Magnetic muscle stimulation produces fatigue without effort

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IN DISEASE AND OLD AGE, muscle function decreases, and greater impairments in performance are associated with increased mortality (6, 9, 10). Although muscle strength and endurance can be assessed with voluntary exercise, measurements can be confounded by changes in the way the muscle is driven by the nervous system and by cardiorespiratory limitations. A means to measure muscle strength and endurance without volition could allow useful assessment of muscle properties and their importance independent of systemic influences.

To determine the fatigue properties of isolated muscles, the muscle is stimulated at a predetermined frequency, and the decline in force produced by a constant stimulus to the muscle is measured. To fatigue human muscles is often less straightforward. They can be fatigued by voluntary activity and the fatigue measured as either a decrease in force produced by a maximal voluntary contraction or as a decrease in the twitch force produced by maximal stimulation of the nerve to the muscle (e.g., Ref. 2). To produce fatigue, subjects can be asked to contract the muscle group maximally or to a submaximal target force. In both cases, neural drive to the muscle, as determined by voluntary and reflex inputs to the motoneurons, plays a part in determining the activity of the muscle. During maximal efforts, muscle is rarely driven to generate its maximal force, and as fatigue develops the ability to drive the muscle falls further. Hence, some of the loss of force of fatigue is not due to muscle properties but reflects failure within the nervous system (for review, see Ref. 5). Furthermore, even if muscle is driven maximally, this does not mean that the frequency of motor unit firing is the same in different subjects. For example, women tend to have slower muscle kinetics than men for biceps brachii (e.g., Ref. 7). Thus full force from the muscle should be generated by lower motor unit firing rates, so that after the same period of maximal exercise, muscle fibers in men will have been activated more times than those in women. When fatigue develops during the performance of submaximal exercise, volitional drive is increased so that the target force is maintained by recruitment of more motor units (2, 11). This means that across the muscle, some muscle fibers will have undergone a lot more activity than others. It is also possible to treat a human muscle like an “isolated” muscle and electrically stimulate the nerve to the muscle or the intramuscular nerve fibers. Functional electrical stimulation is used frequently in people with spinal cord injury to produce high-force fatiguing contractions. However, in neurologically intact subjects, the major deterrent to producing fatigue through electrical stimulation is discomfort. While some subjects will tolerate the intensity and frequency of nerve or muscle stimulation required to produce fatigue, most will not. This is even more problematic in patient groups where subjects may be old or frail.

The article by Swallow and colleagues in the Journal of Applied Physiology (8) presents a new technique for stimulating human muscle at sufficient levels to produce fatigue without the local pain associated with electrical stimulation. As such, it presents a practical rather than conceptual advance that will allow clinical testing of muscle endurance and will aid in research studies of muscle fatigue. Stimulation of quadriceps was carried out using repetitive magnetic stimulation (Magstim Rapid®) via a large, flexible oval coil that could be wrapped securely over the front of the thigh. The coil was fluid cooled to prevent overheating. In magnetic stimulation, a quickly changing magnetic field is generated by a pulse of current flowing through a coil of wire. The magnetic field in turn generates a current inside the body, and this depolarizes axons in the same way as an electrical stimulus (1). The advantage is that with magnetic stimulation the current does not have to pass through the relatively high resistance of the skin so that nociceptors in the skin are not activated. The flexible coil is also an advance over a stiff coil because it allows better coupling of the magnetic field with the tissue. It is not clear how well this technique could be adapted to muscle groups other than quadriceps. It is likely that the knee flexors could also be activated successfully, but smaller coils may need to be developed for other muscles.

Swallow and colleagues (8) chose to stimulate the quadriceps muscle at 30 Hz with an intensity sufficient to produce 30% of the maximal twitch force and an intermittent pattern of 2-s contraction and 3-s rest. By the end of 50 trains of stimuli, the force produced fell by ~35% in control subjects. In patients with severe chronic obstructive pulmonary disease, the same protocol resulted in greater fatigue, showing poorer endurance of the muscle. Muscle biopsy confirmed different muscle properties in the two groups with a reduced proportion of type 1 fibers and a reduced oxidative capacity in the patients’ muscles. Thus the technique provides a noninvasive, well-tolerated way to determine human muscle properties, in particular, endurance. A measure of endurance, the time for force to fall by 30%, had acceptable reliability between days. Other muscle properties that were not measured but could be informative during the fatiguing stimulation protocols include contraction and relaxation rates.

Some uncertainty is introduced into the mechanisms of fatigue in this study because stimulus artefact prevents recording of the electromyogram (EMG) during stimulation. Thus decreases in motor axonal excitability, which would reduce the number of muscle fibers activated (12), and block at the neuromuscular junction or impairment of muscle membrane excitability because of the frequency of stimulation cannot be excluded (4). Such mechanisms are rarely important in fatigue in voluntary contractions but may contribute with this submaximal stimulation technique. However, combining remote nerve stimulation with magnetic stimulation over the muscle should allow such contributions to be determined. Other questions, such as whether, in addition to direct motor axon activation, the stimulus evokes force reflexly through activation of the Ia afferents, may not be
answerable (3). Similarly, it may be difficult to determine whether antagonist muscles are also stimulated and contributing to force measurements.

The stimulation probably activates the intramuscular fibers of the nerves innervating quadriceps. This suggests that the muscle fibers that are stimulated will be a random cross-section of fiber types with the likelihood of stimulation largely dependent on the location of the innervating axons relative to the magnetic coil. The current generated by the magnetic pulse should be strongest under the edges of the coil rather than in its center and will reduce with depth (1). Thus a submaximal contraction produced by this stimulus will not mimic a voluntary contraction that preferentially recruits slower fatigue-resistant fibers. Stimulation should recruit a subset of fibers that are reasonably representative of the whole muscle.

Apart from clinical testing of muscle endurance, possible uses for nonvolitional muscle activation without discomfort include as a substitute for functional electrical stimulation to preserve muscle mass and improve muscle strength and endurance in patients with intact sensation. Of course, feasibility may be limited by the cost of the stimulator. In research, the technique is likely to allow much better comparison of findings in isolated muscle with those in human subjects. It should allow the same protocols to be applied in both conditions so that the behavior of the stimulated human muscle in vivo can act as a step toward translating findings from isolated muscles to voluntary contractions. A proviso here is that the effects of axonal excitability changes and afferent stimulation are considered. Magnetic muscle stimulation may also have an advantage over electrical stimulation in comparing muscle performance from day to day. Careful positioning of the coil may allow forces to be evoked reproducibly with the same stimulus intensity. This could be helpful in determining changes in tetanic forces, as well as changes in other muscle properties with pathology, after exercise, or with training, when changes in voluntary forces are confounded by altered neural drive.

REFERENCES