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Neuronal adaptations to strength training

Neuronale Adaptationen durch Krafttraining

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Summary

The change in neural function with strength training (ST) has been evaluated by use of muscle electromyography (EMG), recently also including measurements of evoked spinal motoneuron responses (H-reflex, V-wave). Elevated EMG amplitudes have been reported after ST, suggesting an increased efferent neural drive to the muscle fibres. Parallel increases in RFD (Rate of force development), EMG amplitude and rate of EMG rise have been observed in the initial phase (0-200 ms) of maximal voluntary contraction following ST. The specific neural adaptation mechanisms responsible for this include increased motoneuron firing frequency and elevated incidence of doublet firing. A neural regulatory mechanism that limits the recruitment and/or discharge rate of motor units has been suggested to exist during maximal voluntary eccentric contraction, as the recorded EMG is markedly reduced. This suppression is removed by ST. However, the specific neural pathways responsible for this remain unidentified. The increase in eccentric muscle strength observed with ST may involve a down-regulation of spinal inhibitory interneuron activity mediated via Golgi organ Ib afferents. Furthermore, training induced reduction in presynaptic inhibition of Ia muscle spindle afferents would result in an elevated excitatory inflow to the pool of spinal motoneurons.

During MVC, the V-wave and H-reflex may be used to quantify training-induced changes in spinal motoneuronal output, motoneuron excitability and/or presynaptic inhibition. ST results in elevated V-wave and H-reflex amplitudes, which could reflect enhanced neural drive in descending corticospinal pathways, elevated motoneuron excitability and/or reduced presynaptic inhibition of Ia afferents. In contrast, maximal M-wave amplitude remains unchanged with ST. Notably, the H-reflex response recorded at rest did not change with ST. Therefore, to evaluate the effect of ST on human neural function evoked spinal motoneuron responses should be obtained during actual muscle contraction and not solely at rest.

Key words: strength training, EMG, H-Reflex, eccentric, inhibition

Zusammenfassung

Veränderungen der neuralen Funktion durch Krafttraining (KT) werden vorwiegend unter Verwendung der Elektromyographie (EMG) unter Einbeziehung der Messung evozierter spinaler Potentiale (H-Reflex, V-Welle) analysiert. Als Ausdruck einer KT-induzierten, erhöhten efferenten Erregung der Muskelfaser konnte eine Zunahme der EMG-Amplituden nachgewiesen werden. Zudem wurde eine parallele Zunahme des maximalen Kraftanstiegs (Rate of force development, RFD), von EMG-Amplituden und der Anstiegsrate der EMGs in den ersten 200 ms nach KT beobachtet. Die spezifischen neuralen Adaptationsmechanismen des Anstiegs der RFD umfassen dabei sowohl eine erhöhte Frequenz der Potentiale als auch ein vermehrtes Auftreten von Doublets.

Während willkürlicher maximaler exzentrischer Kontraktion zeigt sich eine Reduktion der EMG-Aktivität im Sinne eines neuralen Regulationsmechanismus zur Limitierung von Rekrutierung und Frequenzierung der motorischen Einheiten. Diese Suppression ist nach Krafttraining vermindert, wobei die spezifischen neuronalen Mechanismen hierfür bislang nicht abschließend geklärt sind. Möglicherweise führt ein trainingsinduzierter exzentrischer Kraftanstieg zu einer, durch Ib-Afferenzen des Golgi Sehneorgans vermittelten Aktivitätsreduktion spinaler, inhibitorischer Interneurone. Zudem könnte eine Reduktion präsynaptischer, inhibitorischer Ia-Afferenzen der Muskelspindel zu einem höheren Aktivierungsniveau des spinalen Motoneuronenpools führen.

Krafttraining resultiert in einer erhöhten V-Welle und H-Reflex-Amplituden, was als Ausdruck einer erhöhten Aktivität absteigender corticospinaler Bahnen, einer erhöhten Erregbarkeit und/oder einer Reduktion präsynaptischer Hemmungen von Ia-Afferenzen interpretiert wird. Im Gegensatz dazu bleibt die maximale M-Welle nach Krafttraining nahezu unverändert. Da sich die H-Reflex-Antwort in Ruhe nicht verändert, müssen trainingsinduzierte Änderungen evozierter spinaler Potentiale während der Muskelkontraktion und nicht in Ruhe untersucht werden.

