Assessment of Neuroplasticity With Strength Training

Per Aagaard[1], *Jens Bojsen-Møller*[1,2], *and Jesper Lundbye-Jensen*[3]

[1]Department of Sports Science and Clinical Biomechanics, Research Unit for Muscle Physiology and Biomechanics, University of Southern Denmark, Odense M, Denmark; [2]Institute for Physical Performance, Norwegian School of Sport Sciences, Oslo, Norway; and [3]Department of Nutrition, Exercise and Sports, Section of Integrative Physiology, University of Copenhagen, Copenhagen, Denmark

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AAGAARD, P., J. BOJSEN-MØLLER, and J. LUNDBYE-JENSEN. Assessment of neuroplasticity with strength training. *Exerc. Sport Sci. Rev.*, Vol. 48, No. 4, pp. 151–162, 2020. *Including a brief overview of current investigative approaches, the present Perspectives for Progress article offers an overview of potential future experiments in the field of exercise-related neuroplasticity to strength training. It is proposed that the combination of specific experimental approaches and recently developed techniques holds the potential for unraveling spinal and supraspinal mechanisms involved in the adaptation to strength training.* **Key Words:** strength training, neuromuscular plasticity, spinal motor neurons, cortical activation, CNS stimulation, neuroimaging

KEY POINTS

- Neural adaptations to strength training may comprise changes in intrinsic motor neuron properties and improvements in corticospinal connectivity and increased maximal efferent output of spinal motor neurons.
- Future integrated combinations of contemporary and novel experimental approaches are expected to expand our current knowledge about the range and nature of neural adaptations evoked by strength training.
- Increased insight into the mechanisms of neural plasticity accompanying strength training may be translated into improved designs for performance training and rehabilitation protocols in athletes and in old adults and clinical patients.

INTRODUCTION

The present article presents the perspective that the combination of experimental approaches and multiple physiological assessment techniques will enable further insight into the mechanisms of neural plasticity that accompany strength training in humans. We propose that a range of young to old and healthy to diseased populations may benefit from an improved understanding of the neural adaptations to strength training. Although individuals with low or incomplete levels of muscle activation (*i.e.*, very old adults, injured athletes, untrained healthy adults) may be expected to demonstrate a high magnitude of neural adaptation with strength training, even high-level strength athletes may also demonstrate gains in neuromuscular function in response to specific strength training protocols.

Due to the complexity of the central nervous system (CNS), previous research on the neural adaptation to strength training typically has focused on single specific adaptations relating, for example, to neuromuscular activity assessed by surface electromyography (EMG) recordings, intramuscular recordings of single motor unit (MU) recruitment/discharge rates, evoked (spinal/corticospinal) responses in single muscles, or evoked force responses. As an aspect adding complexity to the field, training-induced neural adaptations that involve properties and functions of the CNS should be studied not only at rest or during low-force contractions but also during maximal-force testing or in rapid contractions performed with maximal volitional rate of force development (RFD) and maximal muscle activation. The latter may impose technical challenges, as it is difficult to record muscle activity during maximal voluntary efforts, and it remains a further constraint that only few maximal contractions may be performed before neurophysiological and peripheral mechanisms related to fatigue may influence the results.

Nonetheless, recent advances in available techniques may enable more comprehensive experimental protocols and study designs to evaluate the influence of strength training on neural function in humans. Based on this notion, the present *Perspectives for Progress* article offers a roadmap of future experiments in

Address for correspondence: Per Aagaard, Professor, Ph.D., Muscle Physiology and Biomechanics Research Unit, Department of Sports Science and Clinical Biomechanics, University of Southern Denmark, Campusvej 55, 5230 Odense M, Denmark (E-mail: paagaard@health.sdu.dk).

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the field of exercise-related neuroplasticity, where combinations of experimental approaches and the use of multiple techniques hold the potential for a significant leap forward by unraveling spinal and supraspinal mechanisms involved in the neural adaptations to strength training.

CONTEMPORARY METHODOLOGICAL APPROACHES

A number of isolated experimental approaches have been used over the last decades to evaluate the relation between neurophysiological function and maximal muscle strength including RFD and to address the influence of strength training on neural function. A large number of studies have acquired surface EMG signals during MVC efforts, and increases in EMG amplitudes have been reported after short- and long-term periods of strength training. Considerably fewer studies have performed recordings of single MU action potentials during maximal muscle contraction. In recent decades, a number of studies have measured evoked spinal reflex responses (Hoffmann reflex [H-reflex] and V wave) and corticospinal responses evoked by transcranial magnetic stimulation (TMS) of the motor cortex or by activating the corticospinal pathway with transcranial electrical stimulation (TES) occasionally supplemented by cervicomedullary magnetic or electrical stimulation. More recently, these methods have been supplemented by electrophysiological EMG decomposition algorithms and advanced neuroimaging techniques.

Recording of Muscle and Single MU Activity by Use of EMG

Experimental evidence for changes in neural function with strength training has been provided by means of surface EMG recording during MVC (*e.g.*, [1,2]). Consistent increases in the compound EMG signal amplitude thus have been observed concurrently with gains in MVC force (3–6) and increases in RFD (5,7–12) after weeks to months of strength training in previously untrained young and old adults. Notably, concurrent increases in EMG amplitudes and lower-limb muscle force have also been observed in highly strength-trained individuals (elite weightlifters) when exposed to intensified protocols of heavy-load strength training (13). Observations of a positive correlation between maximal RFD and concurrently recorded surface EMG amplitudes (10,14–16) as well as between training-induced increases in RFD and EMG amplitude (17–19) suggest that strength training can result in an increased neural drive to agonist muscles that in turn contributes to observed gains in RFD and MVC. By definition, the increased activation must result from increased recruitment or increased discharge rates of spinal α-motor neurons after strength training.

Nonetheless, inherent methodological constraints may limit the interpretation of surface EMG signals as the recorded composite EMG signal not only represents the algebraic sum of all MU action potentials recorded by the electrodes but also is affected by varying amounts of action potential amplitude cancellation, which influences the amplitude and frequency content of the interference EMG signal (20–23). Furthermore, it remains challenging to compare composite surface EMG amplitudes from recordings obtained at different time points, for example, before and after periods of training intervention, due to potential variations in electrode placement, alterations in muscle architecture (changes in pennation angles), or potential changes in subcutaneous fat content and conductance of MU action potentials through the skin, respectively, the latter reflecting peripheral rather than neural properties. Consequently, several studies have failed to demonstrate elevated peak EMG amplitudes after strength training (8,17,24,25). Yet, some of the limitations associated with the assessment of surface EMG may be reduced by using standardized normalization procedures, such as normalizing the composite EMG signal amplitude relative to the maximum EMG amplitude recorded during standardized MVC efforts (22) or to the maximal M wave amplitude evoked by electrical stimulation of the peripheral motor nerve.

Experiments using intramuscular (indwelling) wire or needle electrodes have documented that short-term (2 wk) and more prolonged (6–12 wk) strength training can increase maximal discharge rate of spinal motor neurons (*i.e.*, elevated MU discharge rates) during MVCs performed at maximal intentional RFD (7) or in young and old adults performing nonpaced isometric MVC testing (26–28). Similar results have been observed during submaximal contractions (12) as recently verified by high-density surface EMG analysis (29), although not confirmed by all studies (30). Notably, maximal MU discharge rate seems to be positively correlated with RFD *in vivo* (31,32), again supported by high-density EMG analysis (33,34). In terms of adaptive plasticity, maximal MU discharge rates increased (+86%, +71%, and +124% in the first three interspike intervals) in the tibialis anterior muscle during the onset and initial phase of ballistic dorsiflexions after 12 wk of explosive-type strength training, which was paralleled by a corresponding increase in contractile RFD of +82% (7). Notably, a sixfold elevated incidence of MU discharge doublet firing (≤5-ms interspike intervals) was observed after training, which was suggested to also contribute to the observed gain in RFD (7). The findings of this seminal study (7) underline the pivotal role that the adaptive plasticity in MU behavior plays for the improvement in RFD capacity in response to strength training.

More recently, *in vivo* estimates of MU discharge rates have been obtained based on computer-assisted decomposition analysis of the interference EMG signal. Classical single-channel methods for EMG signal decomposition have been limited to only few concurrently active MUs typically performed at low-force contractions (for brief review, see [35]). In contrast, high-density surface EMG analysis with its application of multichannel array electrodes (36,37) enables tens to hundreds of concurrent recording sites, from which algorithm-based source separation can be performed to map the concurrent discharge characteristics of a large number of MUs across a wide range of force levels (35) (Fig. 1).

