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 ANOVAs 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. While 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 underlying mechanisms that are responsible for its occurrence remain
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a matter of debate. Human movements comprise a wide
range of muscle contraction velocities, and eccentric contrac-
tions are an essential part of many everyday functional
tasks. The occurrence of RFE in vivo has been confirmed
in most previous studies. However, the observed in-
crease 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%.

To our knowledge, with the exception of some studies on the
thumb adductors in the hand and one recent investigation
on RFE and bilateral force deficit in human elbow flexors, 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 eccen-
tric contractions when carrying objects and weights. 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 ten-
don units during everyday movements. 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. This wide excursion of the elbow flexor
muscles, with sarcomeres reaching lengths beyond 3.2 μm, provides
a unique opportunity for analyzing RFE in different
regions of the FxL relationship during voluntary contrac-
tions. Although it has been suggested that RFE is greatest on the
descending limb of the FxL relationship during voluntary contrac-
tions, 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. 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 dur-
ing eccentric contractions. Since force enhancement
mechanisms are thought to take place during the stretch and to
depend on the activation and effort level, 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 and Jones et al.
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 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 vol-
untary contractions is mostly related to a reduction in meta-
boelectric energy rather than an increase in maximum force output.

In this study, we aimed to test whether RFE occurs in vol-
owntary 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 meas-
suring the corresponding electromyographic activity (EMG)
and neuromuscular efficiency (NME) of the biceps brachii
muscle for purely isometric reference contractions and for iso-
metric contractions preceded by an active stretch (“enhanced
contractions”). In addition, the dependence of RFE on the indi-
vidual 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’ relative
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 follow-
ing 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 capitul-
um) 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; Artkus, Santa Tereza
do Oeste, PR, Brazil). Active submaximal isokinetic elbow
flexions were performed to verify that the dynamometer and
elbow joint axes remained aligned throughout the entire range of motion. In case of noticeable misalignment, subjects were repositioned until proper alignment throughout the entire active range was achieved. Straps across the thorax, waist, and thigh were used to stabilize subjects. Support to the elbow was provided at the distal part of the humerus using the appropriate accessory provided by the Biodex system. No straps were used around the arm. A tape was placed on the padding of the support accessory marking the edge of the olecranon. This position was maintained throughout all trials. Full extension was defined as 0°. The forearm was kept in the supinated position by adjusting the grip lever accordingly.

Surface EMG of the biceps brachii was recorded using a Miotool 400 EMG system (Miotec Equipamentos Biomédicos Ltda., Porto Alegre, RS, Brazil). Bipolar electrodes (interelectrode spacing 20 mm) were placed at one-third along a line from the cubital fossa to the medial acromion, and a ground electrode was placed on the mid-third of the clavicle. Before placing the electrodes, the skin was shaved and cleaned with alcohol. Skin impedance was checked (Multimeter Fluke 115, Everett, WA, USA) and pronounced acceptable if it was less than 5 kΩ. If it was greater than 5 kΩ, the electrodes were removed and skin preparation continued. The software Miotec Suite 1.0 (Miotec Equipamentos Biomédicos Ltda., Porto Alegre) was used for acquiring synchronized data of EMG, torque, and position at 1000 Hz. NME was defined as the ratio between torque and EMG for each contraction. Weight and height of the participants were measured using a scale and a stadiometer (Soehnle Professional; Soehnle, Backnang, Germany).

