Training the brain and its connections to muscles

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There is no doubt that exercising limb muscles can enhance their strength and endurance. However, while some obvious changes occur within the muscles, changes also occur within the central nervous system. For most muscle groups, there is an obvious avenue to increase muscle strength, and that is to increase the level of voluntary activation that accompanies maximal contractions. Levels of voluntary activation are usually above 80%, but rarely 100%, with attempted maximal isometric efforts for most muscle groups (6), and this can be documented with motor nerve or motor cortical stimulation (11). Hence, an increase in effective descending drive to motoneuron pools should increase voluntary muscle force output, provided that it was not already maximal. This increased drive would recruit more motoneurons or increase their discharge rate.

A paper in this issue (8) attempts to demonstrate, with the use of neuroimaging, a change in the corticospinal tract linking the motor cortex and the spinal cord. Note such a neuroanatomical approach cannot provide information about synaptic properties of the physiological connections with motoneurons. One group of subjects trained the plantar flexors of the ankle on their dominant side with 4 wk of maximal voluntary contractions (16 sessions, each with 36 maximal efforts of 4-s duration), while the control group had no training. After training, strength increased by a mean of 39% on the trained side and 30% on the untrained side. The latter change represents a large cross-training effect and is likely to reflect a learned enhancement of output to motoneurons (2).

Using diffusion tensor imaging (DTI), there was a small but significant reduction (2%; \( P = 0.021 \)) in mean diffusivity (MD) of the left corticospinal tract between the foot area of the motor cortex and the cerebral peduncle. Fractional anisotropy (FA) increased by 1.7%, although this was not significant (\( P = 0.7 \)). No such changes occurred for the contralateral corticospinal tract in the trained group or for either tract in the control group. Although the group size for these analyses was small (≤10), there was a correlation between the improvement in strength and the reduction in mean diffusivity. Additional studies examined functional MRI using blood oxygenation level-dependent imaging during attempted maximal plantar flexion contractions performed supine in the scanner before and after training. No changes were observed in activation of the primary motor cortex for the lower limb.

While the effects of motor learning in the brain have been studied with neuroimaging, there are much less data on the effects of strength training. Strength training has been investigated using transcranial stimulation, but the results are contradictory and difficult to unravel (3). Different paradigms have been used, and it is clear that any task focused on strength training must minimize the effects of confounding complexities, such as motor learning. This is further complicated by the motor system itself, which has many levels (e.g., cortical, subcortical, and spinal) at which direct and indirect changes can occur. Some of this complexity is depicted in Fig. 1.

The work of Palmer and colleagues (8) does provide a tantalizing suggestion that strength training may have ramifications for brain plasticity and, furthermore, that it may affect a major corticofugal tract involved in force production. While the new study will generate an interesting hypothesis and is likely to engender further studies by others, it is probable that, statistically, the result is marginal. In general, one must question the utility of the role of small studies (with low \( N \) and hence borderline statistical value) to the literature and be mindful that they can exert undue influence on the field. The recent report of Button and colleagues (1) highlights the point that the likelihood of obtaining reliable outcomes from small-\( N \) studies is low, and this is reflected in the contradictory outcomes of strength training studies already in the literature.

The authors point out, wisely, in their conclusion that further work is essential. We suggest that such work requires a carefully designed and controlled strength training paradigm coupled with a larger sample size (at least 20 subjects). The work should also include test-retest reliability of the DTI.

Fig. 1. The flow chart shows an abstraction of some possible effects and observables associated with understanding tissue and functional changes and their relationships. Experiments that aim to elucidate the associations between, say, strength training and changes in brain tissue would need to establish that the paradigm under consideration can properly differentiate them, and that any observed effects are truly associated with the task. For example, does the task really reflect only strength and not other activity that may be the cause of observed tissue changes? What other elements covary with the task? As with work involved in functional MRI paradigms, appropriate control tasks may need to be developed so that direct inferences between task activity and observed changes in neural tissue can be made.

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metrics, coupled with measures of confidence in the structural changes, verified for example, by the bootstrap method (4), so as to avoid potentially systematic changes due to technical factors.

Further inspection of the data in the present study reveal that the DTI metrics varied among the trained group, and, with a small cohort, the true variability of these metrics is not known. The changes in MD and FA are driven by data from 3 of the 10 subjects. Is there a decrease in FA associated with a decrease in MD in one subject? The directional diffusion coefficients were not presented and may provide some sense of uniformity in the changes observed in MD and FA. Previous studies suggest that, in some scenarios, radial diffusivity may be associated with myelin and axial diffusivity with axonal changes (7, 9, 10). Decreased MD and increased FA may be driven by reduction in the radial diffusion. Although not conclusive, the directional coefficients may provide better clues about the physiological changes. A priori, physiological changes in myelin would not be expected to change the MD value by much, and 2% changes would already be very large; compared for example to MD changes during maturation (5). Improved statistical power and investigation of directional diffusion coefficients could bring these data to the point of suggesting that new myelination is a good hypothesis that would need to be further tested with more specific measures that indicate myelin changes.

The large improvement in maximal voluntary force on the nontrained side is interesting but not discussed. Results are given for the mean and standard deviation for the change, but these do not seem normally distributed. Looking at the median increase (near zero percent for the untrained group), there is a larger increase of ~40% in the untrained leg compared with ~30% in the trained leg. Furthermore, if the untrained side exhibited a larger (median) change in maximum voluntary contraction, it is intriguing why there are no correlations with the DTI metrics. It may have been instructive to consider nonparametric approaches to some of the comparisons and correlations.

In the fields of study of muscle strength, endurance, and fatigue, there is the ever-present specter of what is cause, what is effect, and what is an epiphenomenon! So, how should we view the new study? Our position is that we should be skeptical but interested to see larger and more detailed studies. Regardless of the level of the evidence in this study, it will be cited as supporting evidence in any future study with similar results, and, for this reason alone, it is imperative that overconfident conclusions or partial views of the data are not presented. If (and it’s a big ‘if’) about 1/2 hr of intense neural activity spread over 1 mo can alter the cellular properties of the major motor tract connecting the brain and spinal cord, then we need to understand the process and its implications.

**DISCLOSURES**

No conflicts of interest, financial or otherwise, are declared by the author(s).

**AUTHOR CONTRIBUTIONS**

Author contributions: all authors drafted the manuscript, revised it, and approved the final version.

**REFERENCES**