So far, only few studies have used these techniques to examine training-induced changes in maximal MU discharge rates. Based on such high-density EMG analysis (128 pin electrodes), Del Vecchio *et al.* (38) reported that during explosive-type muscle contractions, chronically strength-trained individuals were able to recruit MUs with faster conduction velocities in a more compressed time interval around force onset, which was paralleled by elevated RFD compared with that of untrained controls. In addition, recently, high-density EMG analysis in the tibialis anterior muscle demonstrated significant increases (+15% overall) in MU discharge rate assessed at 35%, 50%, and 70% MVC along with decreases in the

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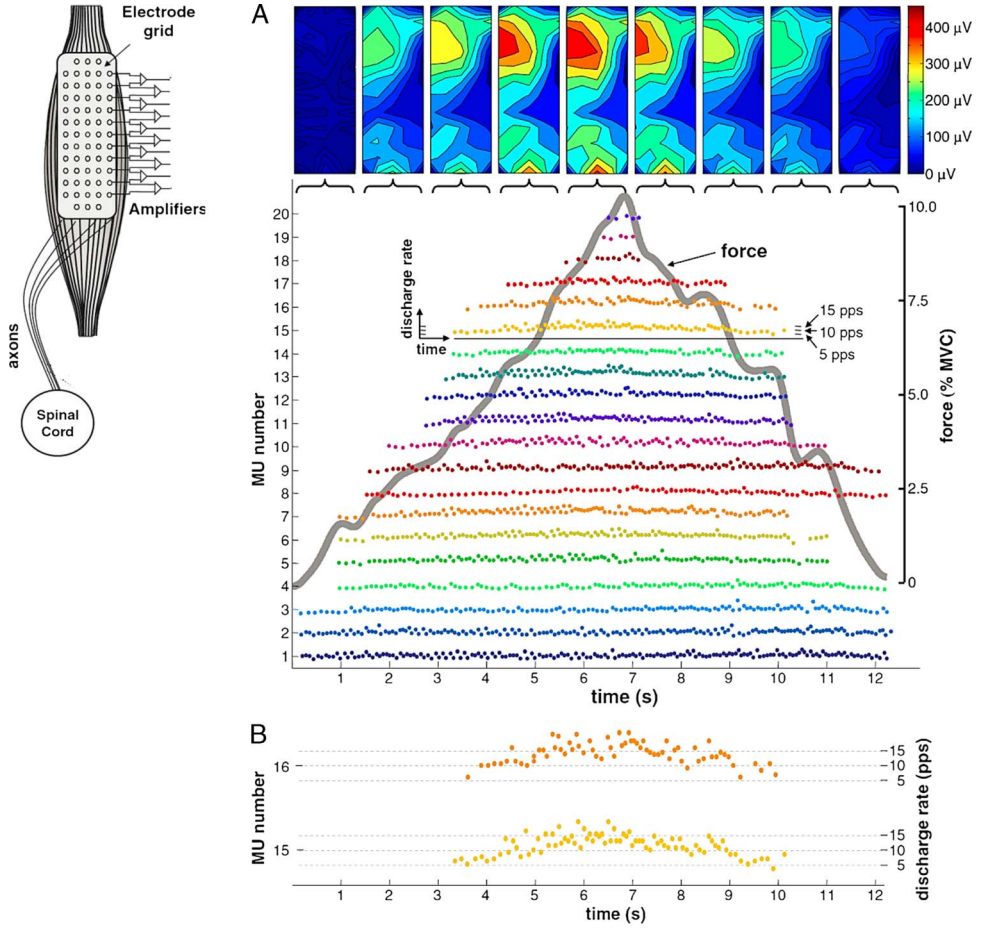

Figure 1. A. Motor unit (MU) discharge patterns during an increasing (6 s) and decreasing (6 s) ramp isometric contraction (to 10% of the maximum) of the abductor pollicis brevis muscle, as estimated from surface EMG recordings obtained with a 13 × 5 electrode grid. Each dot indicates discharge rate of a single MU. The gray thick line represents the exerted muscle force. The upper panel depicts the root mean square (RMS) EMG map under the electrode grid during the same muscle contraction. RMS values were calculated from signal 1-s epochs. B. The discharge rates of two MUs from (A) are shown on an enlarged scale to illustrate the discharge rate modulation during the contraction. [Adapted from (36). Copyright © 2008 Elsevier. Used with permission.]

recruitment-threshold force of MUs after short-term (4 wk) strength training (29) (Fig. 2). The use of similar procedures of high-density EMG decomposition analysis and MU tracking in the knee extensor muscles (vastus lateralis and vastus medialis) revealed increases (+8%–12%) in MU discharge rate assessed at 50% and 70% MVC for high-threshold MUs (≥50% knee extensor MVC) after 2 weeks of high-intensity interval training (HIIT; successive 60-s bouts of ergometer cycling at 100% peak power output) (35). In addition, the HIIT protocol resulted in elevated knee extensor MVC torque (+7%), whereas MU discharge rates and MVC torque remained unchanged in subjects performing low-intensity (65% $\dot{V}O_{2peak}$) continuous ergometer cycling (35). Collectively, the available evidence thus suggests that the discharge behavior of individual MUs is indeed subject to change as a result of strength training, which in turn may be translated into increases in maximal muscle strength and RFD.

Spinal Circuitry Function

In addition to measurements of muscle activity and MU discharge rates, several studies have aimed at investigating the underlying spinal pathways responsible for the increase in muscle activation after strength training.

Evoked spinal responses

In brief, the V wave (methodological variant of the H-reflex) can be elicited by supramaximal electrical stimulation of peripheral nerves during MVC. A key determinant of the V wave amplitude is the recruitment and discharge rates of the motor neuron pool during the MVC, as MU action potentials will only occur for the spinal motor neurons in which the antidromic action potential caused by the stimulus collides with a voluntarily elicited orthodromic action potential (39,40). Given that the size of the evoked V wave response recorded at the muscle will vary in proportion to the product of MU recruitment and MU discharge rates (39,40), changes in normalized V wave amplitude (V/M_{max}) can be used to estimate training-induced gains in efferent spinal motor output. The peak-to-peak V wave amplitude obtained during MVC testing has consistently been found to increase in response to weeks to months of strength training (10,40–46). This has been taken to indicate an increased neural drive to muscle fibers as a result of increased activation of the α-motor neuron pool, in turn caused by factors such as enhanced excitatory inputs to motor neurons from, for example, descending pathways (primarily corticospinal activation supplemented by influences from extrapyramidal pathways), reduced presynaptic inhibition of Ia afferents,

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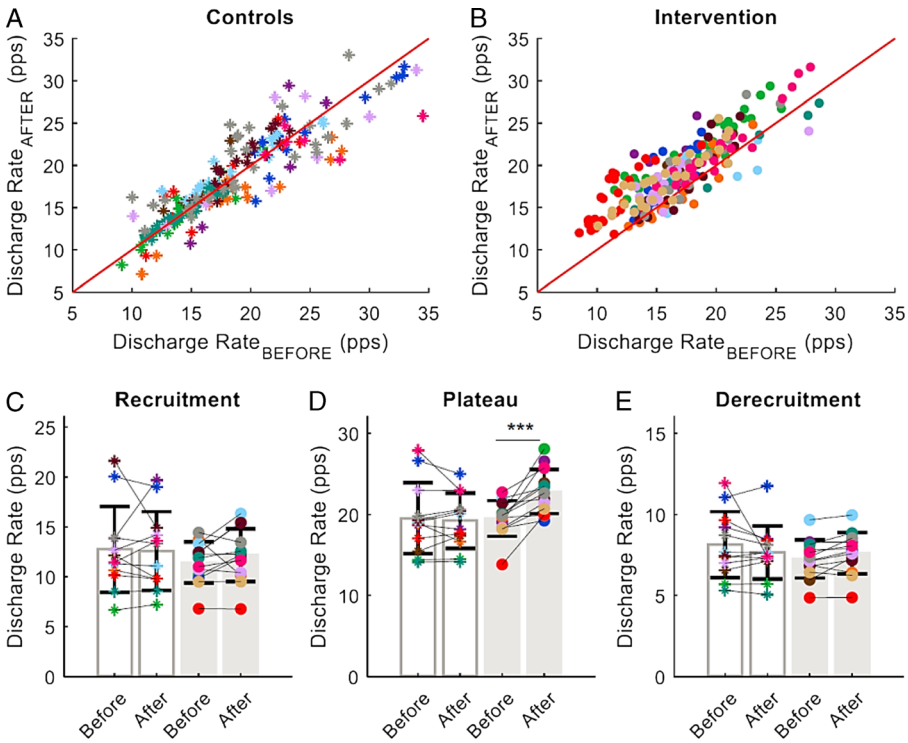

Figure 2. Motor unit (MU) discharge rates for the same MUs assessed before and after 4 wk of strength training for the dorsiflexors (B, intervention, filled circles) and in nontraining controls (A, asterisks). Each subject is indicated by a different gray scale in all panels. C. Average MU discharge rates at MU recruitment (first three interspike intervals) for each subject and group (strength training, gray bars; controls, open bars). D. Average MU discharge rates (first nine interspike intervals) during the plateau phase of trapezoidal ramp contractions. There was a significant increase in discharge rate during the plateau phase after 4 wk of strength training. E. Average MU discharge rate (last three interspike intervals) at MU derecruitment for each subject in the control and strength training groups. (Reprinted from (29). Copyright © 2019 John Wiley and Sons. Used with permission.)

or reduced postsynaptic inhibition of spinal motor neurons. Potential sources of postsynaptic inhibition could include reduced recurrent Renshaw inhibition or suppressed activity in inhibitory Ib interneurons. Moreover, the training-induced gain in V wave amplitude could, at least in part, be related to changes in intrinsic motor neuron properties. Notably, V wave responses were found to remain unchanged in response to endurance training (42), in turn suggesting that maximal contractile efforts (*i.e.*, high-force strength exercise) are required to elicit increases in efferent motor neuron output (neural drive) during MVC.

The H-reflex is evoked by submaximal electrical stimulation of peripheral nerves and can be used to examine training-induced changes in spinal circuitry function at rest and during active muscle contraction (47,48). Mixed results have been observed in response to strength training. Although increased H-reflex amplitudes have been observed after 8–14 wk of heavy-resistance strength training, when obtained during MVC efforts (40,45) or at standardized submaximal force levels (25,49,50), other studies have been unable to demonstrate elevated H-reflex responses during active test conditions in response to strength training (10,41,42,44,46). These discrepancies may at least in part be related to differences between studies in (i) training duration or intensity, (ii) peripheral nerve stimulation intensities, or (iii) the force or EMG background at which the H-reflex was elicited.

