motoneurons. At 10 weeks, the plantaris muscle weight was larger and the succinate dehydrogenase activity lower in the functionally overloaded rats compared to age-matched controls. Training further increased the hypertrophic response, whereas the succinate dehydrogenase activity returned to control levels. In contrast, mean motoneuron size and succinate dehydrogenase activity were similar among the three groups. These data indicate that overload of a specific motor pool, involving both an increase in activation and an increase in target size, had a minimal effect on the size or the oxidative potential of the associated motoneurons. Thus, it appears that the spinal motoneurons, unlike the muscle fibers, are highly stable over a wide range of levels of chronic neuromuscular activity. Brain Research Institute and Physiological Science Department, University of California at Los Angeles, 90095-1761, USA.

• Roy RR, Monke SR, Allen DL and Edgerton VR (1999c). Modulation of myonuclear number in functionally overloaded and exercised rat plantaris fibers. J Appl Physiol. **87** (2): 634-42. **Summary:** The effects of 10 wk of functional overload (FO), with and without daily treadmill endurance training, on the cross-sectional area, myonuclear number, and myonuclear domain size of mechanically isolated single fiber segments of the adult rat plantaris were determined. The fibers were typed on the basis of high-resolution gel electrophoresis for separation of specific myosin heavy chain (MHC) isoforms and grouped as type I(+) (containing some type I MHC with or without any combination of fast MHCs), type IIa(+) (containing some type IIa with or without some type IIx and/or IIb but no type I MHC), and type IIx/b (containing only type IIx and/or IIb MHCs). Type I(+) fibers had a higher myonuclear number than did both fast types of fibers in the control and FO, but not in the FO and treadmill trained, rats. All fiber types

in both FO groups had a significantly larger (36-90%) cross-sectional area and a significantly higher (61-109%) myonuclear number than did control. The average myonuclear domain size of each fiber type was similar among the three groups, except for a smaller domain size in the type IIx/b fibers of the FO compared with control. In general, these data indicate that during hypertrophy the number of myonuclei increase proportionally to the increase in fiber volume. The maintenance of myonuclear domain size near control values suggests that regulatory mechanisms exist that ensure a tight coupling between the quantity of genetic machinery and the protein requirements of a fiber. Brain Research Institute, University of California, Los Angeles, California 90095, USA.

• Shepherd RB (2001). Exercise and training to optimize functional motor performance in stroke: driving neural reorganization? Neural Plast. **8** (1-2): 121-9. **Summary:** Neurorehabilitation is increasingly taking account of scientific findings. Research areas directing stroke rehabilitation are neurophysiology; adaptability to use and activity; biomechanics; skill learning; and exercise science (task, context specificity). Understanding impairments and adaptations enables a reappraisal of interventions-for example, changes in motor control resulting from impairments (decreased descending inputs, reduced motor unit synchronization), secondary soft tissue changes (muscle length and stiffness changes) are adaptations to lesion and disuse. Changes in interventions include increasing emphasis on active exercise and task-specific training, active and passive methods of preserving muscle extensibility. Training has the potential to drive brain reorganization and to optimize functional performance. Research drives the development of training programs, and therapists are relying less on one-to-one, hands-on service delivery, making use of circuit training and group exercise and of technological advances (interactive computerized systems, treadmills) which increase time spent in active practice. Emphasis is on skill training, stressing cognitive engagement and practice, aiming to increase strength, control, skill, endurance, fitness, and social readjustment. Rehabilitation services remain slow to make the changes necessary to upgrade environments, attitudes, and rehabilitation methodologies to those shown to be more scientifically rational and for which there is evidence of effectiveness. School of Physiotherapy, Faculty of Health Sciences, The University of Sydney, Australia. R.Shepherd@cchs.usyd.edu.au.

