

## Tired of fatigue? Factors affecting the force-length relationship of muscle

One of the fundamental properties of skeletal muscle, the force-length relationship (FLR), originally served as primary evidence for the sliding filament model of force generation (4). Past work has examined factors that may affect a muscle's FLR, with evidence that the force depression of fatigued muscle correlates with a rightward shift in the muscle's force-length (FL) behavior (3, 10). This would imply that fatigued muscles favor force generation at longer lengths, possibly due to stretch of series elastic elements resulting in sarcomeres contracting at a shorter length. In a recent study reported in this issue of the *Journal of Applied Physiology*, MacNaughton and MacIntosh (7) show that when the series elastic compliance of a whole muscle (rat medial gastrocnemius) and its aponeurosis and/or tendon is taken into account, force depression resulting from fatigue via repetitive in situ muscle stimulation does not result in a substantial rightward shift in the muscle's FLR. The authors demonstrate this by using sonomicrometry (6) to measure directly muscle fascicle length in situ, finding no significant change in fascicle length before and after fatigue. The use of sonomicrometry allows the authors to show a potential problem with previous interpretations of the rightward shift in FLR due to fatigue. The current method of calculating active force uses the passive force at the actual fascicle length during contraction, instead of the passive force at the length of the inactive muscle.

The authors' method for evaluating the length behavior of the muscle's fascicles directly via sonomicrometry represents an important application of this technique for distinguishing the length change of a muscle's contractile component vs. its series elastic component. The authors note, however, that this effect will be less important for muscles having less connective tissue and, as a result, less series elastic compliance. The gastrocnemius of rodents, like humans, is a muscle that has considerable passive stiffness. Therefore, the author's results should be considered in this context. Past results showing a rightward shift in FL behavior after fatigue largely involved muscles with less connective tissue and a lower passive stiffness (3, 12).

Other aspects of fatigue may also contribute to the observed force depression. Gauthier et al. (3) hypothesized that a rightward shift in the FL curve of fatigued muscles might be explained by a disruption of membrane depolarization into the T-tubule system at short muscle lengths, consistent with measurements showing reduced sarcoplasmic reticulum release of  $\text{Ca}^{2+}$  after fatiguing contractions (14). This possibility is not addressed by the correction of MacNaughton and MacIntosh (7) for determining the FLR for submaximally stimulated muscle. Nevertheless, the authors' results therefore indicate that force depression after fatigue is more likely caused by factors underlying muscle activation rather than being due to myofilament overlap. The authors' findings also suggest that fatigue should not result in a rightward shift of the FL relationship for isolated single muscle fibers. To our knowledge, this shift in the FLR has not been addressed, even though many cellular mechanisms of fatigue have been examined in muscle fibers (14). It

would seem important to test, however, because this experiment would provide direct insight into whether force generation by the contractile elements of a muscle is significantly affected by fatigue.

It is also important to note that a rightward shift in the FLR is observed under conditions of submaximal stimulation for both whole muscles (9), as well as for isolated muscle fibers (11). This shift has generally been considered to result from a change in  $\text{Ca}^{2+}$  sensitivity due to differences in myofilament spacing at short vs. long muscle lengths (2, 13).

Despite the possibility that other factors may underlie observed patterns of force depression after fatigue, the use of sonomicrometry by MacNaughton and MacIntosh (6, 7) highlights the value of the ability of this method to discriminate between length changes of a muscle-tendon unit as a whole vs. the muscle fascicles themselves. This difference has been important in studies of in vivo muscle function, which have shown that muscle-tendon length changes may differ substantially from those of the muscle's fascicles (5), as well as for different segments of the muscle (1).

The extent to which fatigue has a less exaggerated effect on the FLR of a submaximally stimulated muscle deserves further attention, and the authors' study (7) highlights the importance of this. Given that fatigue causes force depression by mechanisms other than those resulting from length effects on myofilament force generation (8, 14), such mechanisms need further study. Because of these findings, it seems likely that exercise-induced fatigue and diminished motor performance are not directly the result of changes in a muscle's FL properties.

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