As H-reflex amplitude is influenced by the same spinal factors as the V wave (only obtained at lower stimulation intensities), the above reports of increased H-reflex amplitudes during maximal and submaximal contraction efforts are suggestive of enhanced spinal motor neuron activation (and excitation) after strength training. This could arise from increased excitatory inputs to the motor neuron pool, reduced presynaptic inhibition of Ia afferents, and reduced postsynaptic inhibition or increased intrinsic excitability of motor neurons. It is noteworthy that training-induced increases in H-reflex amplitudes obtained during active isometric plantar flexor contractions (20% MVC) were positively correlated ($r = 0.59$) with gains in RFD (25), suggesting the change in spinal circuitry function to have importance for functional performance.

Spinal synaptogenesis

The current knowledge on changes in the morphology of spinal neurons induced by strength training is limited, but Adkins *et al.* (51) examined the influence of strength training on the number of excitatory and inhibitory synapses per μm^2 of motor neuron soma surface within the cervical spinal cord in rats. The animals performed either power reaching (high-load skill training), control reaching (low-load skill training), or no reaching (control). Whereas both training protocols resulted in larger motor areas (maps) at the cortical level compared with controls, no difference was observed between training groups, suggesting that the difference in cortical motor maps was related to skill learning (52). However, a difference between training groups was observed at the spinal level, where high-load strength-trained rats exhibited a greater number of excitatory but not inhibitory synapses onto ventral horn motor neurons, compared with skill-trained and untrained animals (51). Although the

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origin of these *de novo* synapses is not clear, the data suggest that strength training may be accompanied by excitatory synaptogenesis in the spinal cord, consistent with the notion of increased motor neuron excitability and elevated muscle activation during maximal contraction efforts after strength training.

Corticospinal Excitability

Experiments using TMS of motor cortical brain areas have demonstrated that short-term (weeks) strength training can result in increased corticospinal excitability manifested by enhanced motor evoked potentials (MEPs) or increased TMS twitch activation (46,53–63). For instance, 4 wk of training for the radial deviator wrist muscles resulted in elevated amplitude muscle twitches evoked by TMS and cervicomedullary magnetic stimulation during low-force contraction conditions, which were suggested to reflect an increased net gain in corticospinal projections to the motor neurons innervating the trained muscles (58). Corresponding evidence of elevated corticospinal excitability assessed by TMS has also been reported after acute strength training (64), although previously also observed after skill training and metronome-paced strength training (62,65–67). Likewise, same-day repeated bouts of ballistic skill training with requirements for maximal movement acceleration was accompanied by acute increases in corticospinal excitability (68).

However, these findings remain somewhat ambiguous because other studies have found none or even negative changes in TMS-evoked motor responses (MEP amplitude) or corticospinal input-output function after short-term (4–8 wk) strength training (67,69–72). Potential factors contributing to the disparate observations could be differences across studies in the muscles examined and relative (% MVC) contraction intensity, respectively. Thus, although Carroll *et al.* (69) recorded responses during contraction levels up to 60% of MVC, other studies examined contraction intensities between 5% and 20% of MVC (67,70,71), where adaptive changes in evoked potential properties may be less likely observed. In line with this notion, no change was observed in MEPs elicited by cervicomedullary stimulation at rest after 4 wk of elbow flexor strength training (73). One further challenge concerning the effect of strength training on corticospinal excitability may also be the type of training applied. Numerous short- and long-term studies have demonstrated that skill learning is accompanied by increased corticospinal excitability and altered intracortical properties (67,74–76) (for review, see, *e.g.*, [77,78]), and strength training *per se* may involve elements of skill learning. Thus, because training protocols vary considerably between studies, different requirements for motor learning may be involved. It has been demonstrated that an acute bout of strength training with timing requirements (metronome-paced) was accompanied by increased corticospinal excitability, whereas self-paced strength training was not (62). Likewise, acute ballistic skill training with timing requirements is accompanied by increases in corticospinal excitability (68). Part of the heterogeneity in the literature on the influence of strength training on corticospinal excitability may thus be related to the specific motor tasks practiced including the type(s) of muscle contraction performed during training, and the extent to which the strength training protocol involves motor learning.

Adaptive Changes at the Cortical Level

Combining cortical magnetic, electrical, and cervicomedullary stimulation

In an effort to localize CNS adaptations evoked by strength training, the combination of different stimulation techniques represents a useful approach. The mechanisms by which descending corticospinal volleys are elicited differ between TES and TMS. Whereas a large proportion of the muscular response to TMS of the upper limb muscles is brought about by trans-synaptic excitation of corticospinal cells, TES activates the corticospinal neurons more directly (79,80), and the combined application of the two stimulation types allows assessment of changes within the primary motor cortex. This would be indicated by differential training-induced changes in the MEPs elicited by TMS compared with TES. For example, Carroll *et al.* (69) combined transcranial magnetic and electrical stimulation at contraction levels up to 60% MVC before and after 4 weeks of strength training for the index finger abductors. The magnitude of training-induced changes in the gain of the relation between MEP size and background EMG activity or absolute muscle torque levels, respectively, did not differ between magnetic (*i.e.*, cortical) and electrical (*i.e.*, subcortical) stimulation, indicating a lack of cortical adaptations at these contraction levels (69).

Investigating changes in intracortical pathways by use of TMS

Based on paired pulse (conditioning) TMS protocols, signs of reduced intracortical inhibition have been observed after strength training. For example, short-interval intracortical inhibition (SICI) assessed by paired-pulse TMS was reduced by −35% (60) and −38% (61) after 4 wk of strength training for the wrist flexors and rectus femoris muscle, respectively. Additional reports of reduced intracortical inhibition after short-term strength training (2–8 wk) have been based on the shortening of the so-called cortical silent period assessed by single-pulse TMS (72,81) (Fig. 3). Although reduced SICI is considered to reflect a downregulated synaptic efficacy of cortical interneuron $GABA_A$ (γ-amino butyric acid) receptors within the primary motor cortex (M1) (61), the cortical silent period evoked by single-pulse TMS has been suggested to originate from circuits of inhibitory $GABA_B$ receptor–mediated interneuron transmission in M1 (81).

Investigating changes in cortical activation by means of electroencephalography

Electroencephalography (EEG) enables recording of motor cortical activity while also allowing connectivity analysis between distinct cortical areas or potentially between measures of EEG and EMG. Although only rarely used to examine the effect of strength training on neural function, EEG has been used to quantify slow negative surface potentials detected at the scalp surface during voluntary movement, denoted as movement-related cortical potentials. After 3 weeks of explosive-type leg extensor strength training, movement-related cortical potential amplitudes recorded during submaximal constant-load leg extensions were significantly attenuated at several electrode positions overlying cortical motor areas, with an earlier (28%) onset compared with pretraining (4) (Fig. 4). These changes were paralleled by gains in maximal strength (+22%) and RFD (32%) (4). The attenuated cortical demand for submaximal voluntary movement

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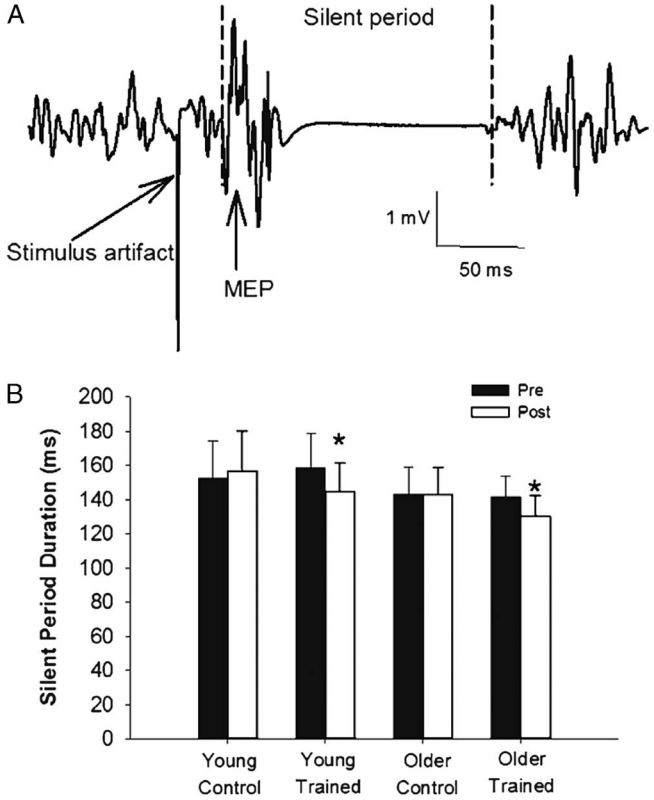

Figure 3. Silent period duration after motor evoked potential (MEP) elicited by transcranial magnetic stimulation (TMS) assessed before and after 2 wk of strength training in young (22 yr) and older (73 yr) adults. A. Sample recording of a silent period from the tibialis anterior muscle of a young participant during 50% maximal voluntary contraction (MVC). Vertical dashed lines indicate the beginning of the MEP and the return of EMG activity, also denoted as the cortical silent period. B. Both young and older individuals showed a reduction in silent period duration after training (*$P < 0.001$), indicating reduced intracortical inhibition. (Reprinted from (72). Copyright © 2014 Springer. Reprinted with kind permission of the American Aging Association.)

was suggested to reflect an enhanced *neural efficiency* as a result of strength training (4).

