Adaptive responses of the neuromuscular system to training

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ABSTRACT

Strength training leads to functional adaptations of the musculo-skeletal and the neuromuscular systems. The properties of muscular activation can be changed to a large extent depending on the type of strength training. For athletic performance the power of muscular action is often much more important than the maximum force capacity. Recognizing this aspect is necessary in order to find the best training parameters.

Sensorimotor training has proven to be highly effective, with respect to considerable improvements in muscle power, as well as to enhanced postural control. For team sports the improvement in postural control is very effective for the reduction of injuries to the lower extremities.

In the present paper, the focus is on the physiological pathways that explain the functional adaptations of power strength training, in order to give coaches and athletes explanations why sensorimotor training can be beneficial for enhanced rate of force development capabilities.

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Introduction

The effects of contractile strength training have been investigated a large variety of training designs. The purpose of the studies has been to better understand the adaptive mechanisms of the human movement system to physical activity. In principle, two modalities of functional adaptations can be substantiated for classical strength training: strength training can either lead to enhancements in the contractile muscular properties of the protein structures themselves or it can lead to improvements in the neural supply to the contracting muscle or muscle group. The two types of adaptation can be addressed specifically by the design of the training programme using variations in the level of the training load, the volume of training session and the duration.

Evidence has been produced that training with a relatively high number of repetitions within one set (i.e. 6-15 RM (maximum repetition) load), which is associated with an extensive exhaustion of the trained muscle group, is followed by an enhancement in strength and power. Athletes working with this method show adaptations in the muscular tissue, enhanced cross-sectional areas, altered pinnation angles and high endocrine involvement (RUTHERFORD, JONES 1992; WALKER ET AL 1998). However, many studies also report improvements in strength and power capabilities after strength training without a substantial adaptation of the muscular profile. Thus, an alternative functional response modality must be considered. Recent publications have given evidence that a specific type of training can enhance spinal and supraspinal mechanisms. In contrast to the muscular adaptations after training with a high number of RMs, neuronal adaptation is associated with training using a low number of repetitions (1-8 RM load), high loads, intensive or explosive types of contraction and sufficiently long periods between sets (AAGAARD ET AL 2001).

The present paper focuses on the neuromuscular adaptive mechanisms that may result from intensive strength training and sensorimotor training.

The motoneurons in the spinal cord is in latest consequence directly linked to the muscle fibres. Due to the fact that the functional properties of the motor units (MU) are directly dependent on the discharge characteristics of the activating spinal motoneurons, it appears logical to separate the various adaptive responses of the neuromuscular system to training in accordance to the different modalities of training.

Increased muscle activation

Increased muscle activation can be achieved by a) alterations in the recruitment properties of activated motoneurons or b) the firing frequency or the motor synchronisation or c) a combination of these three modalities.

EMG (electromyography) studies clearly demonstrate that vigorous intensive strength training is quite often associated with an enhanced EMG input to the trained muscle. Despite the methodological limitation of this approach, a number of studies have consistently shown that neural adaptation can account for the observed gains in strength (NARICI ET AL 1989; MORITANI, DEVRIES, 1979; HAKKINEN ET AL 1985A; HAKKINEN ET AL 1985B; HAKKINEN ET AL 1987)

From a functional point of view, the adaptation in the RFD (rate of force development) is much more often required after strength training than enhanced MVC (maximum forces). From the dynamic, explosive type of strength training in particular it is known that an increase in RFD is closely related to improvements in the neural drive of the trained muscles (JANSSON ET AL 1990; GRUBER, GOLLHOFER 2004). It has been shown that neural adaptations caused by an explosive type of training are primarily responsible for an increase in the speed of voluntary muscle contraction. By analysing single motor unit recordings, the authors were able to demonstrate the preservation of an orderly motor unit recruitment pattern. However, MUs were activated earlier and showed increased firing frequencies after training.