• Shimamura M, Edgerton VR and Kogure I (1987). Application of autoradiographic analysis of 2-deoxyglucose in the study of locomotion. J Neurosci Methods. **21** (2-4): 303-10. **Summary:** Trace amounts of [14C]2-deoxyglucose (2-DG) were used to detect regions of the brainstem involved in forelimb stepping in thalamic and low spinal cats. Under ether anesthesia, cats were transected at the stereotaxic A12 level and T10 segment. Two hours later, 50 microCi/kg of 2-DG was infused i.v. and one of 4 procedures was followed: 3 cats stepped on a motor-drive treadmill (Stepping), 3 were kept in a stationary standing position (Rigidity), 2 were anesthetized with sodium pentobarbital (Anesthetized), and 2 were stimulated in the mesencephalic locomotor region (MLR-induced). Absolute optical densities of the autoradiograms corresponding to identified anatomical structures of the brainstem were generally in the following order: Stepping greater than Anesthetized greater than MLR-induced greater than Rigidity. The 2-DG uptake relative to the pyramidal tract (2-DG ratio) also was

compared for each of the 4 experimental procedures. In the Stepping cats, the 2-DG ratio was highest in the vestibular nuclei, periaqueductal gray, red nucleus and thalamic nuclei. In the Rigid cats, the 2-DG ratio was highest in the medial vestibular nucleus and subthalamic and thalamic nucleus. These findings suggest that the 2-DG tracer method can be useful in associating neural structures with specific kinds of motor functions within a cat. This is particularly true when using the relative activities of different neural structures and in comparing specific neural structures across cats under different experimental conditions when the amount of 2-DG infused is standardized and the optical densities of the autoradiograms are calibrated to a specific level of 2-DG. Department of Neurophysiology, Tokyo Metropolitan Institute for Neurosciences, Japan.

• Smith LA, Eldred E and Edgerton VR (1993). Effects of age at cordotomy and subsequent exercise on contraction times of motor units in the cat. J Appl Physiol. **75** (6): 2683-8. **Summary:** The contraction times (CTs) of functionally isolated motor units (MUs) in the soleus (SOL) and medial gastrocnemius (MG) muscles were determined in cats that had been spinalized at ages 2 (n = 15) or 12 (n = 9) wk and then either subjected to exercise on a treadmill or simply given manipulative care of the hindlimbs. The MUs were tested approximately 12 wk after the low-thoracic cordotomy, and comparisons were made with data from control animals. The CT of 50.9 ms obtained for SOL units (n = 163) in the spinal cats was 22% shorter than the mean of 65.0 ms for MUs (n = 57) from control cats (n = 4). Contrary to expectation, the CT in animals spinalized at 12 wk was significantly shorter than that in the 2-wk group. The CT for MG units (n = 105) in spinal cats was also significantly shorter (11%) than that in controls cats (n = 66, 6 cats), and those units identified by their high fatigue index as being of slow or fatigue-resistant type had a shorter CT than units with a low index. No distinction in CT of exercised and nonexercised groups was detected for either muscle. These findings are discussed in relation to the bearing influences of supraspinal and segmental origin have on CT duration in SOL and MG muscles during growth of the kitten. A slight, significant decrease (6%) in the fatigue index of SOL MUs (n = 144) was detected, but the values remained high (mean 0.87). Brain Research Institute, University of California, Los Angeles 90024-1761.

• Stallknecht B, Lorentsen J, Enevoldsen LH, Bulow J, Biering-Sorensen F, Galbo H and Kjaer M (2001). Role of the sympathoadrenergic system in adipose tissue metabolism during exercise in humans. J Physiol. **536** (Pt 1): 283-94. **Summary:** 1. The relative roles of sympathetic nerve activity and circulating catecholamines for adipose tissue lipolysis during exercise are not known. 2. Seven paraplegic spinal cord injured (SCI, injury level T3-T5) and seven healthy control subjects were studied by microdialysis and (133)xenon washout in clavicular (Cl) and in umbilical (Um) (sympathetically decentralized in SCI) subcutaneous adipose tissue during 1 h of arm cycling exercise at approximately 60 % of the peak rate of oxygen uptake. 3. During exercise, adipose tissue blood flow (ATBF) and interstitial glycerol, lactate and noradrenaline concentrations increased significantly in both groups. Plasma catecholamine levels increased significantly less with exercise in SCI than in healthy subjects. The exercise-induced increase in interstitial glycerol concentration in subcutaneous adipose tissue was significantly lower in SCI compared with healthy subjects (SCI: 25 +/- 12 % (Cl), 36 +/-

