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**Original Article**

# Influences of dynamic exercise on force steadiness and common drive

**X. Ye, T.W. Beck, N.P. Wages**

Department of Health and Exercise Science, University of Oklahoma, Norman, Oklahoma 73019, USA

**Abstract**

**Objectives:** To investigate the influences of dynamic exercise on force steadiness and common drive to motor units. **Methods:** Seventeen men (age 24±4 years; height 181.7±5.7 cm; mass 89.6±14.9 kg) performed 6 sets of 10 repetitions of maximal isokinetic concentric (CON) or eccentric exercise (ECC) with their dominant elbow flexors on separate experimental visits. Before and after the interventions, maximal strength testing and submaximal trapezoid isometric contractions were performed. To quantify force steadiness, we calculated the amplitude of force fluctuations in the flat area of the submaximal trapezoid contractions. In addition, surface electromyographic (EMG) signals from the same portion where we calculated the force steadiness were decomposed into individual motor unit action potential trains. The mean firing rate curves of the detected motor units were then cross-correlated with one another to quantify the common drive. **Results:** Although both interventions induced similar strength losses, the ECC caused greater force fluctuations ($p$=0.002). In addition, unlike the CON, which did not cause any changes in the common drive, the ECC induced an increased common drive to motor units. **Conclusions:** We believe that the increased common drive is an important factor causing greater force fluctuations following the ECC.

**Keywords:** Force Steadiness, Common Drive, Surface EMG Decomposition, Motor Unit, Muscle Spindle

## Introduction

Force steadiness is defined as a muscle's ability to maintain a force around a steady value[1,2], and it can be quantified as the amplitude of the force fluctuations during a constant force portion of a submaximal isometric contraction[1,3]. In addition, force steadiness has been used as a very important assessment to examine muscle functions under various conditions such as fatigue[4-6], aging[3], and resistance training[1,7-9]. For example, during a sustained submaximal isometric contraction, force fluctuations continue to increase due to muscle fatigue[10]. Furthermore, dynamic muscle actions such as concentric exercise (CON) and eccentric exercise (ECC) have been compared for their influences on force fluctuations[2,11]. Specifically, unlike CON, which has no particular effect on force fluctuations, ECC causes increases in both force fluctuations and surface electromyographic (EMG) amplitude during submaximal contractions[11].

An interesting fact of force steadiness is that the absolute steady/smooth force production (zero force fluctuations) can never be achieved, even at a very low force level[12,13]. This phenomenon reflects the control of motor unit activities during a voluntary muscle contraction[12,14]. Specifically, force production is regulated by two main parameters: the recruitment of motor units, and the motor unit firing behavior (motor unit firing rate, firing rates variability, motor unit firing synchronization, and common drive to motor units)[15,16]. Thus, many studies have examined the influences of these motor unit control parameters on force fluctuations; however, controversial findings were reported. For example, Tracy et al.[17] and Laidlaw et al.[18] found that the firing rate variability plays an important role increasing force fluctuations in elderly subjects. However, when comparing strength-trained vs. skill-trained individuals, the difference of their ability to produce a steady force was not affected by the firing rate variability of the active motor units, but more likely was due to the different levels of common drive and motor unit short term firing synchronization[19]. More

The authors have no conflict of interest. The authors state that this study has been approved by the University Institutional Review Board for human subject protection, and a written informed consent has been signed by each participant.

*Corresponding author: Xin Ye, Department of Health and Exercise Science, University of Oklahoma, 1401 Asp Ave. Room 104, Norman, OK 73019, USA E-mail: xin.ye-1@ou.edu*

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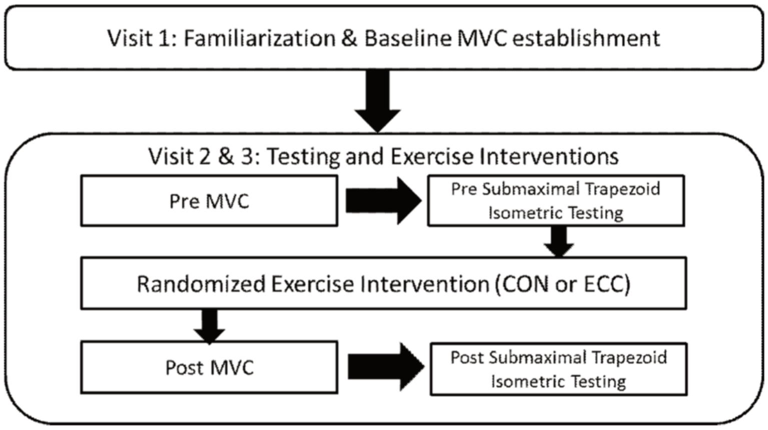


**Figure 1.** The experimental design of this study.

recently, Contessa et al.[12] examined the influences of several motor control parameters on force fluctuations: in addition to the motor unit recruitment during sustained isometric muscle contractions, the authors suggested that the increased force fluctuation is also primarily due to the increased level of common drive to motor units[12].

The concept of common drive was introduced by De Luca and his colleagues[20]: in order to relieve the burden of monitoring and regulating each motor unit separately, central nervous system (CNS) controls active motor units as a pool, instead of individually[20,21]. Specifically, after decomposing indwelling EMG signals from the deltoid and first dorsal interosseuous muscles into individual motor unit action potential trains (MUAPTs), the researchers cross-correlated the mean firing rate curves of the detected motor units, and they found high peak cross-correlation coefficients (r>0.6), thereby indicating that the motor unit mean firing rate curves fluctuated in a similar manner and magnitude at the same time (see Figure 1B in De Luca et al. (1982))[20]. Moreover, when cross-correlating the mean firing rate curves with force output, the peak cross-correlation coefficients were also high, but with a time lag of 0.2-0.3 seconds, thus to indicate that the changes in firing rate activity always preceded those in force output (see Figures 1A and 1C in De Luca et al (1982))[20]. Therefore, the common drive-induced simultaneous changes in the firing rates of the entire active motor neuron pool can influence the variation of force output (force fluctuations) during a constant muscle isometric contraction[1,22].