Schlüsselwörter: Krafttraining, EMG, H-Reflex, exzentrisch, Inhibition

Introduction

Besides structural adaptations of the muscle itself, strength training induces adaptive changes in nervous system function that, in turn, contribute to the training induced increase in maximal contractile muscle force. The change in neural function with strength training has been evaluated by use of (mainly surface) muscle electromyography (EMG) measurements, which recently have included single motor unit recording and measurements of evoked spinal reflex responses (H-reflex, V-wave). The Hoffmann (H) reflex reflects the level of motoneuron excitability and the magnitude of presynaptic inhibition of muscle spindle Ia afferents. The V-wave can be elicited when supramaximal stimulation of the peripheral nerve is superimposed onto voluntary muscle contraction. As discussed below, different lines of evidence exist to demonstrate that strength training can induce substantial changes in human neuronal function (6, 7).

Maximal EMG Amplitude

The EMG interference signal recorded by surface electrodes during maximal voluntary contraction (MVC) constitutes a complex outcome of motor unit recruitment and motor neuron firing frequency (rate coding). In addition, the net EMG signal amplitude relies on the summation pattern of the individual motor unit action potentials, which in turn is affected by the degree of motor unit synchronization.

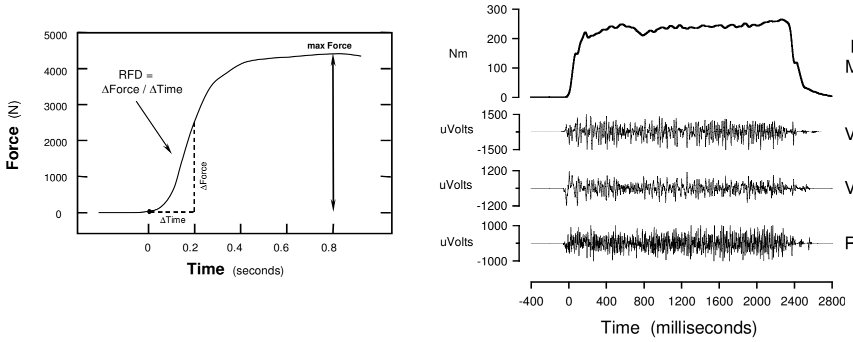

Figure 1: Contractile rate of force development (RFD) is calculated as the slope of the force-time curve (left panel). RFD and maximal contraction force is strongly influenced by the efferent neural drive to the muscle fibers indicated by EMG recording (right panel), which all may increase in response to strength training. Data and graphs adapted from Aagaard et al. 2002

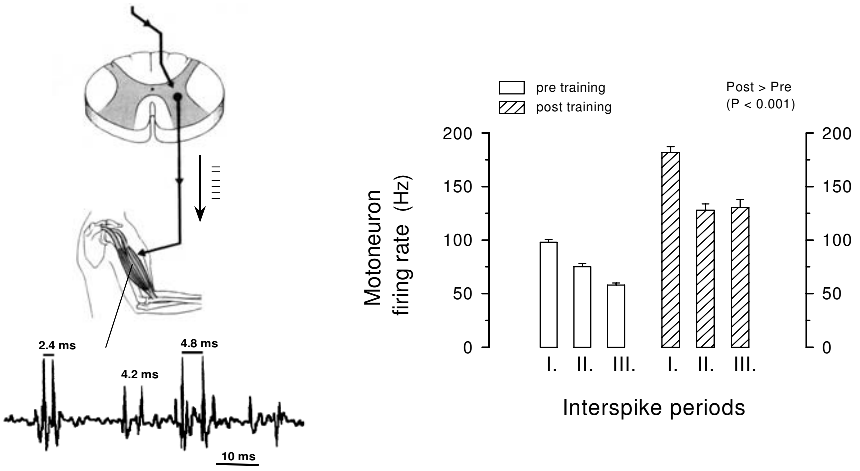

Figure 2: Recording of single motor unit action potentials, with interspike firing interval indicated for each motor unit (left panel). Mean motoneuron firing rates at onset of contraction, before and after a period of strength training (right panel). Data and graphs adapted from Van Cutsem et al. 1998 (18) and Aagaard 2003 (6)

Elevated EMG amplitudes have been reported after strength training, suggesting an increased efferent neural drive to the muscle fibres (2, 5, 10, 15, 18). However, a few studies have been unable to demonstrate increased EMG activity with strength training, which could at least in part be due to altered skin and muscle tissue properties (i.e. changes in subcutaneous fat layer, muscle fiber pennation angle). It is possible, however, to eliminate or reduce these inherent methodological limitations by employing measurements of evoked spinal motoneuron responses and intramuscular EMG recordings.