20 % (Um); healthy: 60 +/- 17 % (Cl), 147 +/- 45 % (Um)) and the increase in ATBF was significantly lower (Cl) or similar (Um) in SCI compared with healthy subjects (SCI: 1.2 +/- 0.3 ml (100 g)(-1) min(-1) (Cl), 1.0 +/- 0.3 ml (100 g)(-1) min(-1) (Um); healthy: 2.8 +/- 0.7 ml (100 g)(-1) min(-1) (Cl), 0.6 +/- 0.3 ml (100 g)(-1) min(-1) (Um)). Accordingly, in both adipose tissues lipolysis increased less in SCI compared with healthy subjects, indicating that circulating catecholamines are important for the exercise-induced increase in subcutaneous adipose tissue lipolysis. In SCI subjects, the exercise-induced increase in subcutaneous adipose tissue lipolysis was not lower in decentralized than in sympathetically innervated adipose tissue. During exercise the interstitial noradrenaline and adrenaline concentrations were lower in SCI compared with healthy subjects ($P < 0.05$) and always lower than arterial plasma catecholamine concentrations ($P < 0.05$). 4. It is concluded that circulating catecholamines are important for the exercise-induced increase in subcutaneous adipose tissue lipolysis while sympathetic nerve activity is not. Department of Medical Physiology, The Panum Institute, University of Copenhagen, DK-2200 Copenhagen N, Denmark. b.stallknecht@mfi.ku.dk.

• Sullivan KJ, Knowlton BJ and Dobkin BH (2002). Step training with body weight support: effect of treadmill speed and practice paradigms on poststroke locomotor recovery. Arch Phys Med Rehabil. **83** (5): 683-91. **Summary:** OBJECTIVE: To investigate the effect of practice paradigms that varied treadmill speed during step training with body weight support in subjects with chronic hemiparesis after stroke. DESIGN: Randomized, repeated-measures pilot study with 1- and 3-month follow-ups. SETTING: Outpatient locomotor laboratory. PARTICIPANTS: Twenty-four individuals with hemiparetic gait deficits whose walking speeds were at least 50% below normal. INTERVENTION: Participants were stratified by locomotor severity based on initial walking velocity and randomly assigned to treadmill training at slow (0.5mph), fast (2.0mph), or variable (0.5, 1.0, 1.5, 2.0mph) speeds. Participants received 20 minutes of training per session for 12 sessions over 4 weeks. MAIN OUTCOME MEASURE: Self-selected overground walking velocity (SSV) was assessed at the onset, middle, and end of training, and 1 and 3 months later. RESULTS: SSV improved in all groups compared with baseline ($P<.001$). All groups increased SSV in the 1-month follow-up ($P<.01$) and maintained these gains at the 3-month follow-up ($P=.77$). The greatest improvement in SSV across training occurred with fast training speeds compared with the slow and variable groups combined ($P=.04$). Effect size (ES) was large between fast compared with slow ($ES=.75$) and variable groups ($ES=.73$). CONCLUSIONS: Training at speeds comparable with normal walking velocity was more effective in improving SSV than training at speeds at or below the patient's typical overground walking velocity. Department of Neurology, University of California, Los Angeles, CA 90095, USA.