Recently, the development of a surface EMG decomposition technology has greatly improved researchers' ability to examine motor unit firing behavior[23]. This technology uses a complicated algorithm to decompose surface EMG signals into constituent MUAPTs. It is also important to mention that the accuracy of this decomposition technology has been improved substantially, with an average accuracy over 92%, and was generally greater than 95%[24,25]. A very recent study by Hu et al.[26] confirmed the accuracy of the decomposition algorithm, and suggested that using this algorithm to decompose surface EMG is valid and reliable[26,27]. In addition, this decomposition technology has been used to investigate common drive to motor units. For example, Beck et al.[1] examined the influences of an 8-week resistance training program on force steadiness and common drive for the vastus lateralis muscle. Although all the subjects became stronger after 8 weeks, the levels of force steadiness and common drive were not affected, thereby suggesting that the overall scheme used by the CNS to regulate motor unit recruitment and firing rate was not part of the neuromuscular adaptations during the early phase of resistance training[1].

To date, very few studies have investigated the acute effects of different types of dynamic exercise (CON and ECC) on common drive to motor units. Particularly, previous studies[2,11] showed that ECC induced greater magnitude of force fluctuations than concentric exercise did. Thus, it is interesting to examine whether or not this possible difference in force steadiness is related to the common drive to motor units following ECC. We expect that force steadiness will be impaired more following ECC when compared with that following CON. In addition, this greater decrement of force steadiness may be partially due to the increased common drive following ECC. This information can potentially be useful for researchers and clinicians alike, as it would help to increase knowledge regarding the effects of different types of dynamic exercises on the neuromuscular system. Obviously, other motor unit control parameters (e.g. newly recruited motor units during a sustained isometric contraction, variability of firing rate, synchronization of motor unit firings) may also influence force steadiness[12]. However, the main purpose of this study was to only investigate the influences of different types of dynamic exercise (CON and ECC) on force steadiness and common drive to motor units for the elbow flexor.

## Materials and methods

### *Experimental design*

This study used a cross-over design to examine the force fluctuations and common drive to motor units before (PRE) and immediately after (POST) two different types of dynamic exercise (CON and ECC). Three visits to the laboratory were required to complete the study. Figure 1 depicts the experimental design: the 1st visit was to familiarize the subjects with the experimental procedures. During the 2nd and 3rd visits, isometric strength and submaximal trapezoid isometric testing were performed before and immediately after the randomized exercise interventions. All testing and exercise interventions were performed on subjects' dominant arms.

*Subjects*

Seventeen men (mean±SD: age, 24±4 years; height, 181.7±5.7 cm; body weight, 89.6±14.9 kg) volunteered to participate in this study. The study was approved by the University Institutional Review Board, and all the subjects completed a health status questionnaire and signed a written informed consent before testing started. All subjects were resistance-trained (performed at least 3 sessions of resistance exercise training per week for at least 6 months before the study) and had no neuromuscular diseases. During this study, all subjects were instructed to refrain from any resistance exercise training.

*Familiarization and baseline isometric strength testing*

The 1st visit was to familiarize the subjects with the testing procedures, as well as to establish each subject's baseline isometric maximal voluntary contraction (MVC) of the elbow flexors. The determination of the dominant arm was based on subjects' throwing preference. Upon arrival, the subjects were instructed to sit in front of a custom-built isometric testing apparatus. The investigator then positioned the subject's wrist through a padded cuff which was connected to a load cell (Model SSM-AJ-500; Interface, Scottsdale, AZ). The subjects were asked to maintain their hand in the supinated position, and to apply a small amount of tension against the load cell. The length of the cuff around the wrist was then adjusted to ensure that the subject's arm and forearm were at a 90° elbow joint angle (Figure 2). With this body position, the subjects performed several submaximal isometric contractions for the purpose of warming up the forearm flexors. Once the subjects felt comfortable with this type of muscle action, they performed three separate 5-second isometric MVCs, with a 2-minute rest between each MVC. The highest MVC value was recorded as the baseline isometric MVC ( $MVC_b$). Once the isometric strength testing was completed, the subjects performed several submaximal trapezoid isometric forearm flexion muscle actions where they increased the force output linearly from 0% to 40% of the $MVC_b$ in 4 seconds, held the force output constant at 40% of the $MVC_b$ for 10 seconds, and then gradually decreased the force output from 40% to 0% of the $MVC_b$ in 4 seconds. A visual template was provided during these trapezoid muscle actions. All the subjects practiced this task several times until they could match the force production with the visual template with minimal fluctuations. The last task of the familiarization visit was involved performing the exercise interventions. Immediately after completion of the trapezoid isometric muscle action, the subjects were positioned in front of an isokinetic dynamometer (LIDO Multi-Joint, Loredan Biomedical, West Sacramento, CA, USA) where they could practice the two different exercise interventions: 10 maximal concentric isokinetic elbow flexion at a velocity of $60^{o}·s^{-1}$, followed by 10 maximal eccentric isokinetic muscle actions at the same velocity. The lever arm of the dynamometer was adjusted to ensure that the elbow joint of the exercising arm was visually aligned with the input axis of the dynamometer. This visit was concluded once the subjects finished practicing both exercise conditions in the dynamometer.

