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Eccentric torque-velocity relationship of the elbow flexors

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Abstract. This study verified the eccentric torque-velocity relationship of human elbow flexors by considering muscle damage induced in maximal eccentric torque measurements. Twenty subjects (26.4 ± 6.2 yrs) were tested twice, separated by 7 days, for maximal voluntary isometric torque at 90° (1.57 rad) of elbow flexion (ISO) and isokinetic eccentric torque (ECC) at velocities of $30^\circ \cdot s^{-1}$ followed by 90° , 150° , $210^\circ \cdot s^{-1}$, and a repeated $30^\circ \cdot s^{-1}$ using a range of movement from 60° to 140° (180° : full extension). ISO preceded each ECC measure to assess the effects of muscle damage and/or fatigue on the measures. The difference in ECC at $30^\circ \cdot s^{-1}$ between the first and second attempts was used to adjust the torque values. The reliability of the measurements was supported by high intra-class correlation coefficient (0.96–0.99) and low coefficient of variation (6.3–9.1%). Peak ECC at all velocities were significantly ($p < 0.05$) greater than ISO (14–16%), but no significant differences were evident among velocities. The second ECC at $30^\circ \cdot s^{-1}$ was significantly ($p < 0.05$) lower ($\sim 10\%$) than the first, and ISO decreased significantly ($p < 0.05$) over the measurements ($\sim 10\%$). Following adjustment, no significant differences in ECC torque among velocities were still evident. It is concluded that eccentric torque is approximately 15% higher than isometric torque without influence of angular velocity for the elbow flexors.

Keywords: Isokinetic, isometric, reliability, muscle damage

1. Introduction

The relationship between force and velocity of muscle contraction has been the focus of ongoing investigations for many years. A typical force-velocity relationship is expressed as a hyperbolic curve for the muscle shortening phase, and an inverse hyperbolic curve for the muscle lengthening phase [2]. Animal studies have confirmed this relationship using stimulated muscle models [14], or by directly measuring cross-bridge tension [17]. A force-velocity relationship, or more appropriately “torque-velocity” relationship for in situ limb muscles, has been also conducted using various human limbs [10,25]. In voluntary shortening (concentric) contractions, the torque-velocity relationship follows the force-velocity relationship shown in animal studies [12,16,25,31]. However, disagreement

exists regarding the torque-velocity relationship for the lengthening (eccentric) phase, such that human muscle lengthening at a higher velocity does not necessarily replicate the extent of increase in force as shown in animal studies [9,11,25]. It has been suggested that one possibility for this anomaly is due to a “safety” inhibition preventing muscle injury [8,31]. The level of inhibition seems to be dependent upon the subject’s strength level [12] and can be altered following resistance training [5,29].

Torque-velocity data for voluntary contractions is most abundant for lower limb muscles, such as the knee extensors. However, conflicting results exist for the eccentric torque-velocity relationship of this muscle group. It has been reported that torque increases with increasing velocity [32], plateaus at the higher velocities [33], is not affected by velocity [6,8,27,34], or decreases with increasing velocity [2,29,31]. Mixed results are also demonstrated for the torque-velocity relationship of the knee flexors [1,13,33].