PERSPECTIVES FOR PROGRESS IN THE ASSESSMENT OF NEUROPLASTICITY ACCOMPANYING STRENGTH TRAINING

Recent technological and methodological advances provide a promising basis for further expanding our insight into the range and mechanisms of neuroplasticity with strength training. Thus, future investigations may benefit from combining techniques such as (i) multimodal measures of strength from single muscles to complex coordination, (ii) multilevel electrophysiological stimulation and recording techniques, (iii) multimodal neuroimaging techniques, (iv) modeling that encompasses combined measures to adaptations in, for example, MU recruitment and discharge modulation, and (v) measures of structural and functional connectivity accompanying strength training.

Activation of Individual Motor Neurons: Training-Induced Changes in Maximal Discharge Rates

For the CNS to exert an adaptive influence on the activation of muscle fibers, modulation of the discharge rates of individual α-motor neurons (the final common pathway [82]) must occur. As discussed above, maximal MU discharge rates constitute a major determinant of early-phase RFD, and hence, training-induced improvements in maximal MU discharge rate have been suggested to underlie increases in RFD with training (1,7,83). Yet, the plasticity in MU discharge characteristics during explosive-type movements and its relation to RFD have only been examined in a single previous study (7). The more recent application of high-density EMG analysis allows the discharge rates of multiple MUs to be estimated concurrently (cf. Figs. 1, 2), which represents an attractive methodological approach to investigate the effect of strength training on the discharge behavior of spinal motor neurons. In support of this notion, Del Vecchio *et al.* (34) recently demonstrated that high-density EMG analysis can be applied during explosive-type contractions to extract information about premotor and early-phase MU discharge rates in up to 10–20 independent MUs that were reliably reidentified during successive contractions (Fig. 5). Consequently, studies using high-density EMG techniques should be conducted to evaluate training-induced changes in MU discharge behavior during explosive-type muscle actions (*i.e.*, at maximal intentional RFD). Furthermore, no reports exist on the influence of exercise intensity (moderate vs heavy strength training loads) on changes in maximal MU discharge rate, which also should be addressed in future investigations.

MU firing rates are affected by synaptic inputs and intrinsic motor neuron properties. Van Cutsem *et al.* (7) suggested that the increased doublet or triplet discharges observed after strength training might originate at least in part from altered intrinsic motor neuron properties, and not solely reflect changes in synaptic input. Delayed depolarization could be a potential mechanism involved (84), consistent with signs of increased motor neuron excitability observed during MVC after strength training (40,45).

Although previous animal studies have demonstrated that activity-dependent changes in the intrinsic properties of α-motor neurons can occur rapidly (85,86) (for review, see [87]), no study so far has succeeded in determining whether strength training is accompanied by such changes. Thus, as elaborated below, future research should investigate if and how strength training may influence the intrinsic properties of spinal α-motor neurons.

Activation of the Motor Neuron Pool: Training-Induced Changes in Recruitment Gain

As skeletal muscles are innervated by hundreds of MUs, the ability to increase MVC force and RFD relates not only to individual motor neuron discharge rates but also to the progressive recruitment of additional MUs. Thus, physiological characteristics within the motor neuron pool — including recruitment gain — may also affect MVC force and maximal RFD (88–90). Specifically, the increase in RFD frequently observed after strength training (3,5,7–12) could be caused, at least in part, by an increased recruitment gain in the spinal motor neuron pool. In support of this notion, Del Vecchio *et al.* (29) recently observed a compressed recruitment range (MUs being recruited earlier relative to MVC force) when assessed during submaximal isometric ramp contractions after 4 wk of isometric strength training for the ankle dorsiflexors. In turn, an increased recruitment gain (*i.e.*, compression of the recruitment range) may not necessarily be caused by a linear increase in net excitation across the motor neuron pool. Rather, it could be caused both by increased excitatory synaptic inputs to the motor

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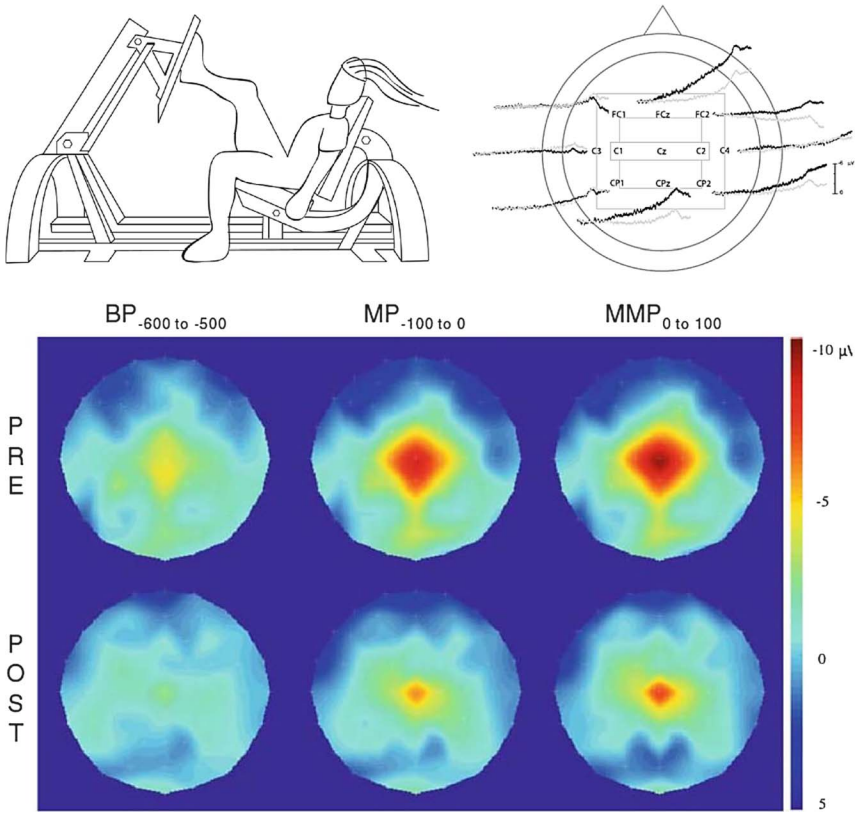

Figure 4. EEG recording of movement-related cortical potentials (MRCP) during 60 successive leg extensions performed against a submaximal constant nominal load (20% $MVIC_{PRE}$) before (PRE) and after (POST) 3 wk (nine sessions) of strength training. Bottom: Two-dimensional topographical maps of MRCP component amplitudes with the anterior-posterior axis arranged vertically, that is, frontal region located at the top. MRCP components: mean electroencephalography (EEG) amplitude between −600 and −500 ms before movement onset (preparation potential: $BP_{-600\ to\ -500}$), mean amplitude between −100 ms and movement onset (motor potential: $MP_{-100\ to\ 0}$), mean amplitude from onset to +100 ms (movement-monitoring potential: $MMP_{0\ to\ 100}$). Amplitudes were computed with reference to baseline −3.5 to −3.0 s before movement onset. (Reprinted from (4). Copyright © 2010 Springer Nature. Used with permission.)

neurons or by changes in intrinsic motor neuron properties (discussed above) as a result of training. An increased recruitment gain (compressed recruitment range) could also result from an earlier recruitment of larger motor neurons. It remains for future studies to investigate whether changes in MU recruitment gain contribute to the improvement in RFD observed after strength training.

Evoked Spinal Responses During Explosive-Type Contractions

Only limited knowledge exists on spinal circuitry function during the onset and early contraction phase of rising muscle force in explosive-type muscle actions, and even less is known about the training-induced change Although no V wave data exist currently, only few studies have recorded the H-reflex amplitude synchronously with muscle force during rapid muscle contractions (91,92). These data reveal a premovement facilitation of the evoked H-reflex response starting 20–40 ms (92) up to 100 ms (91) before muscle activation (onset of EMG), suggesting that a rapid increase in spinal motor neuron excitability (or decrease in presynaptic or postsynaptic inhibition) precedes the efferent outflow of MU action potentials to myofibers (Fig. 6). Future experiments should examine if the modulation in spinal evoked responses (H-reflex and V wave) before and during the initial phase of rising muscle force in explosive-type contractions can be altered in response to strength training. Although representing a considerable technical challenge, future investigative efforts could also benefit from using supplementary techniques to elucidate whether training-induced changes in RFD involve (i) altered utilization of Ia afferent input, (ii) modulation of motor neuron activity by spinal interneurons including recurrent Renshaw inhibition, or (iii) changes in descending cortical motor drive, including altered corticospinal connectivity.

Changes in Synaptic Inputs to Motor Neurons After Strength Training

The firing behavior of motor neurons is strongly governed by synaptic inputs (34,93). Thus, changes in the synaptic input to spinal motor neurons most likely contribute to the increase in maximal MU discharge rate observed after strength training (7,26–28). In broad terms, synaptic inputs to spinal motor neurons arise from (i) afferent inputs, (ii) spinal interneurons, and (iii) descending cortical and brain stem pathways. As elaborated below, adaptive changes in any or a combination of these different inputs in response to strength training could lead to changes in motor neuron recruitment and discharge rates, thus resulting in elevated RFD and MVC forces.