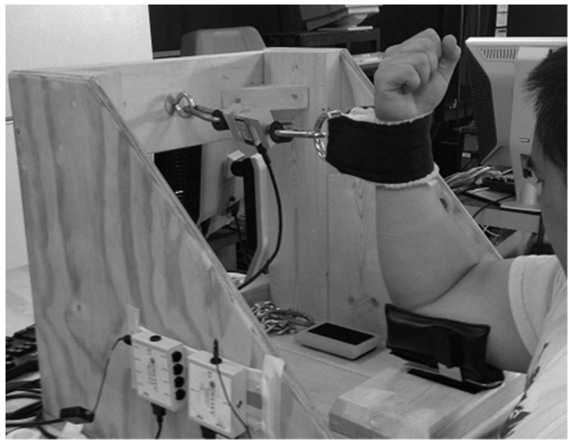

**Figure 2.** A subject performing an isometric muscle action.

*Trapezoid isometric testing and exercise interventions*

Seventy two hours after the first visit, the subjects returned to the laboratory for Visit 2 testing: the pre-isometric strength testing (PRE-MVC), the trapezoid submaximal isometric testing (PRE-submaximal testing), one of the randomly assigned exercise interventions (CON or ECC), the post-isometric strength testing (POST-MVC), and the trapezoid submaximal isometric testing (POST-submaximal testing). After a brief warm-up, the subjects performed a 5-second isometric MVC for the measurement of PRE-MVC. Five minutes after the isometric MVC, the subjects did a trapezoid isometric muscle action in exactly the same manner as they performed during the familiarization visit. Immediately after the trapezoid isometric muscle action, the subjects were positioned in front of the isokinetic dynamometer, where they performed one of the two randomly ordered exercise interventions: (1) 6 sets of 10 maximal concentric isokinetic elbow flexion at a velocity of $60^{o}·s^{-1}$ for the CON, or (2) 6 sets of 10 maximal eccentric isokinetic elbow flexion at a velocity of $60^{o}·s^{-1}$ for the ECC. One minute of rest was provided between the sets. Once the exercise intervention was finished, the subjects returned to the isometric strength testing apparatus for the POST-MVC and POST-submaximal testing in the exactly same manner as they performed during the pre-testing, and then this visit was concluded. The 3rd visit consisted of the exact same testing procedures and order as the subjects performed during Visit 2, except for the different exercise

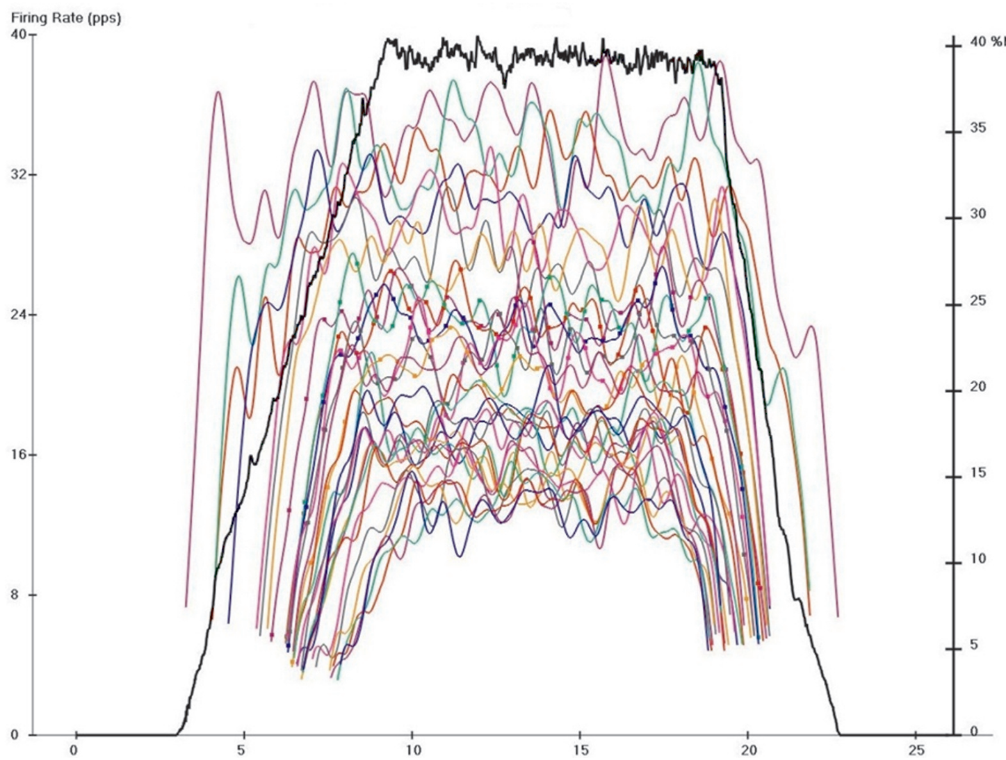


**Figure 3.** An example of average firing rate plots of the detected biceps brachii motor units during a trapezoid isometric contraction. *(X-axis: time scale (s). Y-axis left: motor unit firing rate PPS (pulse per second). Y-axis right: force task template (% MVC). The solid black line shows the trapezoid force output; notice the plateau of force (up to 40% of MVC) in the mid-10 seconds. It is also easy to observe the fluctuations of force in this region. Curves with different colors are mean firing rate curves of detected motor units during this trapezoid isometric muscle action).*

intervention. In addition, during all the submaximal trapezoid isometric contractions, technical difficulties prevented us from using the 40% of PRE- and POST-MVC values. Thus, the same absolute force levels (40% of the $MVC_b$) were used. Extra effort was made to ensure that the PRE-MVC value during each experimental visit was similar (within 2.5% difference) to the $MVC_b$ value.