Rate of Force Development (RFD)

Explosive muscle strength can be defined as the contractile Rate of Force Development (RFD=Δ Force/Δtime) exerted within the initial contraction phase (5, 15) (Fig. 1). RFD reflects the ability of the neuromuscular system to generate very steep increases in muscle force at the onset of contraction, which has important functional significance for the force and power generated during rapid, forceful movements (5, 6, 7). A high RFD is not only vital to the trained athlete but also to different activities of daily living where a sudden force capacity is required, and especially for the elderly individual who needs to counteract sudden perturbations in postural balance to avoid falls.

Parallel increases in RFD, EMG amplitude and rate of EMG rise have been observed in the initial 0-200 ms of contraction following strength training (5, 15, 18). The specific neural adaptation mechanisms responsible for this training-induced increase in RFD seem to include increased motoneuron firing frequency and elevated incidence of so-called discharge doublets (18). Thus, Duchateau and colleagues reported concurrent increases in the rate of force development and maximal firing frequency, together with a 6-fold increase in the incidence of discharge doublets in the firing pattern of individual motor units following strength training (18) (Fig. 2). The presence of muscle fibre hypertrophy (3, 10, 15) and changes in muscle architecture (3) with strength training would additionally contribute to the increase in RFD.

Eccentric Muscle Contraction

A neural regulatory mechanism that limits the recruitment and/or the discharge rate of motor units has been suggested to exist during maximal voluntary eccentric muscle contraction, as the EMG recorded in the quadriceps femoris muscle during maximal eccentric contraction is markedly reduced compared to that of maximal concentric contraction (2, 16, 19). This apparent inhibition in motoneuron activation during maximal eccentric contraction can be downregulated with certain types of strength training. Thus, the observed suppression in eccentric EMG signal amplitude was partially abolished in parallel with a gain in maximal eccentric muscle strength following intense heavy-resistance strength training (2).

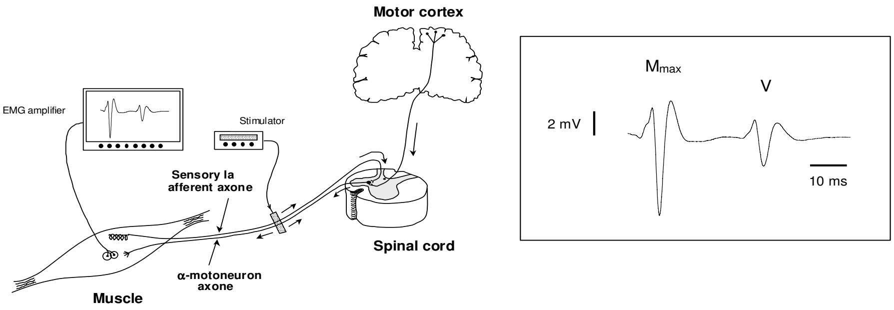

Figure 3: Evoked spinal motoneuron responses recorded in the human soleus muscle. H-reflex and V-wave responses can be elicited by electrical stimulation of Ia afferent axons in the peripheral nerve during ongoing muscle contraction (left panel). Enhanced H-reflex and V-wave responses (right panel) were observed following a period of heavy-resistance strength training, indicating that neural adaptative changes occured at spinal and/or supraspinal levels. Data adapted from Aagaard et al. 2002

To date, the specific neural pathways responsible for the described suppression in muscle activation during maximal eccentric contraction remain unidentified and different explanation models are discussed. During maximal voluntary muscle contraction, efferent motoneuronal output is influenced by central descending pathways, afferent inflow from group Ib Golgi organ afferents, group Ia and II muscle spindle afferents, group III muscle afferents and by recurrent inhibition. All of these pathways may exhibit adaptive plasticity with strength training.