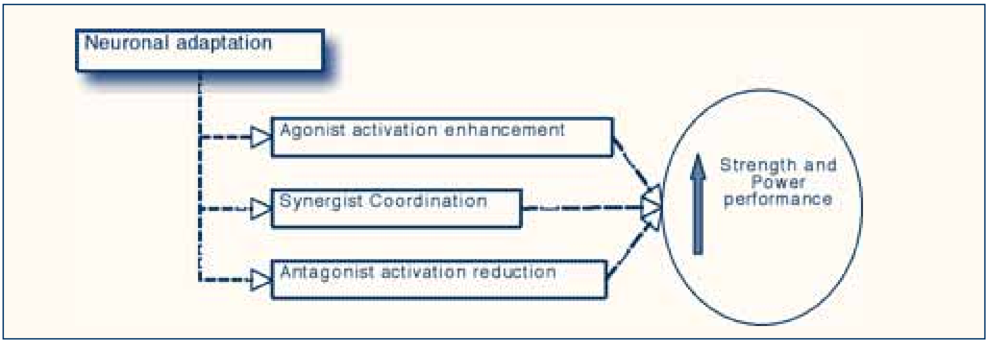

Figure 1: Neuronal adaptations to strength training can be achieved either by enhanced activation of the agonistic muscles, by appropriate coordination of the synergists or by functional decreased activation of the antagonistic muscles (modified from SALE 2002).

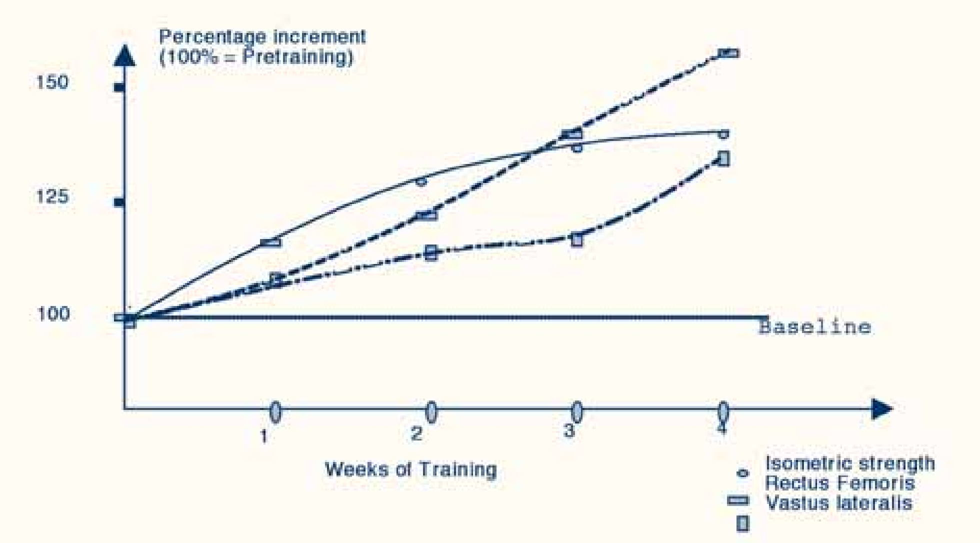

Figure 2: Isometric strength training over four weeks of training was associated with a substantial enhancement of strength and a muscle specific neural adaptation, obtained from surface EMG recordings. (modified from RABITA ET AL 2000)

From intramuscular EMG recordings, there is support for the idea that the explosive type of training is associated with high frequency discharges occurring at the onset of muscular action (VAN CUTSEM ET AL 1998). In the latter study, the subjects trained ballistic dorsiflexion actions with 30 to 40% of 1 RM over a period of 12 weeks. After training the RFD was drastically (+80%) enhanced, mainly due to increased firing rates at the beginning of the isometric test action. From single motor recordings, the authors could demon-

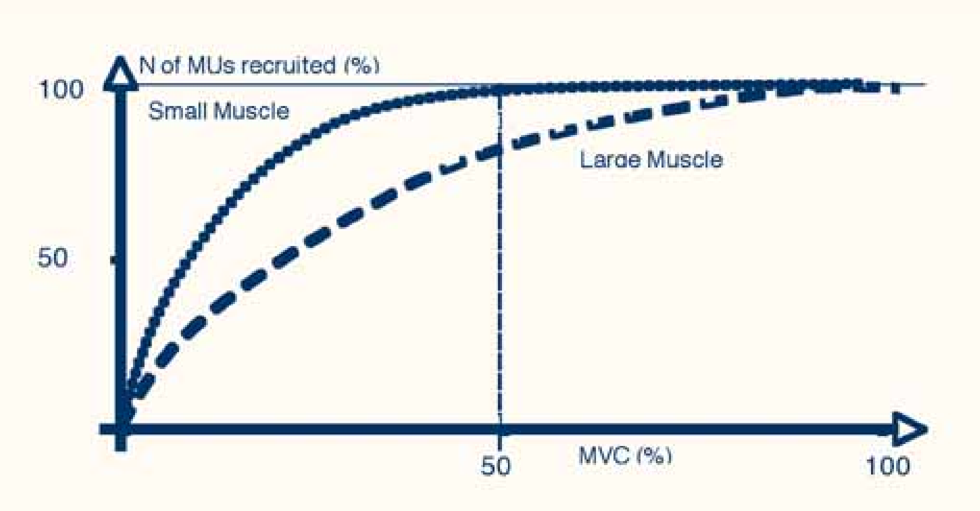

Figure 3: Isometric strength (% MVC) and recruitment of individual MUs in small and in large muscles. It is important to note that both types of muscle are nearly fully activated at a level of 50% MVC (modified from ENOKA and FUGLEVAND 2001)