*Surface EMG signal recording and motor unit decomposition*

Four separate bipolar surface EMG signals were detected from the biceps brachii during the trapezoid isometric muscle actions with a surface array sensor (dEMG sensor, Delsys, Inc., Boston, MA). Prior to placing the sensor over the muscle, the skin was shaved and cleansed with rubbing alcohol. The sensor was then placed over the belly of the biceps brachii and fixed with adhesive tape. The reference electrode (5.08 cm diameter Dermatrode HE-R, American Imex, Irvine, CA) was placed over the 7th cervical vertebrae. The four separate surface EMG signals were amplified (gain=1,000) with a modified Bagnoli 16-channel EMG system (Delsys Inc., Boston, MA). The signals were then filtered with a bandpass filter with cut-off frequencies of 20 Hz and 1,750 Hz, sampled at 20,000 samples/s, and then stored in a laboratory computer (Dell Optiplex 755, Round Rock, TX) for subsequent analyses. After acquisition, the four separate digitized EMG signals were served as the input to the Precision Decomposition III (PD III) algorithm (EMGWorks 4.0 Analysis, Delsys, Inc., Boston, MA), which is designed specifically for decomposing surface EMG signals into their constituent MUAPTs[23,25]. The algorithm then identified and analyzed the shape of each action potential, and assigned these MUAPTs to individual motor units. Once all the motor units were decomposed, the accuracy of each motor unit's decomposition was performed via the "reconstruct-and-test" procedure[25,28]. To reduce the potential influence of motor units with low decomposition accuracy, only motor units that could be decomposed with >90% accuracy were included for analysis in this study. For each individual motor unit, the average firing rates were plotted as a function of time and smoothed with a 400-ms Hanning window (Figure 3), which was originally described by De Luca et al.[20]. This Hanning window digital filter has also been used as a standard to analyze common drive of motor units in many studies[1,19,22] after the original publication[20].

*Measurements of force fluctuations and common drive*

The amplitude of the force fluctuations was quantified by calculating the coefficient of variation (CV= standard deviation ÷ mean × 100%) of the force output from the mid 5-s por-

| | CON | | | ECC | | |
|---|---|---|---|---|---|---|
| **Subject number** | **PRE MVC (N)** | **POST MVC (N)** | **MVC % decline** | **PRE MVC (N)** | **POST MVC (N)** | **MVC % decline** |
| 1 | 559.29 | 351.65 | 37.13 | 539.91 | 291.42 | 46.02 |
| 2 | 390.20 | 320.67 | 17.82 | 400.13 | 279.51 | 30.15 |
| 4 | 399.16 | 303.02 | 24.08 | 403.67 | 304.02 | 24.69 |
| 7 | 379.26 | 301.24 | 20.57 | 393.01 | 286.59 | 27.08 |
| 8 | 618.46 | 381.31 | 38.35 | 631.52 | 391.65 | 37.98 |
| 10 | 371.54 | 274.73 | 26.06 | 358.13 | 249.40 | 30.36 |
| 11 | 498.44 | 364.92 | 26.79 | 509.57 | 379.25 | 25.57 |
| 12 | 428.42 | 300.95 | 29.75 | 415.28 | 371.89 | 10.45 |
| 13 | 507.61 | 390.33 | 23.11 | 536.03 | 416.02 | 22.39 |
| 17 | 354.78 | 302.99 | 14.60 | 350.92 | 236.42 | 32.63 |
| 18 | 406.23 | 266.87 | 34.31 | 396.03 | 265.53 | 32.95 |
| 19 | 501.84 | 346.27 | 31.00 | 517.27 | 359.36 | 30.53 |
| 20 | 524.98 | 447.23 | 14.81 | 514.46 | 439.36 | 14.60 |
| 21 | 380.76 | 307.55 | 19.23 | 365.54 | 301.87 | 17.42 |
| 23 | 632.94 | 449.42 | 28.99 | 629.45 | 340.84 | 45.85 |
| 24 | 447.15 | 318.97 | 28.67 | 427.97 | 305.32 | 28.66 |
| 26 | 414.24 | 250.32 | 39.57 | 401.45 | 256.52 | 36.10 |
| **Mean** | 459.72 | 334.02 | 26.75 | 458.26 | 322.06 | 29.03 |
| **SD** | 86.96 | 57.65 | 7.85 | 90.81 | 61.27 | 9.69 |

**Table 1.** Individual subject data for the isometric elbow flexion isometric strength values before (PRE) and immediately after (POST) the exercise interventions (CON vs. ECC).

tion (mid flat portion of the force output, corresponding to 40% of the $MVC_b$) of each trapezoid isometric muscle action. Common drive was calculated by cross-correlating the plateau regions of the mean firing rate curves between concurrently active motor units[1,12,20,22,29]. Extra care was taken to ensure that the plateau regions of the mean firing rate curves selected for common drive calculation exactly matched the regions that have been selected for calculating the force fluctuations. In this study, all possible combinations of motor units were cross-correlated with one another[22]. For example, if 30 motor units were decomposed from one trapezoid isometric muscle action, then 435 (30 × 29 ÷ 2) separate cross-correlations would be performed, thereby generating 435 peak cross-correlation coefficients ($0<r<1.0$).

We then examined common drive mainly based on the distributions of the peak cross-correlation coefficients. To better visualize the distributions, total numbers of occurrence for peak cross-correlation coefficients at different ranges (r= 0.1-0.3, 0.3-0.5, 0.5-0.7, and 0.7-0.9) were counted. However, since different number of motor units was detected during different trapezoid isometric muscle actions, the total pairs of cross-correlations were also different. Thus, to compare the common drive between different exercise interventions and between different time points, we normalized the occurrence frequency for peak cross-correlation coefficients (normalized occurrence frequency for peak cross-correlation coefficients= number of occurrence for peak cross-correlation coefficients at the specific range ÷ total number of peak cross-correlation coefficients × 100%). For example, if 100 out of total of 400 peak cross-correlation coefficients fell in the 0.3-0.5 range, then the normalized occurrence frequency for peak cross-correlation coefficients corresponding to the 0.3-0.5 range would be 25%.