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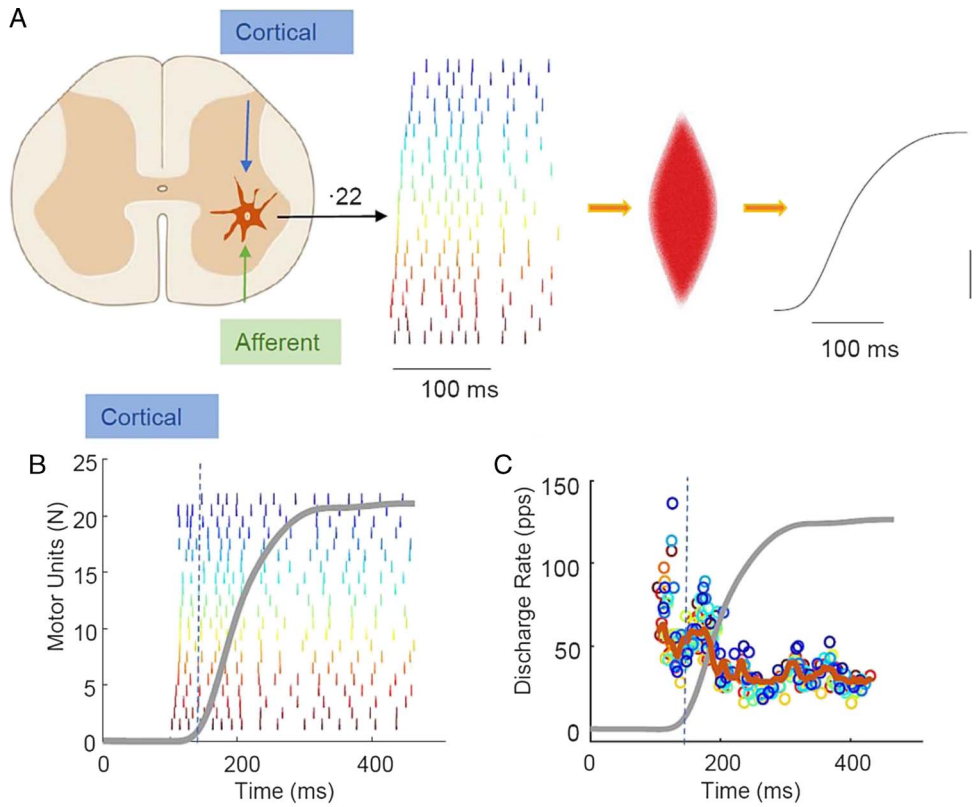

Figure 5. A. Representative example of the motor neuron discharge timings from the spinal cord with the resultant force output. B. Twenty-two motor units (MUs) were identified during an explosive contraction normalized to maximal voluntary force (solid line). C. Discharge rate of the MUs shown in (A). Thick superimposed trace depicts the average number of discharges per MU per second (moving 35-ms time interval), which is an estimate of the neural drive to the muscle. (Reprinted from (34). Copyright © 2019 John Wiley and Sons. Used with permission.)

Ia Afferent Input to Motor Neurons, Spinal Interneuronal Circuits

It is possible that strength training leads to altered levels of excitatory input to the spinal motor neuron pool from muscle spindle Ia afferents, potentially via presynaptic mechanisms or interneuronal relays at the spinal level. Such modulation could, for example, comprise removal of presynaptic inhibition of Ia afferents at the onset and rising phase of RFD, which may be assessed by experimental protocols involving conditioned H-reflex recordings (*e.g.*, [94]).

Training-induced alterations in synaptic input from spinal interneurons may contribute as well to an increased net excitation of agonist motor neurons after strength training, and in some cases even contribute to a decreased excitation of antagonist motor neurons. In support of the latter, disynaptic reciprocal inhibition was found to increase in the antagonist muscle (soleus) at the onset of explosive-type dorsiflexor contractions after 4 wk of strength training, potentially contributing to the training-induced rise in net joint RFD (95).

Autogenic recurrent inhibition of spinal motor neurons via Renshaw cells is considered a limiting factor for maximal MU discharge rate and suggested to have a regulatory influence on the reciprocal Ia inhibitory pathway (96). Renshaw cells receive several types of supraspinal synaptic input (including descending tracts from motor cortical areas) to enhance or depress the recurrent pathway (97,98) (Fig. 7). With increasing activity, progressively more recurrent inhibition (hyperpolarizing current) is added to spinal motor neurons, resulting in lower discharge rates of individual motor neurons at a given synaptic input level and postponed motor neuron recruitment to higher input levels. Both factors contribute to a reduced slope (reduced gain) of the input-output relation for spinal motor neurons

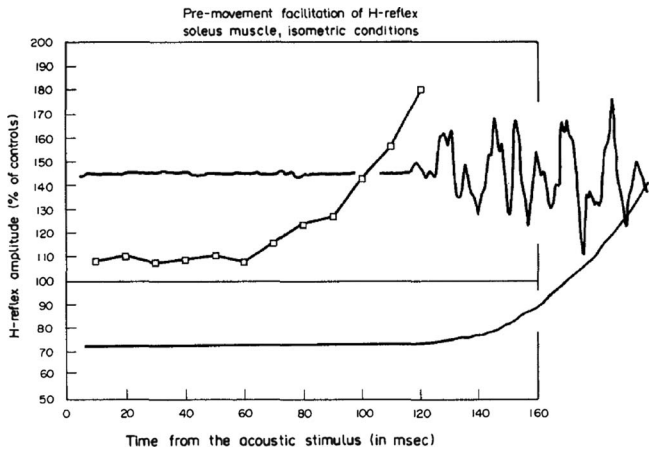

Figure 6. Premovement facilitation of the soleus H-reflex during rapid ("explosive type") voluntary isometric plantar flexor contractions. Full lines denote soleus EMG activity (top trace, arbitrary units), plantar flexor force (bottom trace, arbitrary units), the trace marked with open square symbols depicts the H-reflex amplitude recorded concurrently in the soleus muscle. Each point in the graphs is the grand mean of average values from five subjects. Included in the picture are recordings of EMG and force obtained in the corresponding situations. Graphs and recordings are arbitrarily aligned along the same time base, starting from the reaction time signal. Data from Schieppati *et al.* (92). (Reprinted from (47). Copyright © 1987 Elsevier. Used with permission.)

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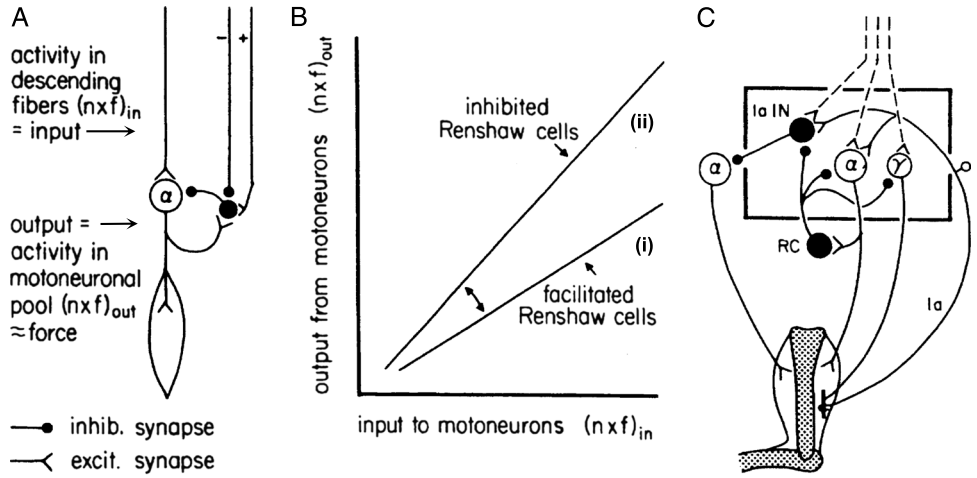

Figure 7. Autogenic recurrent Renshaw cell inhibition. A. Input and output connections of α-motor neurons and Renshaw cells, a specialized type of spinal interneuron. Excitatory (excit.) and inhibitory (inhib.) synapses are shown. Note that Renshaw cells themselves receive both excitatory and inhibitory synaptic inputs, from spinal and higher centers in the central nervous system (CNS). B. Simplified diagram of input-output relations of the motor neuron pool involving facilitation of Renshaw cells (i), where efferent motor neuron output is diminished for a given neuronal input (*i.e.*, a given level of central descending motor drive). Conversely, the inhibition of Renshaw cells (ii) causes an overall disinhibition of the α-motor neuron pool, with a resulting rise in efferent motor output for a given synaptic input. The presence of recurrent inhibition (*i.e.*, input to Renshaw cells from collateral α-motor neuron axons, shown in [A]) provides a basis that allows the input-output relation of the motor neuron pool to be dynamically modulated. C. Motor output stage. Neurons constituting the efferent output are framed by thick lines. Denotations: α, α-motor neurons; γ, γ-motor neurons; IaIN, Ia inhibitory interneurons; RC, Renshaw cells. Right and left muscles represent agonist and antagonist muscles, respectively. [Adapted from (97). Copyright © 1979 Springer Nature. Used with permission.]

(Fig. 7B). Consequently, the recurrent pathway has been suggested to operate as a variable gain regulator for motor neuron output (97,99). Interestingly, Hultborn *et al.* (99) found that this inhibition was several times more effective in reducing motor neuron firing caused by descending pyramidal synaptic excitation compared with direct soma excitation. Nonetheless, the effect of strength training on recurrent Renshaw inhibition remains unexplored and should be examined in future experiments.

Recent human experiments using conditioning (paired) H-reflex stimulation protocols have indicated that recurrent Renshaw inhibition may be elevated during maximal eccentric muscle actions (*i.e.*, resembling condition [i] in Fig. 7B) compared with maximal concentric and isometric muscle actions (100). Notably, this observation may at least in part explain previous reports of reduced activation of muscle fibers during maximal volitional eccentric contractions, as consistently observed by use of surface EMG, V wave recording, transcranial and cervicomedullary magnetic stimulation, and superimposed interpolated twitch analysis (101). Future experiments should investigate if strength training leads to a removal of recurrent Renshaw inhibition (*i.e.*, [i]→[ii] in Fig. 7B), because this training modality has been found to reduce or fully abolish the suppression in motor neuron output during maximal eccentric muscle contraction, in turn resulting in elevated eccentric muscle strength (45,102) (for recent review, see [101]).