• Taub E, Uswatte G and Pidikiti R (1999). Constraint-Induced Movement Therapy: a new family of techniques with broad application to physical rehabilitation--a clinical review. J Rehabil Res Dev. **36** (3): 237-51. **Summary:** A new family of rehabilitation techniques, termed Constraint-Induced Movement Therapy or CI Therapy, has been developed that controlled experiments have shown is effective in producing large improvements in limb use in the real-world environment after cerebrovascular accident (CVA). The signature therapy involves constraining movements of the less-affected arm

with a sling for 90% of waking hours for 2 weeks, while intensively training use of the more-affected arm. The common therapeutic factor in all CI Therapy techniques would appear to be inducing concentrated, repetitive practice of use of the more-affected limb. A number of neuroimaging and transcranial magnetic stimulation studies have shown that the massed practice of CI Therapy produces a massive use-dependent cortical reorganization that increases the area of cortex involved in the innervation of movement of the more-affected limb. The CI Therapy approach has been used successfully to date for the upper limb of patients with chronic and subacute CVA and patients with chronic traumatic brain injury and for the lower limb of patients with CVA, incomplete spinal cord injury, and fractured hip. The approach has recently been extended to focal hand dystonia of musicians and possibly phantom limb pain. Physical Medicine and Rehabilitation Service, Birmingham Department of Veterans Affairs Medical Center, AL 35233, USA. etaub@uab.edu.

• Taub E, Crago JE, Burgio LD, Groomes TE, Cook EW, 3rd, DeLuca SC and Miller NE (1994). An operant approach to rehabilitation medicine: overcoming learned nonuse by shaping. J Exp Anal Behav. **61** (2): 281-93. **Summary:** A new approach to the rehabilitation of movement, based primarily on the principles of operant conditioning, was derived from research with deafferented monkeys. The analysis suggests that a certain proportion of excess motor disability after certain types of injury involves a learned suppression of movement and may be termed learned nonuse. Learned nonuse can be overcome by changing the contingencies of reinforcement so that they strongly favor use of an affected upper extremity in the chronic postinjury situation. The techniques employed here involved 2 weeks of restricting movement of the opposite (unaffected) extremity and training of the affected limb. Initial work with humans has been with chronic stroke patients for whom the approach has yielded large improvements in motor ability and functional independence. We report here preliminary data suggesting that shaping with verbal feedback further enhances the motor recovery. Psychology Department, University of Alabama at Birmingham 35294.

• Taub E, Miller NE, Novack TA, Cook EW, 3rd, Fleming WC, Nepomuceno CS, Connell JS and Crago JE (1993). Technique to improve chronic motor deficit after stroke. Arch Phys Med Rehabil. **74** (4): 347-54. **Summary:** The unaffected upper extremity of chronic stroke patients was restrained in a sling during waking hours for 14 days; on ten of those days, these patients were given six hours of practice in using the impaired upper extremity. An attention-comparison group received several procedures designed to focus attention on use of the impaired upper extremity. The restraint subjects improved on each of the laboratory measures of motor function used--in most cases markedly. Extensive improvement, from a multi-year plateau of greatly impaired motor function, was also noted for the restraint group in the life situation and these gains were maintained during a two-year period of follow-up. For the comparison group only one measure showed small to moderate improvement, and this was lost during the follow-up period; there was essentially no overlap between the individuals of the two groups. Thus, prolonged restraint of an unaffected upper extremity and practice of functional movements with the impaired limb proved to be an effective means of restoring substantial motor function in stroke patients with chronic motor impairment identified by the inclusion criteria of this project. Department of Psychology, University of

Alabama, Birmingham 35294.

• Trimble MH, Behrman AL, Flynn SM, Thigpen MT and Thompson FJ (2001). Acute effects of locomotor training on overground walking speed and H-reflex modulation in individuals with incomplete spinal cord injury. J Spinal Cord Med. **24** (2): 74-80. **Summary:** OBJECTIVE: The purpose of this study was to assess the effect of a single bout of a locomotor-training paradigm on overground walking speed and H-reflex modulation of individuals with incomplete spinal cord injury (SCI). METHODS: Self-selected and maximum walking speeds and soleus H-reflexes (H/M ratios) during standing and stance and swing phases of walking (self-selected velocity) were obtained from 4 individuals with American Spinal Injury Association impairment classification D. Data were collected immediately before and after a single bout of locomotor training with body weight support on a treadmill. The pretraining H/M ratios of the SCI subjects were also compared with values from 4 able-bodied subjects who did not receive the intervention. Maximum H/M ratios while standing and during midstance and midswing phases of overground walking were considerably greater in the SCI subjects than in the control subjects. RESULTS: After the single bout of training, self-selected and maximum overground walking speeds of the subjects with SCI increased by 26% and 25%, respectively. Furthermore, H-reflexes were significantly more depressed in the SCI subjects during overground walking (28% less during stance, 34% less during swing). CONCLUSIONS: Although preliminary, these findings indicate that a single bout of locomotor training produced immediate increases in walking velocity and acute neurophysiologic changes in individuals with incomplete SCI. Department of Physical Therapy, University of Florida, Gainesville, USA.