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There is a scarcity in the literature regarding the torque-velocity relationship of the elbow flexors and studies addressing this area often fail to concur. Two early works [7,28], in which an isokinetic dynamometer was not used, did not report the torque-velocity relationship, but rather the isotonic relationship, demonstrating that eccentric torque was greater than isometric and concentric torque. Later studies [5,9,24] reported that eccentric torque exceeded isometric torque but declined with an increase in angular velocity from $18^{\circ}\cdot\text{s}^{-1}$ to $210^{\circ}\cdot\text{s}^{-1}$, however, the velocity of peak torque and its extent of decline were not the same among the studies. Rodgers and Berger [24] reported that peak eccentric torque occurred at $45^{\circ}\cdot\text{s}^{-1}$ with a 10% decline between $45^{\circ}\cdot\text{s}^{-1}$ and $72^{\circ}\cdot\text{s}^{-1}$. Griffin [9] indicated a peak at $120^{\circ}\cdot\text{s}^{-1}$, and a 9% decline from $120^{\circ}\cdot\text{s}^{-1}$ and $210^{\circ}\cdot\text{s}^{-1}$, while Colson et al. [5] showed a peak at $30^{\circ}\cdot\text{s}^{-1}$ and an approximate 25% decline between $30^{\circ}\cdot\text{s}^{-1}$ and $120^{\circ}\cdot\text{s}^{-1}$. However, in another study [12], eccentric torque exceeded isometric torque by 15% with no difference between the velocities ($30^{\circ}\cdot\text{s}^{-1}$ to $120^{\circ}\cdot\text{s}^{-1}$) for low strength subjects. In contrast, Pousson et al. [23] has reported increases in torque of greater than 30% with increasing velocity from $30^{\circ}\cdot\text{s}^{-1}$ to $60^{\circ}\cdot\text{s}^{-1}$. One study [15] showed a lower angular force in the eccentric phase than the isometric and reported no effect of velocity on eccentric torque. A possible reason for the contradictory findings may lie in the protocols used to determine the torque-velocity relationship.

When determining the torque-velocity relationship, the order of test velocities should be considered. It seems that isokinetic velocities are commonly administered in ascending order with a recommendation for a rest period between measurements of least 60 seconds [21]. Perrine [22] suggested that the reliability in isokinetic testing increased by arranging the order from slow to fast velocity. Routinely, the determination of the torque-velocity relationship consists of concentric, isometric and eccentric actions. Walshe et al. [30] have reported increases in concentric torque after performing eccentric actions. However, it is also possible that a few maximal eccentric actions reduce subsequent force generation ability, since it has been reported that as little as two maximal eccentric muscle actions can induce substantial decreases in muscle strength [19]. Further, it is also possible that eccentric torque is influenced by fatigue if repeated concentric torque measures are performed prior to eccentric torque measures. If the effects of muscle fatigue and the potential for muscle damage are considered, it may be that the torque-velocity relationship is different from those reported previously.

Therefore, the aim of this study was to determine the eccentric torque-velocity characteristic of human elbow flexors by considering the effect of muscle damage and muscle fatigue. To minimize muscle fatigue, this study focused solely on eccentric and isometric torque measurements.

2. Methods

2.1. Subjects and study design

Twenty subjects (10 males and 10 females), who were physically active in various recreational or sporting activities but had not been participating in resistance training for at least the previous six months, were recruited for the study. Approval was granted from the University Human Research Ethics Committee. All subjects signed an informed consent form in accordance with the ethical guidelines in the Declaration Helsinki pertaining to the use of human subjects in medical research. The subjects average (\pm SD) age, height, and weight was 26.4 ± 6.2 yrs, 174.0 ± 7.7 cm, and 69.3 ± 11.5 kg, respectively. Subjects were familiarised with the testing protocol, and participated in two testing sessions (test 1 and test 2) separated by 7 days, consisting of a series of maximal voluntary isometric and eccentric torque measurements of the elbow flexors on an isokinetic dynamometer (Cybex 6000, Ronkonkoma, NY, USA).

2.2. Testing procedures

The isokinetic dynamometer was calibrated before use according to procedures outlined by the manufacturer, and gravity correction was applied using the system operating software (version 4.0). To correct for any torque overshoot due to free acceleration of the lever arm, the dynamometer was operated in powered mode, where the lever arm moves independently of the force generated by subjects at a constant linear acceleration. Subjects were seated with their dominant arm supported at 45° (0.78 rad) of shoulder flexion on an arm curl (preacher curl) bench. The contralateral arm remained relaxed in a comfortable position chosen by the subject, and the subject was instructed not to grip anything. Maximal isometric and eccentric torques of the elbow flexors were measured using the isokinetic dynamometer.