*Statistical analyses*

Two separate two-way [time (PRE vs. POST) × intervention (CON vs. ECC)] repeated-measures analyses of variance (ANOVAs) were used to analyze the isometric MVCs and the amplitude of the force fluctuations over time during the different interventions. When appropriate, follow-up analyses included paired-samples *t*-tests. In addition, to compare the general distributions of peak cross-correlation coefficients before and after different exercise interventions (PRE-CON vs. POST-CON; PRE-ECC vs, POST-ECC; PRE-CON vs. PRE-ECC; POST-CON vs. POST-ECC), 4 separate two-independent-samples Kolmogorov-Smirnov tests were used. All statistical tests were conducted using statistical software (IBM SPSS Statistics 19.0, IBM, Armonk, NY) with alpha set at 0.05.

## Results

*Isometric strength and force fluctuations*

Table 1 shows each individual's isometric strength values before and immediately after both exercise interventions. The intraclass correlation coefficient (ICC) for the PRE-isometric MVCs between the 2nd and 3rd visits was 0.987, with no significant difference ($p$=0.681)[30]. The results from the 2-way re-

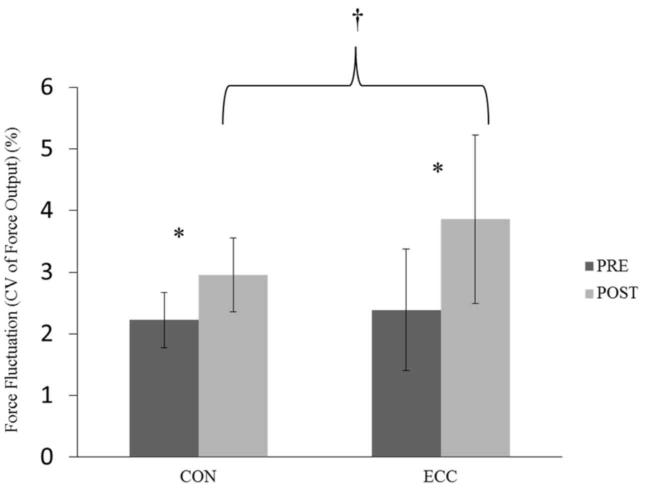


**Figure 4.** Mean force fluctuations (%) (CV of force output) for submaximal trapezoid isometric muscle action before and after both exercise interventions (CON and ECC). (**Significant increase in force fluctuation after an exercise intervention. † Significant difference between CON-POST and ECC-POST force fluctuations).*

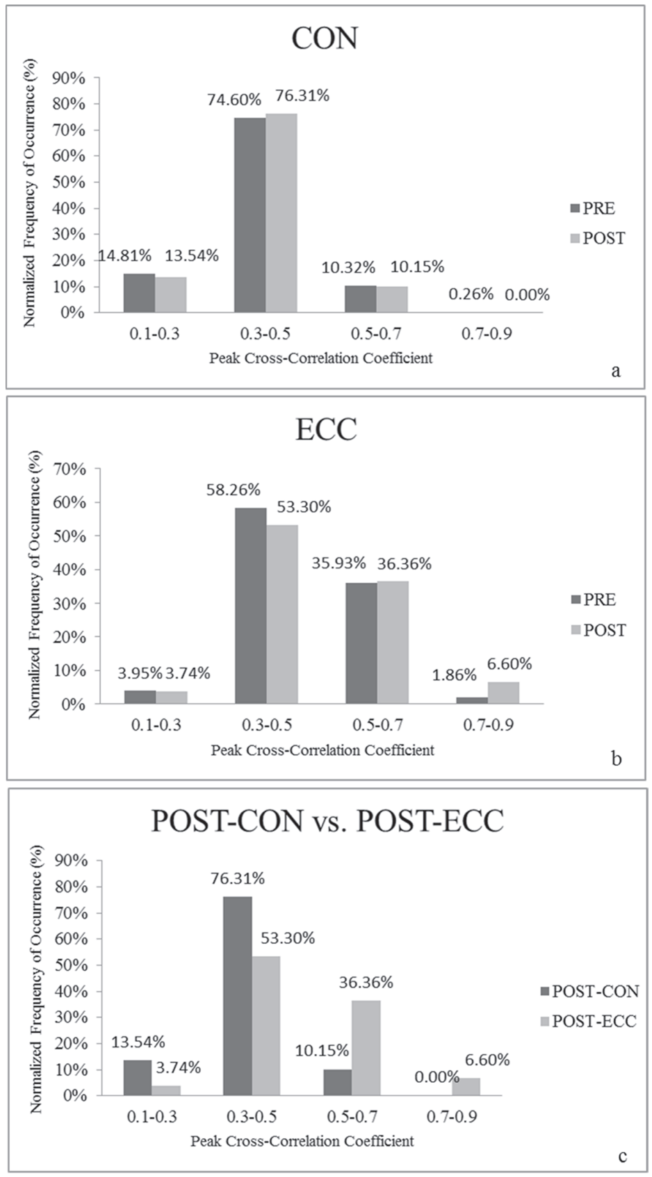


**Figure 5.** An example of histograms of normalized occurrence frequency for peak cross-correlation coefficients for subject No.4 before and after two different exercise interventions. **a.** The comparison of normalized occurrence frequency for peak cross-correlation coefficients before (PRE-CON) and after the CON (POST-CON). **b.** The comparison of normalized occurrence frequency for peak cross-correlation coefficients before (PRE-ECC) and after the ECC (POST-ECC). **c.** The comparison of normalized occurrence frequency for peak cross-correlation coefficients before the CON (POST-CON) and after the ECC (POST-ECC).

peated-measures ANOVA for the isometric strength showed that there was no significant 2-way (time × condition) interaction. However, there was a main effect for time, but not for condition (mean±SD percent strength decline CON vs. ECC= 26.75±7.85% vs. 29.03±9.69%; $p$=0.244). When collapsed across the exercise conditions, the marginal mean isometric MVC decreased significantly over time (mean±SD combined PRE-MVC vs. POST-MVC= 459.00±87.55N vs. 328.04±58.89N; $p$<0.001).