• van der Lee JH (2001). Constraint-induced therapy for stroke: more of the same or something completely different? Curr Opin Neurol. **14** (6): 741-4. **Summary:** The term "constraint-induced therapy" is used to denote a "family of treatment modalities" in which the common feature is discouraging the use of the unaffected or less affected arm, combined with intensive training of the paretic arm. A systematic literature search revealed only three randomized controlled studies on the effectiveness of constraint-induced therapy. The results of several systematic reviews on exercise therapy in stroke rehabilitation indicate that more intensive (i.e. more time spent in) training may be beneficial. Therefore, it is not unlikely that any (as yet unproved) effect of constraint-induced techniques is the result of more training, and the answer to the question in the title of this review seems to be "More of the same". Department of Rehabilitation Medicine, VU University Medical Center, PO Box 7075, 1007 MB Amsterdam, the Netherlands. jh.vanderlee@vumc.nl.

• Wernig A and Muller S (1992). Laufband locomotion with body weight support improved walking in persons with severe spinal cord injuries. Paraplegia. **30** (4): 229-38. **Summary:** After low transection of the spinal cord mammalian quadrupeds can be trained to walk on a driven surface indicating that coordinating neuronal circuits persist in the spinal cord segments caudal to the lesion. We trained 8 persons with incomplete spinal cord lesion on a Laufband (driven treadmill) for 1 1/2 to 7 months (5 days a week, 30-60 minutes daily) starting 5 to 20 months after injury and found significant improvement in the utilisation of the paralysed limbs during locomotion. Locomotion is

described in one additional patient who had trained independently on parallel bars for several years. Five patients had complete functional paralysis in one lower limb when tested in a resting position. In EMG recordings voluntary activity (ie activity induced upon command) was absent or residual in the main flexor and extensor muscles of this limb. In contrast, during locomotion flexion and extension movements were performed and phasic EMG activity was present. In these 5 patients, and in all others reported here, skin sensibility and proprioception are preserved to different degrees in all limbs. In the course of locomotive training of 4 severely paralysed patients the initially habituating flexion reflexes could be entrained in the paralysed limbs as was the case for knee extension during stance. Subsequently, initial body weight support (BWS) of 40% could be reduced to 0%. The distance covered on the Laufband (0-104 m in the first week) increased significantly (200-410 m) in the last week of training as did speed (0-10 to 14-23 m/min). More importantly, this training subsequently allowed patients to walk on a static surface for 100 to 200 meters while voluntary activity remained absent in the paralysed limb when tested at rest. Similar progress was achieved in the 4 less severely paralysed patients. The one patient who had trained independently on parallel bars for several years is described walking on a static surface for 40 meters with the help of a walker, though he had one completely and one near completely paralysed lower limb. It appears that bipedal stepping with consequent knee extension and stabilisation can be taught after unilateral complete or near complete loss of voluntary activity, suggesting the manifestation of complex reflex motor patterns at the spinal level. Department of Physiology, University of Bonn, FRG.

