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Original article

Activation reduction following an eccentric contraction impairs torque steadiness in the isometric steady-state

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Abstract

Background: The isometric steady-state following active lengthening is associated with greater torque production and lower activation, as measured by electromyographic activity (EMG), in comparison with a purely isometric contraction (ISO) at the same joint angle. This phenomenon is termed residual force enhancement (RFE). While there has been a great deal of research investigating the basic mechanisms of RFE, little work has been performed to understand the everyday relevance of RFE. The purpose of this study was to investigate whether neuromuscular control strategies differ between ISO and RFE by measuring torque steadiness of the human ankle plantar flexors.

Methods: Following ISO maximal voluntary contractions in 12 males (25 years), an active lengthening contraction was performed at 15°/s over a 30° ankle excursion, ending at the same joint angle as ISO (5° dorsiflexion; RFE). Surface EMG of the tibialis anterior and soleus muscles was recorded during all tasks. Torque steadiness was determined as the standard deviation (SD) and coefficient of variation (CV) of the torque trace in the ISO and RFE condition during activation-matching (20% and 60% integrated EMG) and torque-matching (20% and 60% maximal voluntary contraction) experiments. Two-tailed, paired *t* tests were used, within subjects, to determine the presence of RFE/activation reduction (AR) and whether there was a difference in torque steadiness between ISO and RFE conditions.

Results: During the maximal and submaximal conditions, there was 5%−9% RFE with a 9%−11% AR ($p < 0.05$), respectively, with no difference in antagonist coactivation between RFE and ISO ($p \geq 0.05$). There were no differences in SD and CV of the torque trace for the 20% and 60% activation-matching or the 60% and maximal torque-matching trials in either the RFE or ISO condition ($p \geq 0.05$). During the 20% torque-matching trial, there were ~37% higher values for SD and CV in the RFE as compared with the ISO condition ($p < 0.05$). A significant moderate-to-strong negative relationship was identified between the reduction in torque steadiness following active lengthening and the accompanying AR.

Conclusion: It appears that while the RFE-associated AR provides some improved neuromuscular economy, this comes at the cost of increased torque fluctuations in the isometric steady-state following active lengthening during submaximal contractions.

Keywords: Eccentric; Force steadiness; History dependence; Residual force enhancement; Tremor

1. Introduction

Residual force enhancement (RFE) is an intrinsic property of skeletal muscle and is characterized by an increase in isometric steady-state force following an eccentric (i.e., active lengthening) contraction, as compared with a purely isometric contraction (ISO) without prior lengthening.[1,2] This phenomenon has been observed from single sarcomeres[3] to the whole human level during electrically stimulated[4] and voluntary contractions.[5,6] While the mechanisms of RFE are still under debate,[7] it is clear that there is a greater contribution of passive force to overall total force production following active lengthening, as compared with an ISO.[8−11] Moreover, when matching isometric force (or torque) levels, the greater contribution of passive force in the force-enhanced state results in an activation reduction (AR), which is observed as a reduction in electromyographic activity (EMG)[5,12,13] and adenosine triphosphate usage.[14] Additionally, during torque- and activation-clamped experiments, the RFE EMG−torque relationship is shifted to the right as compared with ISO,[15] indicating lower activation to achieve a given torque level. The findings of a

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shifted EMG−torque relationship may indicate altered motor unit (MU) recruitment and rate coding strategies in the RFE state. Furthermore, a reduction in the number of active MUs is suggested to contribute to the AR in the RFE state.[16,17] Recent modeling experiments indicated that a greater number of active MUs facilitate the production of steady isometric forces.[18] Therefore, such alterations to neuromechanical coupling could be reflected in a divergence in torque steadiness in the ISO and RFE isometric steady-state following active lengthening, on the basis of reduced MU activation in the RFE state.

