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Original article

Predictors of residual force enhancement in voluntary contractions of elbow flexors

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Abstract

Background: The steady-state increase in muscle force generating potential following a lengthening contraction is called *residual force enhancement* (RFE). In this study, we aimed to test for differences in torque, electromyographic activity (EMG), and the associated neuromuscular efficiency (NME) between isometric voluntary contractions of elbow flexors preceded and not preceded by a lengthening contraction. The dependence of such differences on (i) stretch amplitude, (ii) the region of the force−length (FxL) relationship where contraction occurs, and (iii) the individual's ability to produce (negative) work during the stretch was investigated.

Methods: Sixteen healthy adults participated in the study. Elbow flexor torque, angle, and biceps brachii EMG for purely isometric contractions (reference contractions) and for isometric contractions preceded by active stretches of 20° and 40° were measured at the ascending, plateau, and descending regions of subject-specific FxL curves. All contractions were performed in an isokinetic dynamometer. Two-factor (stretch × FxL region) repeated measures analysis of variance was used to analyze the effect of active stretch on EMG, torque, and NME across conditions. The relationships between mechanical work during stretch—calculated as the torque--angular displacement integral—and the changes in EMG, torque, and NME were analyzed using Pearson correlation.

Results: In general, torque, EMG, and NME following active stretches differed from the values observed for the purely isometric reference contractions. Although the detailed effects of active stretch on torque and EMG differed between regions of the FxL relationship, NME increased by about 19% for all muscle lengths. Up to 30% of the interindividual variability in torque generating potential change in response to active stretching was accounted for by differences in (negative) work capacity between subjects.

Conclusion: Our results suggest that (i) RFE contributes to "flatten" the elbow flexor torque−angle relationship, favoring torque production at lengths where the purely isometric torques are reduced substantially, and (ii) RFE contributes to a reduction in energy cost of torque production during isometric contractions for the entire operating range.

Keywords: Force-length; History-dependent properties; Neuromuscular efficiency; Upper limb; Voluntary contractions

1. Introduction

The capacity of a muscle to produce force is known to depend on the history of contraction.[1−3] Contraction histories that lead to an increase in force compared to the force predicted by the force--length (FxL) and force--velocity relationship have been of special interest to the scientific community. If we stretch an activated muscle and then hold it at a constant length, its isometric force, even after achieving a steady state, will exceed the force obtained if the muscle had been taken to that same length passively and then activated. This difference in isometric force production as a result of a previous active stretch is called *residual force enhancement* (RFE) and has been observed in *in vitro/in situ* muscle preparations ranging from the sarcomere to the muscle tendon unit level.[4−7] Depending on the experimental conditions, the magnitude of RFE can vary from no force enhancement to an increase of 400%.[8]

Despite the general acceptance of RFE as an important muscle property, its role in human movement, and the

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underlying mechanisms that are responsible for its occurrence remain a matter of debate.[9,10] Human movements comprise a wide range of muscle contraction velocities, and eccentric contractions are an essential part of many everyday functional tasks.[11,12] The occurrence of RFE *in vivo* has been confirmed in most previous studies.[10,13–16] However, the observed increase in force output is generally less "dramatic" *in vivo* than it is *in situ* or *in vitro*, and results are less consistent than those described for isolated or *in situ* muscle preparations. For the special case of human voluntary contractions, the greatest mean value of RFE reported in the literature is approximately 16%.[10,13,17,18]

To our knowledge, with the exception of some studies on the thumb adductors in the hand[18–20], and 1 recent investigation on RFE and bilateral force deficit in human elbow flexors,[21] no information is available regarding the role of RFE in upper limb muscles. Flexor muscles in the upper limb typically do not bear body weight but nevertheless are frequently exposed to eccentric contractions when carrying objects and weights.[22] In comparison to lower limb muscles, contractions of upper limb muscles usually have little tendon strain that would affect the relative length changes between fascicles and entire muscle tendon units during everyday movements.[23–26] Considering that history-dependent properties are thought to be related to changes in the contractile element length, it may be that RFE is more pronounced in upper limb than lower limb muscles.