• Wernig A, Muller S, Nanassy A and Cagol E (1995). Laufband therapy based on 'rules of spinal locomotion' is effective in spinal cord injured persons. Eur J Neurosci. **7** (4): 823-9. **Summary:** Rehabilitation of locomotion in spinal cord (s.c.) injured patients is unsatisfactory. Here we report the effects of a novel 'Laufband (LB; treadmill) therapy' based on 'rules of spinal locomotion' derived from lower vertebrates. Eighty-nine incompletely paralysed (44 chronic and 45 acute) para- and tetraplegics underwent this therapy, then were compared with 64 patients (24 chronic and 40 acute) treated conventionally. The programme consisted of daily upright walking on a motor driven LB initially with body weight support (BWS) provided by a harness and assisted limb movements by the therapists when necessary. Forty-four chronic patients with different degrees of paralysis undertook the programme for 3-20 weeks (median = 10.5), 0.5-18 years after s.c. damage. At the onset of LB therapy 33/44 patients were wheelchair-bound (no standing and/or walking without help by others) whereas at the end of therapy 25 patients (76%) had learned to walk independently, 7 patients with help [corrected]. Only 1 subject did not improve. It was striking that voluntary muscle activity in the resting position was still low in several patients who had gained walking capability. Eleven patients who could already walk before LB therapy improved in speed and endurance. Of the 44 patients, six were capable of staircase walking before LB therapy compared with 34 afterwards. In order to validate the apparent superiority of LB therapy two types of comparisons were performed. In a 'temporal' control 12 spastic paretic patients, still wheelchair-bound after the period of postacute conventional therapy, performed LB immediately thereafter. After completion of LB therapy nine of these patients had learned to walk without help from others.(ABSTRACT TRUNCATED AT 250 WORDS). Department of Physiology, University of Bonn, Germany.

• Wernig A, Nanassy A and Muller S (1998). Maintenance of locomotor abilities following Laufband (treadmill) therapy in para- and tetraplegic persons: follow-up studies. Spinal Cord. **36** (11): 744-9. **Summary:** Recent reports indicate that walking capabilities in spinal cord damaged persons significantly improve--as compared to conventional rehabilitation therapy--after intensive training of aided (Laufband) treadmill-stepping. In the present report, follow up investigations on two collectives of spinal cord injured (sci) persons are described who had undergone (Laufband) treadmill therapy either during a period of renewed rehabilitation months or years after spinal cord injury (35 chronic patients) or during their first postacute rehabilitation period (41 acute patients). Among the initially chronic patients, 20 from 25 still wheelchair-bound before the onset of (Laufband) treadmill therapy, ie not capable of raising from the wheelchair and walking without help by other persons, became independent walkers after therapy. Assessment of voluntary muscle activity in resting position before and after the period of therapy had shown only small increases in most patients, indicating the involvement of motor automatisms and better utilisation of remaining muscle function during walking. Follow-up assessments performed 6 months to 6 1/2 years after discharge from the hospital revealed that the walking capabilities achieved by (Laufband) treadmill therapy in the 35 initially chronic patients were maintained in 31 persons, in three they had further improved, in only one it was reduced. These results indicate that the improvements achieved under clinical conditions can be maintained in every day life under domestic surroundings. From 41 initially acute patients, 15 had further improved and none had reduced his walking capability 6 months to 6 years after discharge from the hospital. Department of Physiology, University of Bonn, Germany.

• Wernig A, Nanassy A and Muller S (1999). Laufband (treadmill) therapy in incomplete paraplegia and tetraplegia. J Neurotrauma. **16** (8): 719-26. **Summary:** Recent reports indicate that intensive training of upright walking on a treadmill (German: Laufband, LB), significantly improves walking capability in spinal cord-damaged persons. The aids provided initially are body weight support by a harness and passive setting of one or both limbs by therapists. To facilitate stepping and evoke motor automatisms, "rules of spinal locomotion" need to be applied during training. The effects of this novel locomotion therapy on patients with chronic and acute incomplete paralysis are summarized and discussed here. Many patients with chronic paralysis, still wheelchair-bound and not capable of walking without help from others, became independent and learned to walk for some distance without help. Assessment of voluntary muscle activity in resting position before and after the period of therapy often showed only small increases, rendering the involvement of complex motor reflexes (motor programs) and better utilization of remaining muscle function during walking as main sources for the improvements in locomotion. This idea is supported by electromyographic recordings. Follow-up assessments performed 0.5 to 6.5 years after discharge from the hospital show that the significant improvements achieved by LB-therapy in patients with initially chronic paralysis can be maintained under domestic surrounding. Patients with initially acute paralysis improved their walking capabilities even further. It is suggested that LB therapy may be generally applied in the motor rehabilitation of persons with acute and chronic incomplete paraplegia and tetraplegia. Its use in other diseases is discussed. Department of Physiology, University of Bonn, Germany. wernig@physio.uni-bonn.de .