2.3. Procedures

After being fully informed about the experimental protocol, subjects took part in a standardized warm-up, which consisted of 15 submaximal concentric elbow flexion and extension repetitions at 120/s from 40° to 140°. Following warm-up, the elbow angle of maximal isometric flexor force was identified. Subjects were asked to perform 2 maximum isometric voluntary contractions (MIVCs) at 80°, 90°, and 100° of elbow flexion. The force-generating potential at each angle was then compared for the three angles by accounting for the modeled changes in moment arm at these positions.39 If the estimated force was greatest at either 80° or 100°, another 2 contractions were performed at 70° or 110°, respectively, and this procedure was repeated until the position of maximal force was uniquely identified. This position was then defined as the plateau of the FxL relationship (αplateau). From this position, an angle corresponding to the ascending limb (αplateau + 30°) and an angle corresponding to the descending limb (αplateau – 40°) of the FxL relationship was identified. At each of the three angles (αplateau, αplateau + 30°, αplateau + 30°), maximum voluntary contractions were performed to achieve the aims of this study. These sets of maximal contractions included (i) a purely isometric contraction, (ii) 2 maximum isometric contractions preceded by a “long” active stretch of 40°, (iii) 2 maximum isometric contractions preceded by a “short” active stretch of 20°, and (iv) a final isometric contraction. The order of stretch amplitudes (ii and iii of the series) and the 3 elbow angles corresponding to the different regions of the FxL was randomized. For the ascending limb testing, only the short active stretch could be performed because most subjects could not reach the initial angle needed for the long stretch (αplateau + 30° + 40°). For the isometric reference contractions, subjects were instructed to exert maximum contractions for a period of 5 s. For the stretch-isometric test contractions, subjects were instructed to perform a maximum isometric contraction for 2 s at the initial length, followed by the active stretch, and then by an isometric contraction of 3 s. All stretches were performed at 90°/s. Verbal encouragement and visual feedback of the elbow flexor torque were provided to subjects during all contractions. To minimize fatigue, a rest period of at least 2 min between contractions was strictly enforced and was extended upon a subject’s request.

All contractions were repeated once, and the contraction with the higher torque was used for analysis. The difference between the initial (i) and final (iv) MIVC was less than 10% for all subjects. Elbow angle, torque, and EMG were exported to MATLAB (R2013a; MathWorks, Natick, MA, USA), and a processing routine was used to analyze the data. Torque data were low pass filtered using a fourth-order, recursive Butterworth filter with a cut-off frequency of 10 Hz and were normalized to the MIVC torque at the plateau of the FxL relationship (1 s window around the peak torque). Passive torques after all contractions were also measured (1 s window, 1 s after deactivation), and the passive torques from the purely isometric reference contractions were subtracted from the corresponding stretch-isometric test contractions. EMG data were band pass filtered at 20–500 Hz and rectified. A linear envelope EMG was then calculated by using a low pass, recursive Butterworth filter at 6 Hz. EMG data were normalized to the corresponding MIVC EMG at each angle. Mean normalized EMG, torque, and NME were determined for the isometric reference and for the isometric contractions preceded by the long stretch and the short stretch contractions at each FxL region. Each set of comparisons (long stretch × isometric; short stretch × isometric) was synchronized, and a 500 ms window at 1 s following the end of the stretch was analyzed. Onset of contractions was identified when the elbow flexor torque exceeded the baseline noise by 3 SDs. For comparisons across stretch amplitudes and the different regions of the FxL relationship, all primary outcomes were normalized and expressed as percentage differences from the reference contractions. The (negative) mechanical work during stretch was calculated as the torque–angular displacement integral, normalized by maximum torque (MIVC). This normalization process was performed to account for strength differences among subjects and the resulting unit of work is MIVC°. The peak torque produced at the plateau of the FxL relationship)

2.4. Data analysis

SPSS Version 23.0 software (IBM Corp., Armonk, NY, USA) was used to analyze the data. Mean ± SD across subjects were calculated for normalized torque, EMG, and
NME. Normality of the data was tested using the Shapiro-Wilk test. A 2-factor repeated measures analysis of variance in a linear mixed model approach was used to analyze the effects of stretch (no stretch (isometric reference contraction), short stretch, and long stretch) and the potential interaction between stretch and the regions of the FxL relationship (ascending, plateau, and descending regions) for each outcome measure independently (torque, passive torque, EMG, NME). Significant interactions or main effects were followed up with multiple comparisons between conditions using Bonferroni corrections. Following this initial analysis, a second 2-factor repeated measures analysis of variance was used to analyze the differences in percentage changes of EMG, torque, and NME from the isometric reference conditions between stretch amplitude (short, long) and the regions of the FxL relationship (ascending, plateau, and descending regions). The relationship between the normalized work performed during active stretching and the percentage changes in EMG and torque that could be associated to an increase in NME for each stretch amplitude and for each FxL region was tested using a one-tailed Pearson correlation. An $\alpha$ level of 0.05 was used for all statistical tests.

3. Results

Descriptive statistics for torque, EMG, and NME across conditions are shown in Table 1. A significant interaction between the effect of active stretch and the FxL curve region was observed for torque ($F(2, 33.700) = 9.052, p = 0.001$; Table 1). The elbow flexor torque was significantly decreased following active stretching compared to the isometric reference contraction at the plateau (but not at the ascending and descending limbs) region of the FxL relationship ($F(2, 33.700) = 9.052, p = 0.001$) for both the short ($p = 0.008$) and the long stretch magnitude ($p = 0.002$; Fig. 1).