Maximal isometric torque was recorded at an elbow joint of 90° (1.57 rad), which has been reported as the

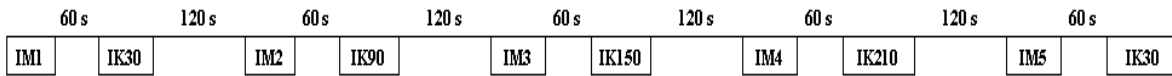


Fig. 1. Timeline of the measurement protocol. IM: maximal isometric torque measurement, IK: maximal isokinetic torque measurement. The numbers shown after IK represent the action velocity.

angle most favourable for generating force [28] and is often chosen for the determination of maximal isometric torque [5,9,19,20]. An isometric torque measurement was collected prior to each isokinetic eccentric torque measurement at four different velocities; 30° , 90° , 150° and $210^\circ \cdot s^{-1}$ (Fig. 1). The purpose of this was to evaluate possible influences of muscle damage or fatigue induced by the protocol as suggested by Borges et al. [2]. It has been suggested that when investigating torque-velocity relations on isokinetic dynamometers, an upward sequence of test velocities is preferable with a return to the lowest velocity for verification and validity [22]. The present study followed this instruction, and the order of velocities was not randomised among subjects and between testing days. Therefore, all subjects were tested from slow to fast velocity, and the slowest velocity ($30^\circ \cdot s^{-1}$) was repeated after the $210^\circ \cdot s^{-1}$ (Fig. 1) to determine the magnitude of decline in torque over the repeated eccentric torque measurements. We checked the actual dynamometer velocity by obtaining the lever arm position signal via AM-LAB system (16-bit data acquisition card and software, Minirack, Lewisham, Aust.) and found no difference between the dynamometer generated velocities in this study (30 – $210^\circ \cdot s^{-1}$) and the actual velocities at which subjects performed the movements.

The range of motion (ROM) for the isokinetic torque measurements was 80° (1.40 rad), moving from 60° (1.05 rad) to 140° (2.44 rad) of elbow flexion, where a full extension of the elbow joint was considered 180° (3.14 rad). The interval between a set of isometric and isokinetic torque measurements was 120 s, with two recordings taken at each contraction mode (Fig. 1). Isometric contractions lasted 4 s and each measure was separated by 60 s of passive rest, a further 60 s of rest was provided before commencement of dynamic movements. Prior to the eccentric torque measurement at each velocity, two sub-maximal eccentric movements were performed as suggested by Hortobágyi and Katch [12] to ‘feel the speed’ of each test velocity and warm up. The interval between sub-maximal contractions was 15 s with 30 s rest before maximal eccentric contractions; each maximal eccentric contraction was separated by 60 s of passive rest.

2.3. Statistical analysis

Intra-class correlation coefficients (ICC) and the coefficients of variation (CV) were calculated for isometric and eccentric torque measures using the values from the two testing days. The peak torque from the two isokinetic torque measurements at each test velocity were averaged and normalised for each subject in relation to his or her average peak isometric torque. A two-way repeated measures ANOVA was used to determine the difference between test 1 and test 2 for the changes in isometric torque over the five testing occasions (2×5) and in eccentric torque (2×5). Analyses were conducted using the software package SPSS (version 11.0) with significance set at $P < 0.05$. Unless otherwise stated, data is presented as means \pm SEM.

3. Results

ICC ranged from 0.96–0.99 for isokinetic torques at different velocities, and 0.98 for isometric torque. The CV for isokinetic torques at different velocities and isometric torque was 6.3–9.1%, and 6.4%, respectively. No significant differences in any of the torque measures were evident between test 1 and test 2 as such the mean values of tests 1 and 2 were combined and used for further analyses.

During isokinetic torque measurement, the angle associated with a peak torque was not significantly different among the four velocities, with the peak torque angle approximating 80° .

The average isometric torque of the 20 subjects was 49.4 ± 4.3 Nm prior to performing isokinetic torque measurements. Changes in isometric torque recorded prior to each eccentric measurement are shown in Fig. 2. Isometric torque decreased significantly over the five measurements (IM1 – IM5), with the final recording (IM5) being significantly lower ($10.2 \pm 2.6\%$) than the first (IM1). No significant difference was observed between the second, third and fourth (IM2, IM3 and IM4) measures.