strate that the frequency of discharge at the early onset was nearly doubled after the training. Functionally, the MUs "learned" to activate with higher starting frequencies and this led to enhanced rates of force development on the MU level.

Observations of a changed discharge frequency are mainly obtained from studies investigating only a small number of single MUs. Therefore, it is not clear if this type of training also alters the recruitment level or even the recruitment order of the motoneurons involved. PATTEN ET AL (2000) demonstrated that ballistic training caused a slight shift in the recruitment threshold to the left, leading to an earlier recruitment of the MUs. However, the authors clearly state that the order of recruitment was preserved, which is in accordance to findings from GARLAND ET AL (1996).

It is important to note that generally a normal healthy subject should be able to recruit all the MUs of a muscle during maximal isometric actions. Therefore, the only explanation of neural adaptation can be seen in the improved firing rates after training. It is well known that in large muscles the recruitment of MUs occurs up to 80% of MVC (ENOKA, FUGLEVAND 2001) whereas in small muscles the recruitment is finished at 50% MVC. Thus, a large variety of force output can be addressed by alterations in the firing pattern of the MUs.

Spinal mechanisms activating the motoneurons

In Figure 4 the various inputs of the central nervous system to the motoneuron of a distinct muscle group are illustrated. Not only do motoneurons receive signals through the central pathways from brain structures, they are also largely influenced by selective inputs from peripheral feedback afferents. Afferent input from sensors in the skin, capsules, ligaments, tendons and muscle are mediated

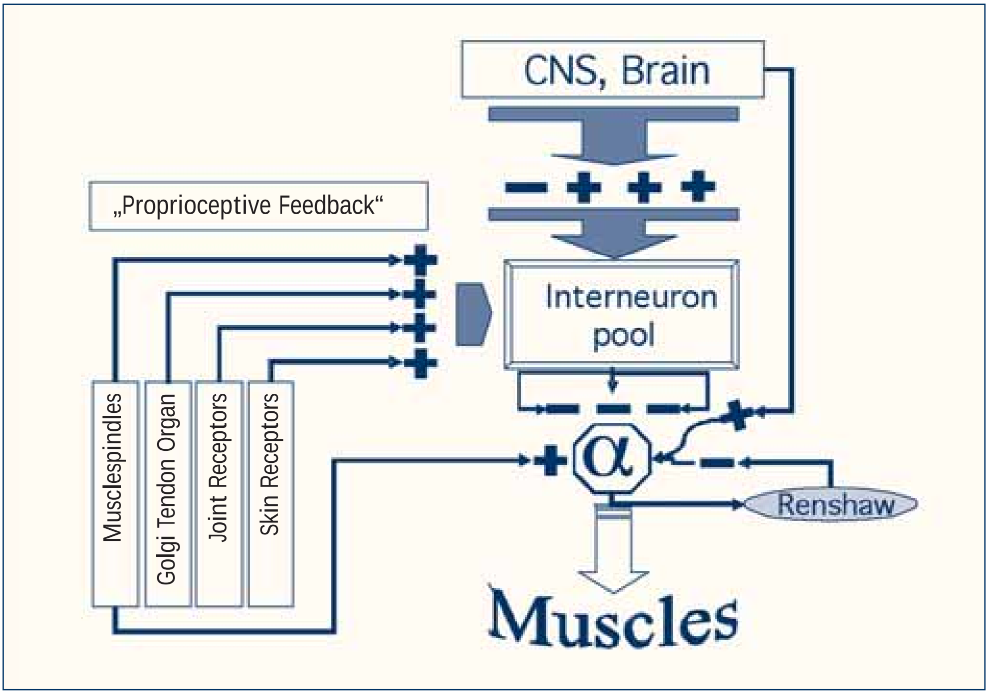

Figure 4: Various sources of afferent influence of the spinal MU. Note that most of the feedbacks are inhibitory, reducing the activation level of the motoneuron.

either directly to the motoneuron or they are connected via interneuronal structures. It is noteworthy that most of the peripheral afferents are looped back, either facilitating or inhibiting the spinal motoneuron.