The results from the 2-way repeated-measures ANOVA for the amplitude of the force fluctuations showed that there was a significant 2-way (time × condition) interaction (F [1, 16]= 7.588, $p$=0.014). The follow-up paired-samples t-tests showed that the amplitude of the force fluctuations significantly increased after both exercise interventions (mean±SD PRE-CON vs. POST-CON= 2.23±0.45% vs. 2.96±0.99%, $t$=3.291, $p$=0.003; PRE-ECC vs. POST-ECC= 2.39±0.60% vs. 3.86±1.36%, $t$=4.160, $p$<0.001). In addition, there was no significant difference of the amplitude of the force fluctuations between PRE-CON and PRE-ECC. However, the magnitude of the increase in the amplitude of the force fluctuations after the ECC was significant larger than that after the CON (mean±SD POST-CON vs. POST-ECC= 2.96±0.99% vs. 3.86±1.36%, $t$=3.494, $p$=0.002; Figure 4).

*Common drive*

Figure 5 shows an example of histograms of normalized occurrence frequency for peak cross-correlation coefficients for subject No.4 before and after two different exercise conditions. The results from the two-independent-samples Kolmogorov-Smirnov tests indicated that there were no significant differences between the distributions of PRE-CON and POST-CON peak cross-correlation coefficients, and between the distributions of PRE-CON and PRE-ECC peak cross-correlation coefficients. However, there were significant differences between the distributions of PRE-ECC and POST-ECC peak cross-correlation coefficients ($p$=0.039), and between the distributions of POST-CON and POST-ECC peak cross-correlation coefficients ($p$<0.001). Therefore, based on Figure 5, the normalized

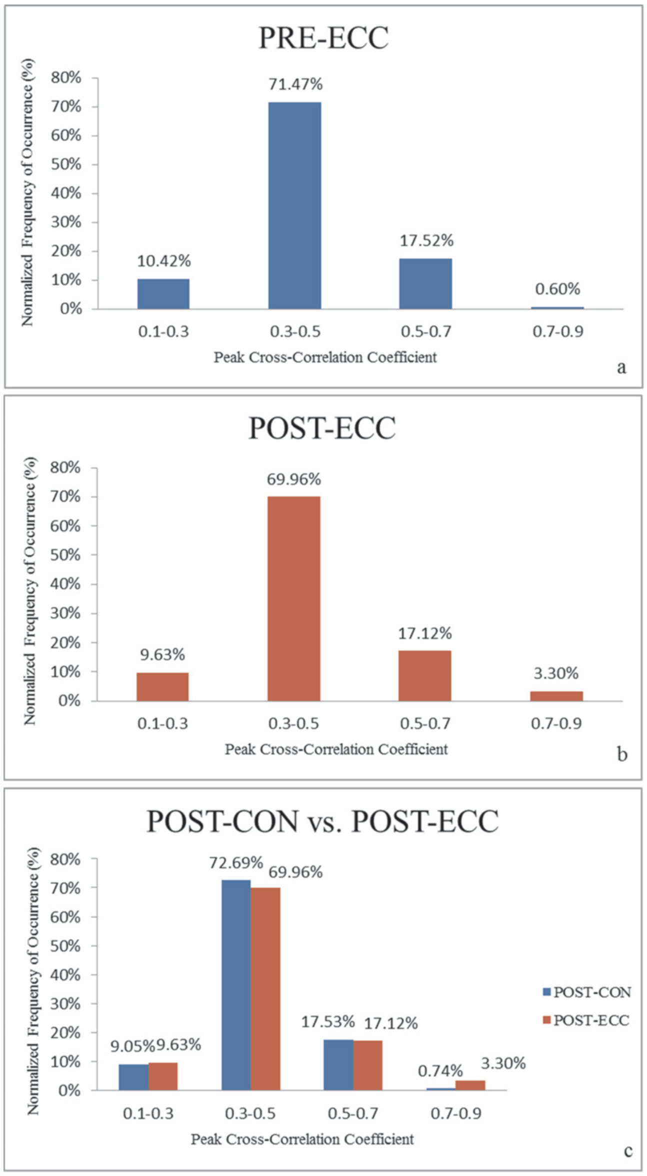


**Figure 6.** Histograms of normalized occurrence frequency for peak cross-correlation coefficients for all the subjects combined. **a.** The normalized occurrence frequency for peak cross-correlation coefficients before the ECC (PRE-ECC). **b.** The normalized occurrence frequency for peak cross-correlation coefficients after the ECC (POST-ECC). **c.** The comparison of normalized occurrence frequency for peak cross-correlation coefficients before the CON (POST-CON) and after the ECC (POST-ECC).

occurrence frequencies of peak cross-correlation coefficients corresponding to ranges 0.1-0.3 and 0.3-0.5 decreased, with those corresponding to ranges 0.5-0.7 and 0.7-0.9 increased, which indicated that after the ECC, the firing rates of detected motor units were fluctuating in a more similar manner and magnitude. Furthermore, comparing to those in the POST-CON, the normalized occurrence frequencies of peak correlation coefficients in the POST-ECC corresponding to ranges 0.5-0.7 and 0.7-0.9 were greater, with those corresponding to ranges 0.1-0.3 and 0.3-0.5 smaller (Figure 5c).