Figure 3 shows peak eccentric torque at the four velocities relative to maximal isometric torque. All ec-

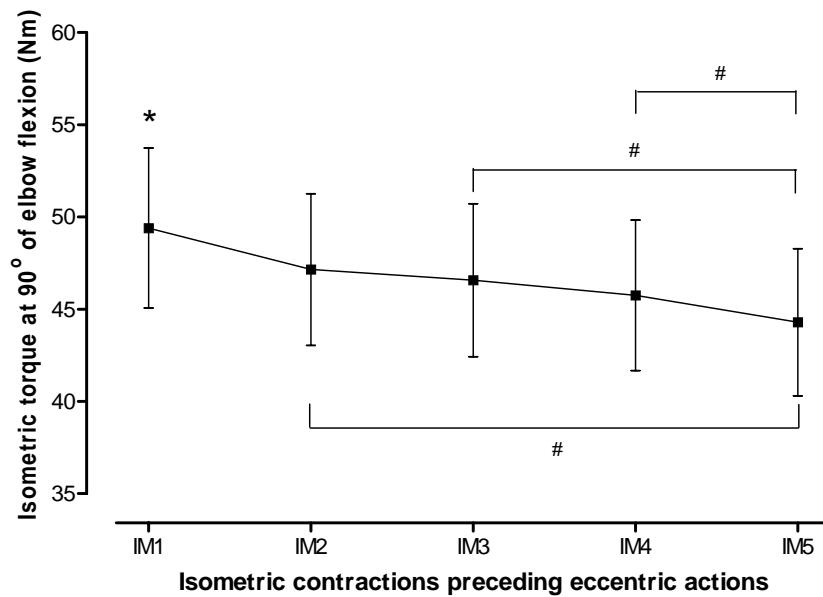


Fig. 2. Changes in maximal isometric torque over five measurement time points. Mean (\pm SE) values of 20 subjects are shown. * Represents significantly greater than all other measurement points; # represents significantly smaller than measurement points IM2, IM3 and IM4.

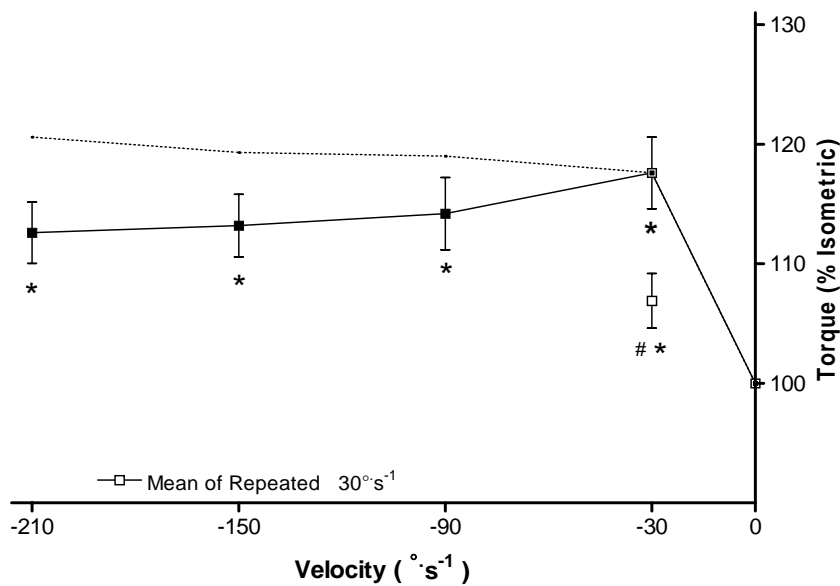


Fig. 3. Normalised eccentric torque-velocity relationship relative to maximal isometric torque. Mean (\pm SE) values of 20 subjects are shown by averaging the results from tests 1 and 2 (solid line). The broken line represents the adjusted mean eccentric torque values following compensation for decrements in isometric torque over the five measurement points and difference in eccentric torque at $30^{\circ}\cdot s^{-1}$ between the initial and second measurement. * Represents significantly greater than maximal isometric torque (unadjusted); # represents significantly lower torque than initial $-30^{\circ}\cdot s^{-1}$ test (unadjusted).