It should be recognized, however, that substantial technical challenges may exist for the use of paired-stimulus protocols (*i.e.*, delivering conditioning and test stimulations within controlled intervals of a few-millisecond duration) for instance during contraction conditions involving, for example, maximal RFD, which may limit the implementation of such techniques. Nonetheless, several research groups have used this technique to study spinal circuitry function during eccentric versus concentric and isometric contractions (100) and to examine the training-induced plasticity during rapid muscle actions performed at maximal voluntary RFD (95).

Intermuscular Coordination

Inhibitory reflex circuitries are known to exist between synergist muscles (*i.e.*, different motor neuron pools) that are subject to modulatory control (103). For example, experiments using spike-triggered stimulation of the radial nerve have revealed an inhibitory influence of brachioradialis afferents on the discharge behavior of biceps brachii motor neurons during low-force elbow flexor contractions (103,104). Interestingly, synergist inhibition was reduced along with a 43% prolonged time to task failure after three successive practice sessions (isometric arm flexor contraction at 20% MVC sustained until failure) (103). Future studies should investigate if similar pathways of synergist inhibition also exist for muscles in the lower limbs and examine the effect of strength training on the inhibitory influence of these pathways. Removing or reducing this source of intersynergist inhibition would potentially contribute to the improvement in mechanical muscle function observed with strength training.

Future investigations of changes in intermuscular coordination and in the underlying mechanisms hold a strong potential to expand the understanding of neurophysiological plasticity with strength training. Future studies may combine stimulation protocols investigating both cortical and spinal circuitries and perform analyses of coupling or coherence (EMG-EMG) between different (agonist or synergist) muscles after strength training.

Cortical Versus Subcortical Modifications After Strength Training

As described above, mixed findings exist to support the presence of cortical adaptations in separation from subcortical (including spinal) adaptations to strength training, and future

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studies may therefore advance our understanding in this regard. Although studies on isolated measures of responses evoked, for example, by TMS may hold a questionable potential to understand specific mechanisms of neuroplasticity, it seems plausible that there is more knowledge to be gained from combining techniques or methodologies in future studies. TMS may indeed yield additional information, for example, on intracortical pathways when applied at subthreshold intensities during contraction (*e.g.*, to elicit a suppression of the EMG) and even more so when TMS is combined with complementary techniques such as transcortical electrical stimulation or cervicomedullary magnetic or electric stimulation (*e.g.*, [69]). In addition, TMS assessment protocols (including cervicomedullary and electrical stimulation) may be combined with peripheral stimulation techniques to address changes in corticomotoneuronal transmission efficacy (105,106).

Magnetoencephalography, EEG, and neuroimaging techniques such as functional magnetic resonance imaging (MRI) may also hold the potential to advance our understanding of CNS adaptations accompanying strength training. In addition, neuroimaging methods may be applied to elucidate potential changes in the morphology and activation of cortical and subcortical structures including the cerebellum, brain stem, etc. Based on both EEG and functional MRI, it is possible to perform dynamic causal modeling analyses to investigate changes in functional or structural network connectivity after strength training. Furthermore, EEG and EMG measures may be combined in the analyses of corticomuscular coherence to assess changes in corticomotoneuronal connectivity. Finally, stimulation and recording techniques may be combined (*e.g.*, EEG and TMS) to investigate complex network functions. It is not unlikely that much is to be learned about neural plasticity with strength training by investigating changes in network function coupling rather than focusing on single location focus. As a fundamental challenge, however, measurements should be performed during maximal voluntary efforts, that is, at MVC or maximal RFD, respectively, with multiple recordings often being necessary. These conditions obviously constitute an inherent challenge for all the methodological approaches discussed in the present review.

Changes in Neuroanatomy With Strength Training

Given the beneficial influence of physical exercise on brain health (107,108) and that specific CNS structures (*e.g.*, brain white matter volume) are associated with muscle structure and function (109), it becomes relevant to examine the plasticity in structural neuroanatomy (gray and white matter volume or density) with strength training in both healthy and clinical/subclinical populations. MRI-based neuroimaging techniques (*e.g.*, diffusion tensor imaging) have provided evidence of altered corticospinal tract microstructure, manifested as enhanced white matter diffusivity after short-term (4 wk) strength training in healthy adults (110). Furthermore, reduced cortical white matter atrophy was observed at 2-year follow-up after long-term (52 weeks) strength training in old women (~70 yr) compared with age-matched controls performing balance-and-toning training (111). Although sparse, these observations suggest that structural and functional changes in neuroanatomy may occur in response to both short- and long-term strength training. Future experiments should be performed to expand these observations in both young and old adults, potentially including neurological patients with stroke, multiple sclerosis, Parkinson disease, mild cognitive impairment, or dementia (including Alzheimer disease), to identify the dose-response relation of these changes and to examine their potential positive impact on functional capacity.

SUMMARY

The present article presents a perspective for future experiments in the field of exercise-related neuroplasticity related to strength training. We propose that the combination of specific experimental approaches and including recently developed techniques may provide an increased insight into the range and mechanisms of neuroplasticity with strength training.

Specifically, it is suggested that future investigative efforts should focus on (i) integrating multimodal measures of strength from single muscles to complex coordination, (ii) multilevel (spinal, supraspinal, and cortical) electrophysiological stimulation and recording techniques, (iii) multimodal neuroimaging techniques, (iv) high-density EMG recording techniques to assess adaptive changes in MU recruitment and discharge modulation, and (v) measures of structural and functional connectivity accompanying strength training.

Increased knowledge about the specific spinal and supraspinal pathways involved in the neural adaptation to strength training is likely to be transferable into an improved design of training and rehabilitation protocols for athletes, recreational exercisers, old adults, and clinical patients.

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References

1. Aagaard P. Training-induced changes in neural function. *Exerc. Sports Sci. Rev.* 2003; 31:61–7.
2. Felici F. Neuromuscular responses to exercise investigated through surface EMG. *J. Electromyogr. Kinesiol.* 2006; 16:578–85.
3. Häkkinen K, Kallinen M, Izquierdo M, et al. Changes in agonist-antagonist EMG, muscle CSA, and force during strength training in middle-aged and older people. *J. Appl. Physiol.* 1998; 84:1341–9.
4. Falvo MJ, Sirevaag EJ, Rohrbaugh JW, Earhart GM. Resistance training induces supraspinal adaptations: evidence from movement-related cortical potentials. *Eur. J. Appl. Physiol.* 2010; 109:923–33.
5. Tillin NA, Folland JP. Maximal and explosive strength training elicit distinct neuromuscular adaptations, specific to the training stimulus. *Eur. J. Appl. Physiol.* 2014; 114:365–74.
6. Trezise J, Blazevich AJ. Anatomical and neuromuscular determinants of strength change in previously untrained men following heavy strength training. *Front Physiol.* 2019; 10:1001.
7. Van Cutsem M, Duchateau J, Hainaut K. Changes in single motor unit behaviour contribute to the increase in contraction speed after dynamic training in humans. *J. Physiol.* 1998; 513:295–305.
8. Aagaard P, Simonsen EB, Andersen JL, Magnusson P, Dyhre-Poulsen P. Increased rate of force development and neural drive of human skeletal muscle following resistance training. *J. Appl. Physiol.* 2002; 93:1318–26.
9. Barry BK, Warman GE, Carson RG. Age-related differences in rapid muscle activation after rate of force development training of the elbow flexors. *Exp. Brain Res.* 2005; 162:122–32.
10. Del Balso C, Cafarelli E. Adaptations in the activation of human skeletal muscle induced by short-term isometric resistance training. *J. Appl. Physiol.* 2007; 103:402–11.
11. Tillin NA, Pain MTG, Folland JP. Short-term training for explosive strength causes neural and mechanical adaptations. *Exp. Physiol.* 2012; 97(5):630–41.