One of the most important feedback-loops is the Ia-afferent from the muscle spindles. This reflex pathway directly facilitates the homonymous MUs (i.e. extensors) and inhibits the antagonist muscle (i.e. flexors) of the ipsilateral side. On the contralateral side, the afferents are connected in the opposite manner, facilitating the flexors and inhibiting the extensors. On the other side, afferents from Ib-Golgi-Tendon-Units (GTO) generally inhibit homonymeous and facilitate antagonistic MUs. Influences from skin- and joint-receptors converge together with the Ia and Ib afferents into the Ib-interneuron pool. However, in humans it has been shown that, especially in stance and locomotion, the Ib-inhibition is reversed into facilitation. This reflex pathway is dependent on the load acting on the lower limb (GOLLHOFER ET AL 1989). Functionally this Ib-mechanism has been addressed as the load-receptor modulation.

From a functional point of view, the spinal network of feedback represents the backbone of the neural adaptations resulting from learning and training. By modulations originating from changed inputs from the brain as well as from the sensors of the proprioceptive system, the input from the interneuron pool to the motoneurons, i.e. the activation of the last common path to the muscle, can be drastically adjusted to either the mechanical needs of a distinct movement or to the level of experience and training of the individual.

Sensorimotor training

For rehabilitation of injuries to the locomotor system, sensorimotor training is widely believed to restore neuromuscular functions. The various receptors in the joint complexes, in the tendons and ligaments, in the musculer and skin structures are trained in order to enhance proprioceptive contributions in functional situations. The aim is to improve the efficacy of the afferent feedback in order to attain functional limb control and achieve appropriate neuromuscular access to the muscles encompassing joint complexes. KONRADSEN ET AL (1993) and TROPP (1986) compared postural stability of healthy subjects and with individuals with chronic ankle instability. Other approaches have investigated the sensory angular reproduction of different joint dynamics under active or passive conditions (FREEMAN ET AL 1965; GLICK ET AL 1976; LOFVENBERG ET AL 1995; TROPP, 1986). These studies demonstrate a proprioceptive deficit during reproduction of distinct angular dynamics in cases of chronic ankle instability.

Enhancement of proprioceptive generated muscle activation has been assumed from experiments of the knee (PERLAU ET AL 1995) and ankle joint (JEROSCH, BISCHOF 1994). However, only a few controlled studies are available demonstrating an improved afferent supply to the muscles after training.

In a series of experiments, GOLLHOFER investigated the neuromuscular adaptations following sensorimotor training interventions. Based on longitudinal studies, the author presents experimental data that demonstrate the adaptability of the afferent and efferent contributions. In those studies, the hypothesis that a specifically designed sensorimotor training will have a positive impact on the neural activation and strength during a maximal isometric leg extension was verified. GRUBER and GOLLHOFER (2004) investigated 12 female subjects before and after a 4-week training programme with a total of 8 training sessions. Each session (60 min in duration) comprised various exercises for balance and body stabilisation. No classical strength training exercises were allowed during the entire training period. EMGs of the shank muscles as well as force parameters of the isometric maximum strength measurements revealed significantly increased neuromuscular activation and isometric power after the training period. The sensorimotor training produced the best neuromuscular adaptations at the initiation of the force pro-