centric torque measures at the four different velocities were significantly higher than the isometric torque, ranging from $17.6 \pm 3.0\%$ at $30^{\circ}\cdot s^{-1}$ to $12.6 \pm 2.5\%$ at $210^{\circ}\cdot s^{-1}$. No significant differences in eccentric torque among the four velocities were evident. As

shown in Fig. 3, when the eccentric torque at the velocity of $30^{\circ}\cdot s^{-1}$ was re-measured following the $210^{\circ}\cdot s^{-1}$, the torque was significantly lower by $10.7 \pm 3.4\%$. The magnitude of this difference was not significantly different from the difference in isometric torque between

the first and last measurements shown in Fig. 2.

As shown by the dotted line in Fig. 3, when the eccentric torque was adjusted by considering the decline in the isometric torque (Fig. 2) and the difference in eccentric torque at $30^\circ \cdot s^{-1}$ between the initial and the re-measured attempt, the torque-velocity relationship continued to show no influence of velocity on eccentric torque.

4. Discussion

The reliability of the measurements for isometric and eccentric torque were acceptable as indicated by the high intra-class correlation and the low coefficient variation values, and meeting the criteria of clinical reliability as described by Griffin [9]. It is important to note that body positioning has been shown to influence reliability, and the seated preacher curl position used in this protocol appears superior to a supine position [9]. Since the level of isometric loading prior to eccentric contraction has been demonstrated to affect isokinetic testing reliability [18], this research highlighted the need for a preload of at least 65% of the subjects' maximal voluntary contraction to gain reproducible results. During the present study, subjects were instructed to contract maximally at the beginning of the range of movement (60° elbow flexion), which was consistent with the instructions in other studies [15,19]. Therefore, it seems unlikely that the testing protocol of the present study had any inherent errors and we are confident that the peak torque obtained for each velocity was accurate.

Although many studies have reported the torque-velocity relationship of the elbow flexors, this study appears to be the first to consider muscle damage induced by repeated eccentric torque measurements. Since only two maximal eccentric actions have been shown to induce decreases of approximately 20% in maximal isometric strength [19], it seems reasonable to assume that repeated eccentric measurements influence the torque-velocity relationship. The present study estimated the effect of muscle damage and/or fatigue by employing isometric torque measurements prior to the eccentric torque determination at the four selected velocities, and compared the first eccentric torque measure at $30^\circ \cdot s^{-1}$ with the re-measured value that was collected following the measurement at $210^\circ \cdot s^{-1}$ (Fig. 1). Isometric torque decreased approximately 10% from the first through fifth measurements (Fig. 2), with the eccentric torque at $30^\circ \cdot s^{-1}$ decreasing similarly ($\sim 10\%$) after 8 maximal isokinetic eccentric torque measurements (Fig. 3). It

has been reported that the magnitude of the decrease in isometric torque immediately following eccentric exercise of the elbow flexors is dependent on the number of actions, with studies showing that 2, 6 and 12 maximal eccentric actions result in decreases of 20%, 33% and 40%, respectively [19,20]. In the present study, the smaller decreases could be explained by the reduced range of movement ($60\text{--}140^\circ$) compared to that ($90\text{--}180^\circ$) of studies [19,20] showing larger decreases. It has been reported that the severity of muscle damage is increased when eccentric actions are performed at longer muscle lengths [4]. It may be that muscle fatigue was also associated with the decrease in the torque. However, eccentric actions have been shown to be metabolically more efficient than concentric actions [26], and Parcell et al. [21] demonstrated that fatigue has no significant influence on maximal concentric isokinetic torque when recovery between efforts was greater than 60 s. Since the recovery time was at least 60 s in the present study, it was considered that the effect of fatigue would have been negligible.