One likely mechanism for the selective increase in eccentric muscle strength with strength training could be a downregulation in spinal inhibitory interneuron activity mediated via Golgi organ Ib afferents. Furthermore, the H-reflex appears to be markedly suppressed during both active and passive muscle lengthening compared to shortening, suggesting the presence of substantial presynaptic inhibition of Ia afferents during eccentric muscle contraction. A training-induced reduction in presynaptic inhibition of Ia afferents, therefore, would result in an elevated excitatory inflow to the spinal motoneuron pool during maximal eccentric muscle contraction, which would increase maximal eccentric muscle strength.

Evoked Spinal Motoneuron Responses

The Hoffmann (H) reflex can be used to examine training induced changes in the spinal neural circuitry at rest and during active contraction, as it reflects the level of motoneuron excitability and the magnitude of presynaptic inhibition of muscle spindle Ia afferents (8, 12, 14). The V-wave is a variant of the H-reflex that can be elicited when supramaximal stimulation of the peripheral nerve is superimposed onto voluntary muscle contraction (4, 9, 17) (Fig. 3). When obtained during maximal muscle contraction, such evoked spinal responses may be used to quantify the training-induced change in efferent motoneuronal output (V-wave) and motoneuron excitability and/or presynaptic inhibition (H-reflex, V-wave) (4, 13). Importantly, the evoked motoneuron response is normalized to the maximal M-wave amplitude, which reduces the measuring bias associated with electrode positioning, etc.

Elevated V-wave and H-reflex amplitudes have been reported following strength training (4, 13), which could reflect enhanced neural drive in descending corticospinal pathways, elevated motoneuron excitability, reduced presynaptic inhibition of Ia afferents and/or reduced postsynaptic motoneuron inhibition (6, 7). In contrast, the maximal M-wave amplitude appears to remain unchanged in response to strength training (4, 13, 18). Notably, when obtained at rest the H-reflex response do not seem to change with strength training (4, 11). Thus, to examine the change in human neural function induced by strength training, evoked spinal motoneuron responses should be obtained during actual muscle contraction and not solely at rest.

Conclusions

It is evident that strength training results in neuronal adaptations. Increases in EMG-Amplitude, rate of EMG rise and motoneuron firing rates underline the neuronal basis of training effects like an increase in rate of force development. In spite of the adaptation mechanisms are not precisely known, reduced presynaptic and spinal inhibitions may be considered a valid explanation model, mainly during eccentric MVC. Besides basic EMG (amplitude, frequency) and force measurements (RFD, MVC), evoked spinal motoneuron responses (H-Reflex, V-Wave) during muscle activity are useful methods to evaluate the neuronal adaptation induced by strength training.

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Kommentar

Stand für die Beurteilung der Effizienz von Krafttraining in der Vergangenheit insbesondere die strukturelle Anpassung des Muskelgewebes im Vordergrund, so weisen aktuelle Arbeiten auf die Bedeutung einer zeitnahen, trainingsinduzierten neuronalen Anpassung hin. Neben dem Freizeit- und Leistungssport spielt dies sowohl in der konservativen und (post)operativen Rehabilitation von Beschwerden und Verletzungen, als auch in der Prävention von Beschwerden des Stütz- und Bewegungsapparates (z.B. Sturzprophylaxe bei Älteren, Optimierung der funktionellen Gelenkstabilität) eine wichtige Rolle.

In Anbetracht einer zunehmenden Bewegungsarmut und damit (auch) einer Reduktion der motorischen Kompetenz in der bundesdeutschen Allgemeinbevölkerung ist die Notwendigkeit eines Krafttrainings evident. Allerdings ist eine weit reichende Akzeptanz (v.a. eines gerätegestützten Trainings) insbesondere im medizinischen Umfeld derzeit (noch) nicht abschließend gelungen.

Die Effekte der bereits bei kurzfristiger Anwendung einsetzenden, neuronalen Adaptation nach Krafttraining lassen sich unabhängig von Lebensalter und Geschlecht nachweisen. Das Training selbst ist für jedermann zugänglich und auch bei geringem Zeitbudget durchführbar.

Die von Per Aagaard anlässlich des Sportärztekongresses in Hamburg präsentierten Daten betonen die trainingsinduzierten, neuronalen Adaptationen und die Notwendigkeit eines Krafttrainings in eindrucksvoller Weise.

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