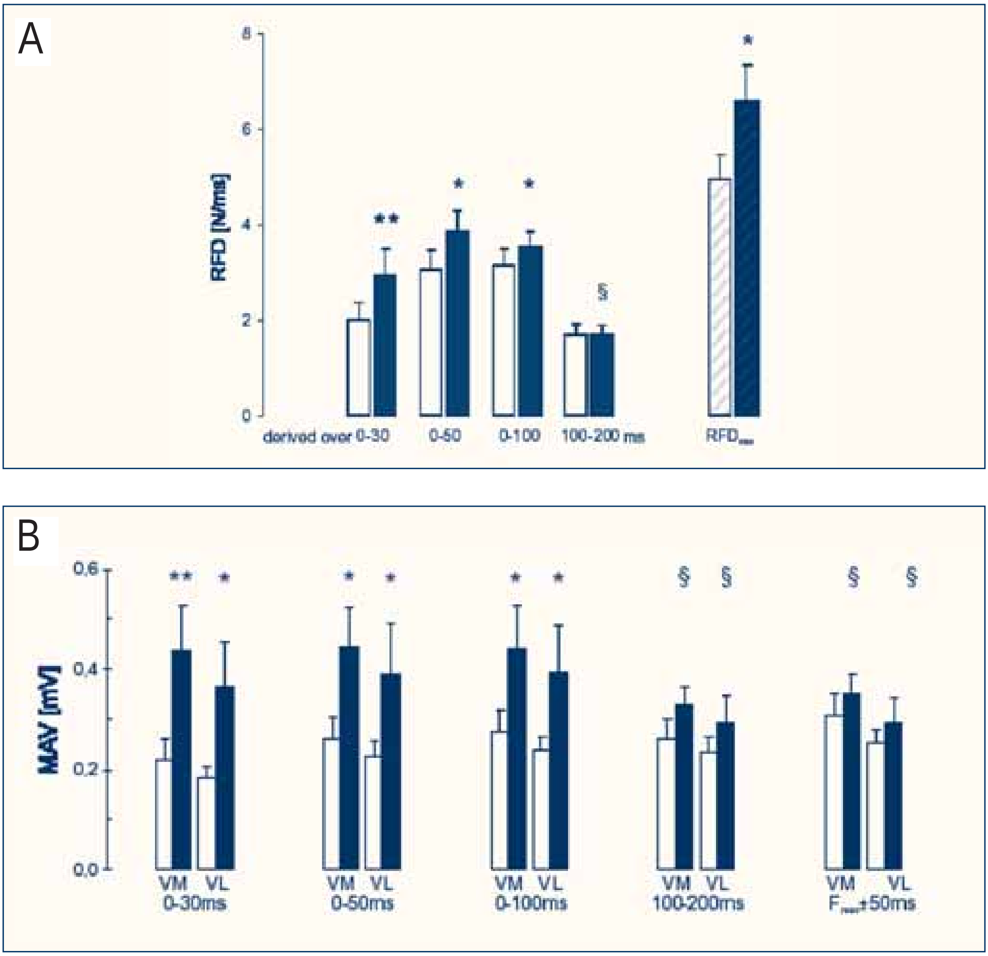

Figure 5: (A) Rate of force development (RFD) (means (±SE)) in the time intervals of early force production before (open bars) and after (filled bars) the four-week sensorimotor training programme. (B) Mean activation amplitudes (MAV) (means (±SE)) of the muscles vastus medialis (VM) and vastus lateralis (VL) before (open bars) and after (filled bars) the sensorimotor training. * $P < .05$; ** $P < .01$

duction. Explosive strength and neuromuscular activation at the onset of voluntary actions seemed to be efficiently enhanced (see figure 5).

Increments in strength and in neural activation reflect adaptive processes on the motoneuron level. From walking (SINKJAER ET AL 2000) and from voluntary ramp contractions (MACEFIELD ET AL 1993) it has been shown that afferent feedback is provided especially at the onset of muscular action. MEUNIER and PIERROT-DESEILLIGNY (1989) indicated that both homonymous and heteronymous contributions of Ia afferents facilitate muscular actions. From a functional point of view, it must be pointed out that enhanced gain in neuromuscular control is of vital importance for stiffening of muscles encompassing joint systems. Thus, it may be suggested that sensorimotor training has a great impact on the proprioceptive supply of the trained muscle. The enhancement has been interpreted as a modulation of the presynaptic inhibition of the motoneuron. In contrast to classical strength training, the increased RFD values were not associated with increased maximum strength (HAKKINEN ET AL 1998; AAGAARD ET AL 2002). Thus it may be assumed, that sensorimotor training is beneficial for an enhanced access of the neuromuscular system to the motoneuronpool, but not for an enhanced contractile force under maximum conditions.

The gain in neuromuscular activation may arise from enhanced reflex contributions acting on a spinal level, induced by the training.

Conclusion

Neuromuscular adaptation is neither unique in occurrence nor easy to identify. There are numerous possibilities for the neural system to either facilitate or inhibit the final motoneuron. On the basis of a large number of electromyographic studies, evidence has been produced indicating a high specifity of the neural adaptation seen after different training regimen. Recently, additional techniques have revealed detailed insights into the mechanisms on the spinal level. By means of H-reflex techniques, the degree of presynaptic influences on the motoneuron excitability can be addressed. By means of additional transcranial magnetic stimulation (TMS), the central and peripheral adaptations following training can be distinguished. In future, the various tools of electrophysiological methods need to be combined in order to examine changes in the motor cortex and spinal reflex pathways as well as to explain changes in the motoneuron discharge properties.

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