The present study adjusted the eccentric torque by considering the decreases in torque during the measurements as quantified from the repeated isometric and isokinetic torque measurements. This revealed that the eccentric torque was still not significantly influenced by angular velocity (Fig. 3, dotted line). The adjusted torque-velocity relationship obtained in the present study (Fig. 3) is consistent with the previously reported results of Hortobágyi and Katch [12]. However, the present results conflict with those presented by Komi et al. [15] who used four velocities ranging from $60^\circ\text{--}230^\circ \cdot s^{-1}$, although the discrepancies could be due to the smaller sample size used in that study and the specifically designed isokinetic machine. The magnitude of difference in torque between eccentric and isometric actions is similar to other investigations [5, 9,24] but smaller than that of Pousson et al. [23] who reported that eccentric torque was approximately 30% and 56% higher than the isometric values at velocities of 30° and $60^\circ \cdot s^{-1}$, respectively.

Methodological differences may account for the inconsistencies in the eccentric torque-velocity relationship amongst studies. The positioning of the subject has been considered previously, however, other methodological issues include the range of movement of the measured limb, choice of velocities, the order of measurements, and gender and training status of subjects used in the study. The angle producing peak eccentric torque in our study was approximately 80° of elbow flexion, with no significant differences among the ve-

locities. In contrast, Hortobágyi and Katch [12] reported that peak torque was observed at a more extended elbow angle (105° – 112°) for the velocities from 30° to $120^{\circ}\cdot\text{s}^{-1}$. The shape of the torque-velocity relationship does not appear to be influenced significantly even when the torque is obtained from a constant angle [5,12].

Consideration should also be given to whether the 80° ROM was performed at a constant velocity movement or were there portions of acceleration and deceleration. In the present study, the time required for the lever arm to accelerate to the test velocities of $210^{\circ}\cdot\text{s}^{-1}$ and $30^{\circ}\cdot\text{s}^{-1}$ was shown to be 0.18 s, and 0.55 s, respectively. Since the time required to move the lever for the ROM (80°) was 0.38 s for $210^{\circ}\cdot\text{s}^{-1}$ and 2.67 s for $30^{\circ}\cdot\text{s}^{-1}$, it is possible that the velocity was lower at the optimum angle that occurred approximately 20° from the starting angle (60° of elbow flexion) especially for the fast velocity measurement. Therefore, it might be that the peak torque obtained in the measurements at fast velocities such as 150 and $210^{\circ}\cdot\text{s}^{-1}$ was lower than the actual torque. Chen and Chou [3] have stated that the acceleration phase of isokinetic torque measurements may hamper researchers from achieving reliable results. Although the results of the present study showed no significant difference between velocities for peak torque, it may have been better to take into account the ROM needed to achieve the desired constant velocity and the optimal angle to generate maximal force.

The force-velocity relationship reported for animal muscles is different from the torque-velocity relationship shown in the present study. The animal studies have reported that eccentric torque increases with increases in contraction velocity [25]. It remains unclear why this is not the case for human muscles as shown for the elbow flexors in the present study (Fig. 3). Gulch [11] hypothesised that the dissimilarity is due to neural inhibition, which occurs in voluntary muscle contractions but not in electrically stimulated muscles in animal studies. Such neural inhibition is proposed to result in a reduction in the number of available motor units for torque production [8,27,34]. This inhibitory mechanism is supported by the observation that electrical stimulation during maximal voluntary eccentric contractions evokes increases in eccentric torque of 10–40% [12,34]. It has been shown that the level of inhibition can be altered by resistance training [5], although this benefit is proposed to result from a reduction in the co-activation level of antagonist muscles [23]. The role of the inhibition is not known but could be a form of

protection against extreme muscle tension [34]. Further studies are necessary to investigate such inhibitory mechanisms.

In summary, results from the present study suggest that a muscle's torque generating capability may be affected by damage induced from repeated eccentric torque measurements. Based on the current results, the magnitude of the torque decrement could be expected to approximate 10%. After adjusting the torque-velocity relationship by taking the muscle damage effect into account, this study demonstrated that eccentric torque exceeded isometric torque by approximately 15% with no significant influence of angular velocity. The protocol used in this study appears useful for determining the eccentric torque-velocity relationship.

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