There was no significant interaction between active stretch and region on the FxL relationship for EMG or NME ($F(2, 49.701) = 1.067, p = 0.372$ and $F(2, 51.937) = 0.371, p = 0.745$, respectively). There was a significant reduction in

| FxL curve region    | Contraction   | Torque* (MIVC) | EMG (MIVC) | NME         |
|---------------------|---------------|----------------|-------------|-------------|
| **Ascending (plateau + 30°)** | Reference     | 0.65 ± 0.12    | 1.04 ± 0.14  | 0.63 ± 0.15  |
|                     | Short stretch  | 0.71 ± 0.15    | 0.92 ± 0.17  | 0.79 ± 0.18  |
|                     | Long stretch   | —              | —           | —           |
| **Plateau**         | Reference     | 0.96 ± 0.08    | 1.07 ± 0.16  | 0.90 ± 0.13  |
|                     | Short stretch  | 0.85 ± 0.11    | 0.84 ± 0.17  | 1.05 ± 0.24  |
|                     | Long stretch   | 0.85 ± 0.08    | 0.87 ± 0.26  | 1.05 ± 0.30  |
| **Descending (plateau − 40°)** | Reference | 0.68 ± 0.10    | 1.03 ± 0.14  | 0.67 ± 0.14  |
|                     | Short stretch  | 0.72 ± 0.14    | 0.97 ± 0.17  | 0.76 ± 0.17  |
|                     | Long stretch   | 0.70 ± 0.09    | 0.92 ± 0.12  | 0.78 ± 0.16  |

* Statistically significant interaction between stretch effect and the FxL curve region ($p = 0.008$).
† Normalized to angle-specific values.
‡ Statistically significant differences between short stretch and reference in Bonferroni ($p < 0.008$).
§ Statistically significant differences between long stretch and reference in Bonferroni ($p < 0.003$).

Abbreviations: EMG = electromyographic activity; FxL = force-length; MIVC = maximum isometric voluntary contraction; NME = neuromuscular efficiency.

There was no significant main effect of stretch on passive torque, regardless of the region of the FxL relationship or the amplitude of the stretch ($p = 0.889$). There was a significant main effect of FxL region on the percentage change in torque ($F(2, 48.205) = 29.905, p < 0.001$) and the percentage change in EMG ($F(2, 45.478) = 4.394, p = 0.018$) between the contractions preceded by active stretch and the isometric reference contractions (Fig. 2A, B). There was no difference between stretch amplitude for the percentage changes in torque ($F(1, 57.820) = 0.286, p = 0.595$) or EMG ($F(1, 57.524) = 0.123, p = 0.727$).

The percentage increase in NME observed for all contractions preceded by an active stretch was not statistically different across stretch amplitudes ($F(1, 50.930) = 1.054, p = 0.309$) or regions on the FxL curve ($F(2, 45.656) = 2.230, p = 0.147$).
p = 0.119). NME increased on average by 19% for contractions preceded by a stretch compared to the corresponding isometric reference values (Fig. 2C).

The normalized work performed during the stretch was $-18.3 \pm 7.9\text{ MIVC}^\circ$, $-17.2 \pm 2.8\text{ MIVC}^\circ$, and $-19.6 \pm 3.4\text{ MIVC}^\circ$ for the short active stretches performed at the ascending, plateau, and descending limb of the FxL relationship, respectively. For the long stretches, the normalized work performed was $-35.6 \pm 7.8\text{ MIVC}^\circ$ and $-35.4 \pm 6.6\text{ MIVC}^\circ$ for plateau and the descending regions of the FxL relationship. With the exception of contractions on the ascending limb, a normal distribution of the work performed by the different subjects during the stretch was observed. There was a significant moderate correlation between the normalized negative work and the percentage change in torque from the isometric reference for the short ($r = -0.544, p = 0.015$) and the long ($r = -0.491, p = 0.027$) stretch amplitude at the plateau of the FxL relationship (Fig. 3). Work was not significantly correlated to changes in EMG or NME.