Torque steadiness represents the ability of an individual to precisely and accurately sustain a target torque level. Meanwhile, fluctuations in torque during voluntary contractions can produce variability in movement. Typically, lower torque fluctuations are associated with greater fine movement control.[19] Changes in torque steadiness (or force steadiness) have been observed in relation to age, sex, fatigue, physical activity level, contraction intensity,[20−23] and clinical conditions such as Parkinson's disease.[24] These variations in torque steadiness have been attributed to changes in MU size and motor neuron (MN) pool activation strategies.[18,20,25,26] Furthermore, it appears that torque steadiness depends mostly on the discharge characteristics of recruited MUs rather than on their force production capacity,[20] as demonstrated by the relationship between increasing variability of MU discharge rate and increased force fluctuation. For lower contraction intensities (e.g., 20% maximal effort), there is reduced torque steadiness and a higher MU discharge variability[27] than at higher intensity contractions. Eccentric contractions have also been shown to have greater torque fluctuations compared with concentric contraction or ISO,[20,28] which is likely due to the lower activation and therefore lower MU discharge rate that occurs in eccentric contractions. Collectively, torque steadiness represents the cumulative activity of the MN pool,[18,29,30] so the measurement of torque steadiness provides a quantitative measure of effective control signals from the nervous system. Therefore, fluctuations in torque during a submaximal task represent an important aspect of motor control, and measuring torque steadiness can offer insight into the control (or lack thereof) during everyday contractions that involve preceding movement/activation.

While there has been a great deal of research investigating the basic mechanisms of RFE, little work has attempted to understand its everyday relevance.[5] Therefore, the purpose of this study was to investigate whether neuromuscular control strategies differ between ISO and RFE by measuring torque steadiness during both torque- and activation-matching conditions. Torque steadiness (i.e., standard deviation (SD) and coefficient of variation (CV) of the torque trace) is not expected to differ during the activation-matching experiments because MU recruitment factors potentially affecting torque steadiness should not differ. However, torque is expected to be less steady in the RFE conditions during the torque-matching experiments, owing to the stretch-induced decrease in activation necessary to achieve an equivalent torque output as in the ISO condition.

2. Methods

2.1. Participants

Data were collected within a single testing session from 12 healthy males (25 ± 4 years, 178 ± 7 cm, and 75 ± 9 kg). Males who were 18−35 years old without a history of neurologic, vestibular, and neuromuscular disorders or musculoskeletal injuries in the lower limb were recruited. Participants gave informed, written consent, and all procedures were approved by the University of Guelph Research Ethics Board and conformed to the Declaration of Helsinki.

2.2. Experimental set-up

A HUMAC NORM dynamometer (CSMi Medical Solutions, Stoughton, MA, USA) was used to record all torque, angular velocity, and position values. The participants were seated with their right hip at 90° of flexion and right knee at 100° of extension, with their medial malleolus aligned with the dynamometer's axis of rotation. Flexion at the knee reduced the contributions of the gastrocnemius to plantar flexion (PF) torque, allowing for changes in PF EMG to be attributed primarily to the soleus.[31] The right knee was immobilized with the dynamometer's leg restraint positioned superiorly over the distal femur. Movement at the torso was restricted with a 4-point seatbelt harness. The right foot was fixed to a dorsi/plantar flexor dynamometer foot pedal adaptor with 1 inelastic strap and a custom-built ratchet tightening strap positioned over the ankle and another inelastic strap at the mid-distal portion of the metatarsals (Fig. 1A). The maximum PF and ankle dorsiflexion (DF) angles were set to 25° and 5°, respectively, allowing for 30° of ankle excursion to optimize stretch on the plantar flexors.

Prior to EMG electrode placement, skin locations were thoroughly shaven and cleaned with alcohol. Silver-silver chloride (Ag/AgCl) electrodes (1.5 cm × 1.0 cm; Kendall, Mansfield, MA, USA) were used for all EMG recordings. As described previously,[32] 1 electrode was placed on the soleus along the midline of the lower leg approximately 2 cm inferior to the border of the gastrocnemius muscle, a second electrode was placed on the calcaneal tendon, and a ground electrode was placed on the patella. To record antagonist muscle activation, 1 electrode was positioned over the right tibialis anterior approximately 7 cm inferior and 2 cm lateral to the tibial tuberosity, and a second electrode was placed over the distal tendon of the tibialis anterior. Torque, angular position, and stimulus trigger data were sampled at 1000 Hz using a 12-bit analog-to-digital converter (PowerLab System 16/35; ADInstruments, Bella Vista, Australia). The EMG data were sampled at 2000 Hz and band pass filtered between 10 and 1000 Hz. All data were analyzed with LabChart software (Version 8.0; ADInstruments).

2.3. Nerve stimulation and maximal voluntary contractions (MVCs)

To normalize voluntary EMG, maximal compound muscle action potentials (M_{max}) at 5° DF were recorded from the