After we combined peak cross-correlation data across subjects, a total of 33192 pairs of cross-correlation (PRE-CON= 7995; POST-CON= 8290; PRE-ECC= 8170; POST-ECC= 8737) were performed between the mean firing rate curves of concurrently active motor units (decomposed from 68 submaximal isometric contractions: 17 subjects × 4 contractions / subject). The peak cross-correlation coefficients range from r= 0.17 to 0.85, with an average value around r=0.4. Similar to the individual data we demonstrated, the two-independent-samples Kolmogorov-Smirnov tests for the group data indicated that there were no significant differences between the distributions of PRE-CON and POST-CON peak cross-correlation coefficients, and between the distributions of PRE-CON and PRE-ECC peak cross-correlation coefficients. However, there were significant differences between the distributions of PRE-ECC and POST-ECC peak cross-correlation coefficients ($p$=0.041), and between the distributions of POST-CON and POST-ECC peak cross-correlation coefficients ($p$=0.045). To examine exactly where the changes occurred to the distribution of peak cross-correlation coefficients after the ECC, we then created 2 histograms (Figure 6a, 6b) to compare the normalized occurrence frequency for peak cross-correlation coefficients before and after the eccentric exercise intervention. In addition, Figure 6c describes the comparison between normalized occurrence frequency for peak cross-correlation coefficients of POST-CON and POST-ECC. Based on Figure 6, the normalized occurrence frequencies of peak cross-correlation coefficients corresponding to ranges 0.1-0.3, 0.3-0.5 and 0.5-0.7 decreased, but there was an increase in the range of r=0.7-0.9 (PRE vs. POST=0.60% vs. 3.30%).

## Discussion

*Isometric strength and force steadiness*

The result of isometric strength from the current study showed that both exercise interventions caused similar strength losses for the elbow flexors (% force decline CON vs. ECC=27% vs. 29%). This finding is similar to those from previous studies that have used similar subject population and experimental procedures[31,32]. However, contrary to our findings for isometric strength, the amplitude of the force fluctuations increased to a greater extent following the ECC than the CON, even though the same absolute submaximal isometric forces (40% of the $MVC_b$) were performed after both exercise interventions.

It is very important to point out that, the current study used slightly different experimental procedures when comparing to previous research studies[2,11] that have also examined the force functions following different types of dynamic exercise. For example, we had each subject perform 40% $MVC_b$ before and after the exercise interventions. Thus, to compensate for the exercise-induced strength loss, a higher percentage of the POST-MVC was required to achieve the desired force production. Therefore, it was expected that the increases in the amplitudes of force fluctuations following both exercise interventions would be similar. However, this did not happen. This finding indicated that there is a mismatch between the isometric strength decline and the increase in force fluctuations following ECC, which is in agreement with the conclusions from a previous study[2]. Specifically, after six sets of five repetitions of eccentric dumbbell curls, the authors found that the increase in force fluctuations only lasted for 1 hour, whereas markers of muscle damage such as strength and creatine kinase concentration were not recovered until 120 hours after the exercise intervention[2]. These observations, accompanied by our findings in the current study, suggest that the increased amplitude of the force fluctuations was specific to eccentric exercise, but not necessarily related to the decrease in the MVC.

One question remains unanswered, however, is whether or not muscle damage occurred due to the ECC. Although using the reductions in MVC is a relatively accurate and reliable method to assess muscle damage[33], Nosaka et al.[34] suggested that the isometric strength loss immediately after eccentric exercise is not strongly associated with changes in muscle damage markers. In addition, even though training status may play an important role influencing the degree of muscle damage following a bout of ECC, evidences from a previous study indicated that ECC may still induce muscle damage in resistance-trained men. Specifically, similar to our findings of isometric strength, Falvo et al.[35] observed about 30% loss in bench press isometric strength immediate after ECC in resistance trained individuals. However, their subjects' strength was not recovered until 48 hours after the exercise, thereby indirectly indicating the presence of muscle injury following ECC. Therefore, in the current study, although there was no direct evidence for muscle damage, it is still possible that the ECC disturbed some neuromuscular functions in the biceps brachii, causing a greater increase in the amplitude of force fluctuations; and these changes were not reflected as the immediate reduction in isometric strength.

*Common drive*

It is suggested that common drive is one of the main factors affecting force variation during sustained isometric contractions1[2,20]. Therefore, as the general scheme that regulates the entire pool of the active motor units, the level of common drive to motor units was examined in this study by cross-correlating the firing rate curves of concurrently active motor units. The main finding from this study is that the CON did not cause any changes in peak cross-correlation coefficient distribution, thereby indicating a relative stable common drive level after the CON. When comparing this result with those from Contessa et al. that have also examined common drive following fatiguing intervention[12], there is a discrepancy regarding common drive. However, it is important to mention that different techniques of motor unit decomposition have been used. Specifically, the authors decomposed intramuscular EMG signals. Obviously, the biggest advantage of using indwelling EMG decomposition technique is that it allows the investigators to track and use the same motor units that are identified for at least two successive contractions. Thus, they were able to directly compare the cross-correlation coefficients before and after the intervention, even though the number of motor units that have been detected were much smaller (in their study, 42 pairs of motor units from 4 subjects were examined)[12]. In contrast, motor units that the current study and previous studies[1,22,36] have examined were decomposed from the sEMG signals. Although surface EMG decomposition technology allows researchers to decompose many more motor units per muscle contraction, same individual motor unit cannot be tracked through different muscle contractions. Therefore, it might not be appropriate to directly compare the results from the current study with those from Contessa et al.[12].

Unlike the CON, the ECC caused changes in the distributions of the peak cross-correlation coefficients by increasing the normalized occurrence frequency for peak cross-correlation coefficients corresponding to the range 0.7-0.9, and decreasing the normalized occurrence frequencies for peak cross-correlation coefficients corresponding to the ranges 0.1-0.3, 0.3-0.5, and 0.5-0.7. These changes in the distributions of peak cross-correlation coefficients following the ECC indicated that the firing rates of the detected motor units fluctuated in a more similar manner and magnitude, which could be considered as an indicator of an increase in the common drive from the CNS to the motor units.