4. Discussion

The primary aim of this study was to determine the role of RFE produced by different stretch magnitudes on the torque-generating potential and NME of the elbow flexors at the plateau, ascending, and descending limbs of the FxL relationship. In general, torque, EMG, and NME following active stretches differed from the values observed for the purely isometric reference contractions. While although the detailed effects of active stretch on torque and EMG differed between regions of the FxL relationship, NME increased in a similar manner for...
all muscle lengths. There was a substantial interindividual variability in torque-generating potential in response to active stretching, which was partly accounted for by differences in the (negative) work capacity between subjects.

RFE has been observed in isolated muscle preparations on the ascending limb, plateau, and descending limb of the length—tension relationship. We did not find enhancement in maximum torque-generating potential at any muscle length or stretch amplitude. Instead, we observed a reduction in torque potential following active stretching at the plateau of the FxL relationship, whereas torque potential was unaffected on the ascending or descending limbs.

Owing to the limited number of studies on in vivo RFE, and the different experimental conditions (amplitude of stretch, final muscle length, and muscle analyzed), comparisons across studies with regard to a possible dependence of RFE on the regions of the FxL relationship cannot be drawn easily. Previous studies on RFE at different muscle lengths opted to control for joint angles, neglecting what region of the FxL relationship on which the muscles might be working. Considering that the FxL relationship may shift with respect to the joint angle across individuals, and may shift depending on the level of activation, conclusions about the dependence of RFE on the FxL relationship are limited.

Following active stretching, the torque—angle curve was flatter than the corresponding curve for the purely isometric reference contractions (Fig. 1). Previous studies on human knee flexor and extensor muscles also revealed a joint dependence of voluntary contraction-induced RFE. For example, Shim and Garner found RFE for the knee extensors at 100° of knee flexion (long length) but not at 40°. They also reported significant RFE for the knee flexors at 10° of knee flexion (long length) but not at 70°. Similarly, Power et al. found greater RFE at long (100° of knee flexion) compared to short muscle length (60° of knee flexion). It seems, therefore, that the flattening of the torque—angle curve for muscles in the enhanced state is a result observed in human muscles other than those investigated here.

There was no increase in torque-generating potential after stretch in the elbow flexors in our study. At a casual glance, this might be interpreted as a lack of RFE in voluntary elbow flexor contractions. However, there was a mean increase in NME of 19% for the isometric contractions preceded by stretch, suggesting that some mechanism enabled greater force production for a given activation cost. Isometric force and EMG are not always related in a linear manner, and the greatest NME for the elbow flexors appears to occur at about 50% of MIVC. Therefore, an increased NME might be partly accounted for by this nonlinearity. The approximately 20% decrease in EMG observed at the plateau corresponds to a decrease in torque of approximately 15%, if we adopt the force—EMG relationship for submaximal contractions by Doheny et al. This reduction is slightly greater than the 11% observed experimentally in our study. On the ascending and descending limb of the FxL relationship, a small but nonsignificant increase in torque-generating potential was observed for contractions preceded by stretch despite a significant reduction in EMG. This is a clear indication of an increase in NME for these 2 regions, independent of any nonlinearity that may exist between force and EMG.

Since NME in the enhanced state was similar across all regions of the FxL relationship, our initial hypothesis of a greater RFE on the descending limb compared to the other regions of the FxL relationship is not supported. Rather, our results indicate that RFE may contribute to a more equal torque capacity of the elbow flexor muscles across their working range than is possible for purely isometric contractions not preceded by stretch, and that forces can be produced for less activation, and thus less metabolic cost, than otherwise possible. This finding suggests a variety of possible functional roles for voluntary muscle contractions following active muscle stretching besides other than the generally accepted notion of increased force potential.

It is generally accepted that RFE increases with the amplitude of muscle stretching in isolated muscle preparations. Bullimore et al. showed that RFE increased with stretch amplitude only when the extra stretch occurred on the descending limb of the FxL relationship. In our study, the comparisons between stretch amplitudes (40° and 20°) were always within a given region of the FxL relationship. Interestingly, however, the effect of stretch amplitude on EMG and on torque did not depend on the FxL region (Fig. 2).

Lee and Herzog reported that the effect of stretch amplitude on RFE differed between voluntary and electrically activated adductor pollicis muscle. Specifically, for the electrically stimulated muscle, they found the expected increase in RFE with increasing stretch magnitude. However, for the voluntary contractions, RFE increased from the smallest to the intermediate stretch amplitude, but then decreased from the intermediate to the greatest stretch amplitude, leaving the RFE for the shortest and longest stretches the same. Therefore, there is precedence in human voluntary contractions where stretch amplitude did not affect the amount of RFE or NME.