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12. Vila-Chã C, Falla D, Farina D. Motor unit behavior during submaximal contractions following six weeks of either endurance or strength training. *J. Appl. Physiol.* 2010; 109:1455–66.
13. Häkkinen K, Komi PV, Alén M, Kauhanen H. EMG, muscle fibre and force production characteristics during a 1 year training period in elite Weight-Lifters. *Eur. J. Appl. Physiol.* 1987; 56:419–27.
14. de Ruiter CJ, Vermeulen G, Toussaint HM, de Haan A. Isometric knee-extensor torque development and jump height in volleyball players. *Med. Sci. Sports Exerc.* 2007; 39:1336–46.
15. Folland JP, Buckthorpe MW, Hannah R. Human capacity for explosive force production: neural and contractile determinants. *Scand. J. Med. Sci. Sports.* 2014; 24:894–906.
16. Hernández-Davó JL, Sabido R, Moya-Ramón M, Blazevich AJ. Load knowledge reduces rapid force production and muscle activation during maximal-effort concentric lifts. *Eur. J. Appl. Physiol.* 2015; 115:2571–81.
17. Blazevich AJ, Horne S, Cannavan D, Coleman DR, Aagaard P. Effect of contraction mode of slow-speed resistance training on the maximum rate of force development in the human quadriceps. *Muscle Nerve.* 2008; 38:1133–46.
18. Andersen LL, Andersen JL, Suetta C, Kjær M, Søgaard K, Sjøgaard G. Effect of contrasting physical exercise interventions on rapid force capacity of chronically painful muscles. *J. Appl. Physiol.* 2009; 107:1413–9.
19. de Ruiter CJ, Hutter V, Icke C, et al. The effects of imagery training on fast isometric knee extensor torque development. *J. Sports Sci.* 2012; 30:166–74.
20. Day SJ, Hulliger M. Experimental simulation of cat electromyogram: evidence for algebraic summation of motor-unit action-potential trains. *J. Neurophysiol.* 2001; 86:2144–58.
21. Farina D, Merletti R, Enoka RM. The extraction of neural strategies from the surface EMG. *J. Appl. Physiol.* 2004; 96:1486–95.
22. Keenan KG, Farina D, Maluf KS, Merletti R, Enoka RM. Influence of amplitude cancellation on the simulated surface electromyogram. *J. Appl. Physiol.* 2005; 98:120–31.
23. Vigotsky AD, Halperin I, Lehman GJ, Trajano GS, Vieira TM. Interpreting signal amplitudes in surface electromyography studies in sport and rehabilitation sciences. *Front Physiol.* 2018; 8:985.
24. Narici MV, Hoppeler H, Kayser B, et al. Human quadriceps cross-sectional area, torque and neural activation during 6 months strength training. *Acta Physiol. Scand.* 1996; 157:175–86.
25. Holtermann A, Roeleveld K, Engstrøm M, Sand T. Enhanced H-reflex with resistance training is related to increased rate of force development. *Eur. J. Appl. Physiol.* 2007; 101:301–12.
26. Patten C, Kamen G, Rowland DM. Adaptations in maximal motor unit discharge rate to strength training in young and older adults. *Muscle Nerve.* 2001; 24:542–50.
27. Kamen G, Knight CA. Training-related adaptations in motor unit discharge rate in young and older adults. *J. Gerontol. Med. Sci.* 2004; 59:1334–8.
28. Christie A, Kamen G. Short-term training adaptations in maximal motor unit firing rates and after-hyperpolarization duration. *Muscle Nerve.* 2010; 41:651–60.
29. Del Vecchio A, Casolo A, Negro F, et al. The increase in muscle force after 4 weeks of strength training is mediated by adaptations in motor unit recruitment and rate coding. *J. Physiol.* 2019; 597:1873–87.
30. Stock MS, Thompson BJ. Effects of barbell deadlift training on submaximal motor unit firing rates for the vastus lateralis and rectus femoris. *PLoS ONE.* 2014; 9:e115567.
31. Enoka RM, Duchateau J. Rate coding and the control of muscle force. *Cold Spring Harb. Perspect. Med.* 2017; 7:a029702.
32. Duchateau J, Baudry S. Maximal discharge rate of motor units determines the maximal rate of force development during ballistic contractions in human. *Front Hum Neurosci.* 2014; 8:234.
33. Del Vecchio A, Falla D, Felici F, Farina D. The relative strength of common synaptic input to motor neurons is not a determinant of the maximal rate of force development in humans. *J. Appl. Physiol.* 2019; 127:205–14.
34. Del Vecchio A, Negro F, Holobar A, et al. You are as fast as your motor neurons: speed of recruitment and maximal discharge of motor neurons determine the maximal rate of force development in humans. *J. Physiol.* 2019; 597:2445–56.
35. Martinez-Valdes E, Falla D, Negro F, Mayer F, Farina D. Differential motor unit changes after endurance or high-intensity interval training. *Med. Sci. Sports Exerc.* 2017; 49:1126–36.
36. Merletti R, Holobar A, Farina D. Analysis of motor units with high-density surface electromyography. *J. Electromyogr. Kinesiol.* 2008; 18:879–90.
37. Enoka RM. Physiological validation of the decomposition of surface EMG signals. *J. Electromyogr. Kinesiol.* 2019; 46:70–83.
38. Del Vecchio A, Negro F, Falla D, Bazzucchi I, Farina D, Felici F. Higher muscle fiber conduction velocity and early rate of torque development in chronically strength trained individuals. *J. Appl. Physiol.* 2018; 125:1218–26.
39. Upton AR, McComas AJ, Sica RE. Potentiation of "late" responses evoked in muscles during effort. *J. Neurol. Neurosurg. Psychiat.* 1971; 34:699–711.
40. Aagaard P, Simonsen EB, Andersen JL, Magnusson P, Dyhre-Poulsen P. Neural adaptation to resistance training: changes in evoked V-wave and H-reflex responses. *J. Appl. Physiol.* 2002; 92:2309–18.
41. Fimland MS, Helgerud J, Gruber M, Leivseth G, Hoff J. Functional maximal strength training induces neural transfer to single-joint tasks. *Eur. J. Appl. Physiol.* 2009; 107:21–9.
42. Vila-Chã C, Falla D, Correia MV, Farina D. Changes in H reflex and V wave following short-term endurance and strength training. *J. Appl. Physiol.* 2012; 112:54–63.
43. Unhjem R, Lundestad R, Fimland MS, Mosti MP, Wang E. Strength training-induced responses in older adults: attenuation of descending neural drive with age. *Age (Dordr.).* 2015; 37:9784.
44. Tøien T, Pedersen Haglo H, Unhjem R, Hoff J, Wang E. Maximal strength training: the impact of eccentric overload. *J. Neurophysiol.* 2018; 120:2868–76.
45. Duclay J, Martin A, Robbe A, Pousson M. Spinal reflex plasticity during maximal dynamic contractions after eccentric training. *Med. Sci. Sports Exerc.* 2008; 40:722–34.
46. Tallent J, Goodall S, Gibbon KC, Hortobágyi T, Howatson G. Enhanced corticospinal excitability and volitional drive in response to shortening and lengthening strength training and changes following detraining. *Front. Physiol.* 2017; 8:57.
47. Schieppati M. The Hoffmann reflex: a means of assessing spinal reflex excitability and its descending control in man. *Prog. Neurobiol.* 1987; 28:345–76.
48. Knikou M. The H-reflex as a probe: pathways and pitfalls. *J. Neurosci. Methods.* 2008; 171:1–12.
49. Lagerquist O, Zehr EP, Docherty D. Increased spinal reflex excitability is not associated with neural plasticity underlying the cross-education effect. *J. Appl. Physiol.* 2006; 100:83–90.
50. Vangsgaard S, Taylor JL, Hansen EA, Madeleine P. Changes in H reflex and neuromechanical properties of the trapezius muscle after 5 weeks of eccentric training: a randomized controlled trial. *J. Appl. Physiol.* 2014; 116:1623–31.
51. Adkins DL, Boychuk J, Remple MS, Kleim JA. Motor training induces experience-specific patterns of plasticity across motor cortex and spinal cord. *J. Appl. Physiol.* 2006; 101:1776–82.
52. Remple MS, Bruneau RM, VandenBerg PM, Goertzen C, Kleim JA. Sensitivity of cortical movement representations to motor experience: evidence that skill learning but not strength training induces cortical reorganization. *Behav. Brain Res.* 2001; 123:133–41.
53. Griffin L, Cafarelli E. Transcranial magnetic stimulation during resistance training of the tibialis anterior muscle. *J. Electromyogr. Kinesiol.* 2007; 17:446–52.
54. Beck S, Taube W, Gruber M, Amtage F, Gollhofer A, Schubert M. Task-specific changes in motor evoked potentials of lower limb muscles after different training interventions. *Brain Res.* 2007; 1179:51–60.
55. Kidgell DJ, Stokes MA, Castricum TJ, Pearce AJ. Neurophysiological responses after short-term strength training of the biceps brachii muscle. *J. Strength Cond. Res.* 2010; 24:3123–32.
56. Lee M, Gandevia SC, Carroll TJ. Unilateral strength training increases voluntary activation of the opposite untrained limb. *Clin. Neurophysiol.* 2009; 120:802–8.
57. Carroll TJ, Lee M, Hsu M, Sayde J. Unilateral practice of a ballistic movement causes bilateral increases in performance and corticospinal excitability. *J. Appl. Physiol.* 2008; 104:1656–64.
58. Carroll TJ, Barton J, Hsu M, Lee M. The effect of strength training on the force of twitches evoked by corticospinal stimulation in humans. *Acta Physiol.* 2009; 197:161–73.
59. Goodwill AM, Pearce AJ, Kidgell DJ. Corticomotor plasticity following unilateral strength training. *Muscle Nerve.* 2012; 46:384–93.
60. Weier AT, Pearce AJ, Kidgell DJ. Strength training reduces intracortical inhibition. *Acta Physiol (Oxf.).* 2012; 206:109–19.