It is well known that the increased common drive could also be a consequence of fatigue[12], and in general, ECC tends to induce a larger degree of fatigue compared with CON or isometric muscle actions. Thus, one may argue that the increased common drive was not due to the ECC itself, but possibly the muscle fatigue induced by the ECC. However, our findings of isometric strength indicated that both CON and ECC caused similar isometric strength losses. Following this result (similar decrements in fatigue), one would assume that force steadiness and common drive should also be similar after both exercise interventions. However, this did not happen: there was an increased common drive level only following the ECC, but not the CON, even though both interventions caused similar levels of fatigue. In addition, our findings also suggested that the common drive was greater after the ECC than that after the CON. Therefore, the increased common drive was specific to the ECC. And as a result, it might have contributed to the greater magnitude of force fluctuations following the ECC.

A previous study by De Luca et al.[29] suggested that "the degree of common drive is likely influenced by the ongoing activity of muscle spindles during a contraction" (pp. 1627). This hypothesis indicates that the reduced sensitivity to proprioceptive feedback from muscle spindles can result in the increased degree of common drive to motor units, which leads to a decrement in force steadiness[12]. Specifically, when a muscle is stretched or lengthened, the primary sensory fibers (Ia afferent neurons) of the muscle spindle respond to the changes in muscle length and velocity, transmit this proprioceptive feedback to the spinal cord, and then stimulate alpha motor neurons projecting to the same muscle being stretched or lengthened by increasing the monosynaptic reflex excitability at the spinal cord level. Fang et al.[37] used electroencephalogram (EEG) to examine the movement-related cortical potential (MRCP) signals during maximal concentric and eccentric exercise. It was suggested that a significant longer time for early preparation and a significant greater magnitude of cortical activity are needed for maximal eccentric contractions. The authors[37] then proposed that the unique cortical activity during the maximal eccentric contraction is employed by the CNS to reduce potential damage in the exercising muscle(s) ("damage reduction" mechanism) by suppressing the muscle activation level. Specifically, this suppressed muscle activation is likely achieved by gating the presynaptic Ia afferent input from the lengthening muscle, thus depressing monosynaptic reflex excitability[37]. Therefore, in the current study, immediately after a total of 60 repetitions of maximal eccentric contractions, it is possible that the presynaptic Ia afferent input from the biceps brachii was still suppressed by the CNS, thereby resulting in an increased common drive.

In addition, the increased common drive following the ECC in the current study might also be due to the altered sensitivity to proprioceptive feedback from the possibly disturbed muscle spindles. However, to date, the exact effects of muscle lengthening exercise (eccentric) on the proprioceptors such as muscle spindles and Golgi tendon organs are still unknown. In fact, the only research that has examined the direct effects of eccentric muscle action on muscle spindles was based on an animal model[38]: the authors did not found direct evidence of damage on the intrafusal fibers of muscle spindles from the cat medial gastrocnemius muscle after a series of eccentric contractions. However, a human study[39] that has examined the effects of eccentric exercise on force and position sense indirectly supports our hypothesis. Specifically, the authors found that the sense of limb position was disturbed immediately after a bout of eccentric muscle contractions, and it was not recovered until 96 hours following the exercise intervention. Therefore, eccentric exercise might have desensitized the receptors (e.g. muscle spindles), which are responsible for position sense[40]. Thus, further research should be done to test this hypothesis. For example, if the muscle spindles were believed to be desensitized by eccentric exercise, a decreased tendon jerk reflex would be expected over a period of time following the exercise intervention.

*Limitations*

Our study showed a few novel findings regarding force steadiness and common drive to motor units following different types of dynamic exercise. However, this study is not without limitations. First and foremost, instead of using traditional measurement tools such as blood creatine kinase concentration and muscle soreness, which were performed in most previous research studies that have investigated eccentric exercise-induced muscle damage, we only used isometric strength loss to evaluate the acute effects of high intensity dynamic exercise on muscle function. Although this marker is relatively accurate and reliable, it did not allow us to distinguish fatigue-related reductions in strength from muscle damage related reductions[33]. In fact, no direct evidence showed that muscle damage occurred after the ECC in the current study, even though we believe that the ECC might have affected some neuromuscular properties. Therefore, when interpreting the data from this study, it is not accurate to state that the increased common drive following the ECC is due to muscle damage. Instead, cautions should be taken that this increased common drive was caused by the ECC itself, which is possibly a mixed effect of muscle fatigue and damage. And for future studies, it would be better and very interesting to investigate the acute effects of eccentric exercise on muscle functions (e.g. muscle strength, muscle soreness) immediate, 1 hour, 24 hours, 48 hours, and 120 hours after the interventions. Because it will not only indicate whether or not muscle damage occurs following the ECC, but will show the time window of how long eccentric exercise can affect force steadiness and common drive. Second, we are aware that, other motor unit control parameters (e.g. number of newly recruited motor units, firing rate variability of active motor units, synchronization of active motor units) also have various effects on force steadiness[12,17-19]. Therefore, future investigations should also focus on the influences of these parameters on force steadiness in resistance-trained individuals, because less is known in this population.

In conclusion, there was no change in common drive to motor units in the biceps brachii after concentric exercise. However, unlike the concentric exercise intervention, the common drive to motor units increased after the eccentric exercise intervention. This increased common drive following the ECC is possibly due to a unique "damage reduction" mechanism-induced depression in presynaptic Ia afferent input activity from the biceps brachii. In addition, the desensitization of the muscle spindles during the ECC may also contribute to the increased common drive to motor units. Therefore, we believe that the increased common drive to motor units is at least partially responsible for the greater magnitude of force fluctuations following the maximal eccentric exercise in resistance-trained men.

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