Despite the non-statistically significant difference between the 20° and 40° stretch for torque, EMG, or NME observed in our study, visual inspection of the percentage change in torque and EMG between the 2 stretch amplitudes shows a trend that deserves attention. Although an apparently greater reduction in EMG after the long stretch amplitude compared to the short stretch amplitude was observed, isometric torque after the long stretch tended to be higher than the isometric torque after the short stretch. This apparently paradoxical effect led to a 6% higher NME for the long compared to the short stretch condition. Although not statistically significant, this increase in NME for the increased stretch magnitude may provide some interesting functional advantages.

RFE during human in vivo voluntary contractions is not as consistent as that observed in isolated muscle preparations. We found a high intersubject variability for all outcome measures. Variable results have also been found by others who sometimes group people into responders (i.e., individuals who responded to the active stretch with a significant increase in torque) and nonresponders (i.e., individuals who did not present any residual force/torque enhancement after active
Although grouping subjects according to outcome should be done with caution (since a purely random result would give some positive and some negative torque changes), the strategy used in these studies highlights the need for a better understanding of individual characteristics that may favor RFE properties during voluntary contractions.

In our study, the differences in elbow torques between the isometric contractions following active stretch and the purely isometric reference contractions at the plateau region of the FxL relationship were shown to depend on an individual’s ability to produce work during the stretch. Mechanical work during muscle stretch has been suggested as a possible predictor of RFE in isolated extensor digitorum longus and soleus muscles from mice. However, in contrast to this previous study in which work was changed by changing the magnitude of stretch, we found that a significant linear relationship between work and torque change exists for a given stretch magnitude. Subjects who produced great relative eccentric work had a small loss in torque after stretch. Paternoster et al. found RFE for multijoint and torque change exists for a given stretch magnitude. Subjects we found that a significant linear relationship between work which work was changed by changing the magnitude of stretch, and torque after stretch. Paternoster et al. found RFE for multijoint and torque change exists for a given stretch magnitude. Subjects we found that a significant linear relationship between work and torque change exists for a given stretch magnitude. Subjects who produced great relative eccentric work had a small loss in torque after stretch. Paternoster et al. found RFE for multijoint and torque change exists for a given stretch magnitude. Subjects we found that a significant linear relationship between work and torque change exists for a given stretch magnitude.

We conclude from the results of our study that RFE contributes to a greater NME of the elbow flexors on the plateau and ascending and descending limbs of the FxL relationship. The increase in NME occurs without a significant increase in maximal torque-generating potential but is primarily caused by a reduction in EMG for similar torques, thus resulting in a greater torque/EMG ratio. Furthermore, the torque and EMG changes that ultimately result in the enhancement in NME differ in a characteristic manner based on the region of the FxL relationship. 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.

This study has limitations that need to be kept in mind when interpreting our results. First, maximum voluntary torque production is complex in nature and depends on multiple factors, such as motivation and familiarization. All subjects in our study were accustomed to performing elbow flexor contractions against high resistance, because only subjects with a minimum of 6 months’ experience in strength training were included. In addition, instructions were given consistently across trials by two researchers, and any fatigue- or motivation-related effect was controlled for by repeating the reference contraction from the beginning of testing at the end of each series of dynamic contractions. Second, FxL regions were identified for all elbow flexors as a group, whereas different muscles within an agonist group may present different FxL curves. Finally, the EMG of the biceps brachii muscle was used in our study as a measure of elbow flexor activation. The biceps brachii muscle has been shown to contribute most to the elbow flexor torque and was found to represent well the EMG of the remaining elbow flexor muscles during isometric contractions (e.g., Doheny et al. ). We acknowledge that EMG is merely a proxy for activation, but one that is generally accepted in human studies and one that probably works well for the steady-state situations analyzed here.

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Authors’ contributions

HdB conceived of the study, participated in the data collection and analysis, and drafted the manuscript; DdC helped to design the study, carried out the data collection and exploratory analysis, and helped to draft the manuscript; RLS wrote and ran the MATLAB routine for the data analysis and prepared graphs for the manuscript. All authors have read and approved the final version of the manuscript, and agree with the order of presentation of the authors.

Competing interests

The authors declare that they have no competing interests.

Supplementary materials

Supplementary data a video slider associated with this article can be found in the online version at https://doi.org/10.1016/j.jshs.2018.06.001.

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