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61. Kidgell DJ, Frazer AK, Daly RM, et al. Increased cross-education of muscle strength and reduced corticospinal inhibition following eccentric strength training. *Neurosci.* 2015; 300:566–75.
62. Leung M, Rantalainen T, Teo WP, Kidgell D. Motor cortex excitability is not differentially modulated following skill and strength training. *Neurosci.* 2015; 305:99–108.
63. Mason J, Frazer A, Horvath DM, et al. Adaptations in corticospinal excitability and inhibition are not spatially confined to the agonist muscle following strength training. *Eur. J. Appl. Physiol.* 2017; 117:1359–71.
64. Colomer-Poveda D, Romero-Arenas S, Lundbye-Jensen J, Hortobágyi T, Márquez G. Contraction intensity-dependent variations in the responses to brain and corticospinal tract stimulation after a single session of resistance training in men. *J. Appl. Physiol.* 2019; 127:1128–39.
65. Muellbacher W, Ziemann U, Boroojerdi B, Cohen L, Hallett M. Role of the human motor cortex in rapid motor learning. *Exp. Brain Res.* 2001; 136:431–8.
66. Rogasch NC, Dartnall TJ, Cirillo J, Nordstrom MA, Semmler JG. Corticomotor plasticity and learning of a ballistic thumb training task are diminished in older adults. *J. Appl. Physiol.* 2009; 107:1874–83.
67. Jensen JL, Marstrand PCD, Nielsen JB. Motor skill training and strength training are associated with different plastic changes in the central nervous system. *J. Appl. Physiol.* 2005; 99:1558–68.
68. Lundbye-Jensen J, Petersen TH, Rothwell JC, Nielsen JB. Interference in ballistic motor learning: specificity and role of sensory error signals. *PLoS ONE.* 2011; 6:e17451.
69. Carroll TJ, Riek S, Carson RG. The sites of neural adaptation induced by resistance training in humans. *J. Physiol.* 2002; 544:641–52.
70. Lee M, Gandevia SC, Carroll TJ. Short-term strength training does not change cortical voluntary activation. *Med. Sci. Sports Exerc.* 2009; 41:1452–60.
71. Kidgell DJ, Pearce AJ. Corticospinal properties following short-term strength training of an intrinsic hand muscle. *Hum. Mov. Sci.* 2010; 29:631–41.
72. Christie A, Kamen G. Cortical inhibition is reduced following short-term training in young and older adults. *Age (Dordr.).* 2014; 36:749–58.
73. Nuzzo JL, Barry BK, Jones MD, Gandevia SC, Taylor JL. Effects of four weeks of strength training on the corticomotoneuronal pathway. *Med. Sci. Sports Exerc.* 2017; 49:2286–96.
74. Kleim JA, Hogg TM, VandenBerg PM, Cooper NR, Bruneau R, Remple M. Cortical synaptogenesis and motor map reorganization occur during late, but not early, phase of motor skill learning. *J. Neurosci.* 2004; 24:628–33.
75. Hristiansen L, Larsen MN, Grey MJ, Nielsen JB, Lundbye-Jensen J. Long-term progressive motor skill training enhances corticospinal excitability for the ipsilateral hemisphere and motor performance of the untrained hand. *Eur. J. Neurosci.* 2017; 45:1490–500.
76. Christiansen L, Madsen MJ, Bojsen-Møller E, Thomas R, Nielsen JB, Lundbye-Jensen J. Progressive practice promotes motor learning and repeated transient increases in corticospinal excitability across multiple days. *Brain Stimul.* 2018; 11:346–57.
77. Sanes JN, Donoghue JP. Plasticity and primary motor cortex. *Annu. Rev. Neurosci.* 2000; 23:393–415.
78. Luft AR, Buitrago MM. Stages of motor skill learning. *Mol. Neurobiol.* 2005; 32:205–16.
79. Edgley SA, Eyre JA, Lemon RN, Miller S. Comparison of activation of corticospinal neurons and spinal motor neurons by magnetic and electrical transcranial stimulation in the lumbosacral cord of the anaesthetized monkey. *Brain.* 1997; 120:839–53.
80. Di Lazzaro V, Oliviero A, Profice P, et al. Comparison of descending volleys evoked by transcranial magnetic and electric stimulation in conscious humans. *Electroencephalogr. Clin. Neurophysiol.* 1998; 109:397–401.
81. Latella C, Kidgell DJ, Pearce AJ. Reduction in corticospinal inhibition in the trained and untrained limb following unilateral leg strength training. *Eur. J. Appl. Physiol.* 2012; 112:3097–107.
82. Sherrington CS. *The Integrative Action of the Nervous System*. New Haven, CT: Yale University Press; 1906.
83. Maffiuletti NA, Aagaard P, Blazevich AJ, Folland J, Tillin N, Duchateau J. Rate of force development: physiological and methodological considerations. *Eur. J. Appl. Physiol.* 2016; 116:1091–116.
84. Calvin WH, Schwindt PC. Steps in production of motoneuron spikes during rhythmic firing. *J. Neurophysiol.* 1972; 35:297–310.
85. Carp JS, Wolpaw JR. Motoneuron properties after operantly conditioned increase in primate H-reflex. *J. Neurophysiol.* 1995; 73:1365–73.
86. Romer SH, Deardorff AS, Fyffe REW. Activity-dependent redistribution of Kv2.1 ion channels on rat spinal motoneurons. *Physiol. Rep.* 2016; 4:e13039.
87. MacDonell CW, Gardiner PF. Mechanisms and functional implications of motoneuron adaptations to increased physical activity. *Appl. Physiol. Nutr. Metab.* 2018; 43:1186–93.
88. Kernell D, Hultborn H. Synaptic effects on recruitment gain: a mechanism of importance for the input-output relations of motoneurone pools? *Brain Res.* 1990; 507:176–9.
89. Hultborn H, Zhang M, Meehan CF. Control and role of plateau potential properties in the spinal cord. *Curr. Pharm. Des.* 2013; 19:4357–70.
90. Nielsen JB, Morita H, Wenzelburger R, Deuschl G, Gossard JP, Hultborn H. Recruitment gain of spinal motor neuron pools in cat and human. *Exp. Brain Res.* 2019; 237:2897–909.
91. Eichenberger A, Rüegg DG. Relation between the specific H reflex facilitation preceding a voluntary movement and movement parameters in man. *J. Physiol.* 1984; 347:545–59.
92. Schieppati M, Nardone A, Musazzi M. Modulation of the Hoffmann reflex by rapid muscle contraction or release. *Hum. Neurobiol.* 1986; 5:59–66.
93. Heckman CJ, Enoka RM. Motor unit. *Compr. Physiol.* 2012; 2:2629–82.
94. Hultborn H, Meunier S, Morin C, Pierrot-Deseilligny E. Assessing changes in presynaptic inhibition of I a fibres: a study in man and the cat. *J. Physiol.* 1987; 389:729–56.
95. Geertsen SS, Lundbye-Jensen J, Nielsen JB. Increased central facilitation of antagonist reciprocal inhibition at the onset of dorsiflexion following explosive strength training. *J. Appl. Physiol.* 2008; 105:915–22.
96. Hultborn H, Pierrot-Deseilligny E. Changes in recurrent inhibition during voluntary soleus contractions in man studied by an H-reflex technique. *J. Physiol.* 1979; 297:229–51.
97. Hultborn H, Lindström S, Wigström H. On the function of recurrent inhibition in the spinal cord. *Exp. Brain Res.* 1979; 37:399–403.
98. Pierrot-Deseilligny E, Morin C. Evidence for supraspinal influences on Renshaw inhibition during motor activity in man. In: Desmedt JE, editor. Spinal and Supraspinal Mechanisms of Voluntary Motor Control and Locomotion (*Prog Clin Neurophysiol.* Vol. 8). Basel: Karger; 1980. p. 142–69.
99. Hultborn H, Denton ME, Wienecke J, Nielsen JB. Variable amplification of synaptic input to cat spinal motoneurones by dendritic persistent inward current. *J. Physiol.* 2003; 552:945–52.
100. Barrué-Belou S, Marque P, Duclay J. Recurrent inhibition is higher in eccentric compared to isometric and concentric maximal voluntary contractions. *Acta Physiol (Oxf.).* 2018; 223:e13064.
101. Aagaard P. Spinal and supraspinal control of motor function during maximal eccentric muscle contraction: effects of resistance training. *J. Sport Health Sci.* 2018; 7:282–93.
102. Aagaard P, Simonsen EB, Andersen JL, Magnusson SP, Halkjær-Kristensen J, Dyhre-Poulsen P. Neural inhibition during maximal eccentric and concentric quadriceps contraction: effects of resistance training. *J. Appl. Physiol.* 2000; 89:2249–57.
103. Riley ZA, Baudry S, Enoka RM. Reflex inhibition in human biceps brachii decreases with practice of a fatiguing contraction. *J. Neurophysiol.* 2008; 100:2843–51.
104. Barry BK, Riley ZA, Pascoe MA, Enoka RM. A spinal pathway between synergists can modulate activity in human elbow flexor muscles. *Exp. Brain Res.* 2008; 190:347–59.
105. Taube W, Leukel C, Nielsen JB, Lundbye-Jensen J. Repetitive activation of the corticospinal pathway by means of rTMS may reduce the efficiency of corticomotoneuronal synapses. *Cereb. Cortex.* 2015; 25:1629–37.
106. Taube W, Leukel C, Nielsen JB, Lundbye-Jensen J. Non-invasive assessment of changes in corticomotoneuronal transmission in humans. *J. Vis. Exp.* 2017; 123:e52663.
107. Barha CK, Galea LA, Nagamatsu LS, Erickson KI, Liu-Ambrose T. Personalising exercise recommendations for *Brain* health: considerations and future directions. *Br. J. Sports Med.* 2017; 51:636–9.
108. Lautenschlager NT, Cox K, Cyarto EV. The influence of exercise on *Brain* aging and dementia. *Biochim. Biophys. Acta.* 2012; 1822:474–81.
109. Kilgour AHM, Todd OM, Starr JM. A systematic review of the evidence that brain structure is related to muscle structure and their relationship to brain and muscle function in humans over the lifecourse. *BMC Geriatr.* 2014; 14:85.
110. Palmer HS, Håberg AK, Fimland MS, et al. Structural brain changes after 4 wk of unilateral strength training of the lower limb. *J. Appl. Physiol.* 2013; 115:167–75.
111. Best JR, Chiu BK, Hsu CL, Nagamatsu LS, Liu-Ambrose T. Long-term effects of resistance exercise training on cognition and brain volume in older women: results from a randomized controlled trial. *J. Int. Neuropsych. Soc.* 2015; 21:745–56.

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