• Wernig A, Nanassy A and Muller S (2000). Laufband (LB) therapy in spinal cord lesioned persons. Prog Brain Res. **128**: 89-97. **Summary:** Department of Physiology, University of Bonn, Germany. wernig@physio.uni-bonn.de.

• Wirz M, Colombo G and Dietz V (2001). Long term effects of locomotor training in spinal humans. J Neurol Neurosurg Psychiatry. **71** (1): 93-6. **Summary:** The long term effects of locomotor training in patients with spinal cord injury (SCI) were studied. In patients with complete or incomplete SCI coordinated stepping movements were induced and trained by bodyweight support and standing on a moving treadmill. The leg extensor muscle EMG activity in both groups of patients increased significantly over the training period, associated with improved locomotor ability in those with incomplete SCI. During a period of more than 3 years after training, the level of leg extensor EMG remained about constant in incomplete SCI in those who regularly maintained locomotor activity. By contrast the EMG significantly fell in those with complete SCI. The results suggest a training induced plasticity of neuronal centres in the isolated spinal cord which may be of relevance for future interventional therapies. ParaCare, Paraplegic Centre of the University Hospital Balgrist, Forchstrasse 340, CH-8008 Zurich, Switzerland.

• Whiting WC, Gregor RJ, Roy RR and Edgerton VR (1984). A technique for estimating mechanical work of individual muscles in the cat during treadmill locomotion. J Biomech. **17** (9): 685-94. **Summary:** Mechanical work, the product of force and length change, was assessed in selected hindlimb extensors of two adult cats during three different speeds of unrestrained treadmill locomotion. Forces were measured using implanted transducers placed on the soleus (SOL) and medial gastrocnemius (MG) tendons. A three dimensional technique of muscle length estimation using high speed cinematography was found preferable to either two dimensional or trigonometric measurements derived from anatomical and kinematic parameters. Length excursions increased in both muscles as treadmill speed increased. However, at all speeds of locomotion, the uniarticular SOL exhibited a greater range of motion than the biarticular MG. Increases in treadmill speed resulted in higher peak forces in the MG and constant or slightly lower peak forces in the SOL. These speed-dependent changes in length and force resulted in higher total positive work, lower total negative work, and higher net work for both muscles with increasing speeds. These data illustrate the importance of three-dimensional kinematics in determining changes in muscle length and describe the relative force and work changes in a slow and fast ankle extensor with changes in speed of locomotion.

• Wolf SL (2001). From tibialis anterior to Tai Chi: biofeedback and beyond. Appl Psychophysiol Biofeedback. **26** (2): 155-74. **Summary:** This keynote presentation highlights events that have contributed to scientific explorations of one research clinician. Steve Wolf traces his scientific roots to early studies in single motor unit control under the guidance of his primary mentor, John Basmajian, MD. This work led to subsequent studies on the role of EMG feedback in predicting successful outcomes in upper extremity use and in ambulatory capabilities among patients with chronic stroke. These findings are contrasted to further efforts to condition entire reflexes rather than

individual muscles through use of operant-conditioning paradigms. The findings from applications of EMG biofeedback to stroke patients became the basis for minimal motor criteria in the treatment of the impaired upper extremities of patients with chronic stroke, using "forced use" or "constraint-induced movement therapy." Last, investigations into center of pressure feedback using computerized balance machines resulted in a series of experiments that ultimately led to the finding that Tai Chi as an exercise form for older adults can have a substantially favorable effect in delaying the onset of fall events. Emory University School of Medicine, Department of Rehabilitation Medicine, Center for Rehabilitation Medicine, 1441 Clifton Road NE, Atlanta, Georgia 30322, USA. swolf@emory.edu.