Contraction of the elbow flexors often involves large changes in muscle length.[23,27] In addition, the operating range of the elbow flexors is often found to include the ascending, the plateau, and the descending region of the FxL relationship, a feature that is not commonly observed in other muscles of humans.[28–30] This wide excursion of the elbow flexor muscles, with sarcomeres reaching lengths beyond 3.2 μm,[31] provides a unique opportunity for analyzing RFE in the different regions of the FxL relationship during voluntary contractions. Although it has been suggested that RFE is greatest on the descending limb of the FxL relationship in isolated fiber and muscle preparations,[2,32,33] the dependence of RFE on the regions of the FxL relationship has not been systematically analyzed for voluntary contractions.

One important factor to keep in mind when analyzing RFE in human muscles is the complex neuromuscular control involved in voluntary force production. Maximal voluntary activation is harder to achieve for eccentric than concentric and isometric contractions.[34] Maximal work/torque achieved during voluntary eccentric contractions is only a fraction of what a muscle could do if a neural regulatory mechanism did not limit the recruitment and/or discharge of motor units during eccentric contractions.[34,35] Since force enhancement mechanisms are thought to take place during the stretch and to depend on the activation and effort level,[19,36] the difficulty in reaching a truly maximal eccentric force may limit RFE in voluntary contractions.

In addition, it has been suggested that activation—or its *in vivo* proxy, the electromyogram—seems to depend on the history of contraction. Oskouei and Herzog[19,36] and Jones et al.[37] showed that the activation required to exert a given submaximal force with the thumb adductor muscle is less if the contraction is preceded by active lengthening. In addition, Joumaa and Herzog[38] found that the metabolic energy cost of force production (ATP consumption per unit of force) was reduced after active stretch in skinned fibers of rabbit psoas muscle. It may be possible that the role of RFE in human voluntary contractions is mostly related to a reduction in metabolic energy rather than an increase in maximum force output.

In this study, we aimed to test whether RFE occurs in voluntary contractions of the human elbow flexors and to examine if RFE depends on the region of the FxL relationship and the stretch amplitude. RFE was quantified by analyzing the maximum torque-generating potential on the ascending, plateau, and descending regions of the FxL relationship, and by measuring the corresponding electromyographic activity (EMG) and neuromuscular efficiency (NME) of the biceps brachii muscle for purely isometric reference contractions and for isometric contractions preceded by an active stretch ("enhanced contractions"). In addition, the dependence of RFE on the individual capacity for producing (negative) work during stretch was evaluated.

We expected that RFE in the elbow flexors would manifest itself by (i) an increase in torque-generating potential and/or (ii) an increase in the NME of torque production. In addition, we expected RFE to be (i) greatest on the descending limb of the FxL relationship, (ii) greater for long compared to short stretches, and (iii) positively related to the subjects' capacity to produce (negative) work during stretch.

2. Methods

2.1. Subjects

Sixteen subjects (8 males and 8 females) participated in this study. All subjects gave free, written, informed consent, and all procedures were approved by the Human Research Ethics Board of the Federal University of Santa Catarina. The following inclusion criteria were observed: (i) age between 18 and 35 years; (ii) active in strength training for at least the past 6 months; and (iii) in good general health and having no pain, injuries, or surgeries in the shoulder, elbow, or wrist. Mean ± standard deviation (SD) age, height, and weight were 26 ± 5 years, 170 ± 9 cm, and 69 ± 6 kg, respectively.

2.2. Instruments

Elbow flexor torques were measured using a Biodex Multi-Joint System 4 isokinetic dynamometer (System 4 Pro; Biodex Medical Systems, Shirley, NY, USA). Subjects were seated with the back and legs supported and the hip and knee joint at 80° and 90° of flexion, respectively. The dynamometer was oriented at 30° to the chair in the transverse plane. Position and height of the dynamometer and chair were adjusted such that the elbow flexion axis (center of the trochlea and capitulum) was aligned with the axis of the dynamometer arm. The shoulder was positioned at 30° of flexion and 30° of abduction using a goniometer (Goniometer G-20; Arktus, Santa Tereza

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