

ORIGINAL ARTICLE

Effects of prior concentric training on eccentric exercise induced muscle damage

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Background: Exercise induced muscle damage (EIMD) from strenuous unaccustomed eccentric exercise is well documented. So too is the observation that a prior bout of eccentric exercise reduces the severity of symptoms of EIMD. This has been attributed to an increase in sarcomeres in series. Recent studies have suggested that prior concentric training increases the susceptibility of muscle to EIMD following eccentric exercise. This has been attributed to a reduction of sarcomeres in series, which decreases muscle compliance and changes the length-tension relation of muscle contraction.

Objective: To assess the effects of prior concentric training on the severity of EIMD.

Methods: Four men and four women (mean (SD) age 21.1 (0.8) years) followed a four week concentric training programme. The elbow flexor musculature of the non-dominant arm was trained at 60% of one repetition maximum dynamic concentric strength performance, three times a week, increasing to 70% by week 3. After three days of rest, participants performed 50 maximal isokinetic eccentric contractions on both arms. All participants gave written informed consent before taking part in this study, which was approved by the school ethics committee. Strength, relaxed arm angle (RAA), arm circumference, and soreness on active extension and flexion were recorded immediately before eccentric exercise, one hour after, and at 24 hour intervals for three days. Data were analysed with fully repeated measures analyses of variance.

Results: Strength retention was significantly ($p < 0.01$) greater in the control arm than the trained arm (84.0 (13.7)%, 90.4 (14.7)%, 95.2 (10.5)%, 103.5 (7.6)% v 75.5 (11.3)%, 77.6 (15.3)%, 80.1 (13.9)%, 80.9 (12.5)%) at one, 24, 48, and 72 hours respectively. Similarly, soreness was greater in the trained arm (0.7 (0.6), 3.1 (1.4), 3.0 (1.5), 1.9 (2.3)) than in the untrained arm (0 (0.2), 1.6 (1.3), 1.4 (0.6), 0.6 (0.4)) at one, 24, 48, and 72 hours respectively ($p < 0.05$). Concentric training induced a significant reduction in RAA ($165.2 (6.7)^\circ$ v $157.3 (4.9)^\circ$) before the eccentric exercise bout ($p < 0.01$). This was further reduced and remained lower in the trained arm at all time points after the eccentric exercise ($p < 0.01$). The arm circumference of the concentrically trained arm was significantly greater than baseline ($p < 0.05$) at 72 hours (30.3 (2.9) v 29.8 (3.3) cm).

Conclusions: These findings extend the understanding of the effects of prior concentric training in increasing the severity of EIMD to an upper limb exercise model. The inclusion of concentric conditioning in rehabilitation programmes tends to exacerbate the severity of EIMD in subsequent unaccustomed exercise. However, where concentric conditioning is indicated clinically, the net effect of conditioning outcome and EIMD may still confer enhanced strength performance and capability to dynamically stabilise a joint system.

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Exercise induced muscle damage (EIMD), particularly that which follows strenuous unaccustomed exercise or exercise that contains high frequencies of eccentric muscle actions, is well documented. Symptoms associated with EIMD include soreness, tenderness, changes in range of motion, strength loss, and release of muscle proteins such as creatine kinase.¹ Changes in these symptoms are often evaluated as indirect markers of muscle damage, with the universally recognised standard being histological verification.² Symptoms associated with EIMD have also been noted in patients undertaking key phases of standardised physical rehabilitation programmes after surgical interventions such as reconstruction of the anterior cruciate ligament and autogenous chondrocyte implantation.^{3,4} Exercise challenges during rehabilitation programmes inherently represent unaccustomed and strenuous tasks to a recently restored musculoskeletal system. Systematic exercise stresses may have been imposed on an involved musculoskeletal system that has low physiological capacity following clinically appropriate periods of quiescence. For example, contemporary rehabilitation programmes after autogenous chondrocyte implantation may involve three months of non-weight bearing activities.⁵ This has given rise to clinical concerns that routine provocation of EIMD during

the rehabilitation process may attenuate the recovery of the neuromuscular system to optimal levels of performance capacity and hinder the dynamic stabilisation of the musculoskeletal system.^{6,7}

The initial process in EIMD is thought to be mechanical.⁸⁻¹⁰ The symptoms of EIMD appear to be exacerbated when damaging exercise occurs at longer muscle lengths, which corresponds to the plateau or descending limb of the length-tension curve of muscle contraction.¹¹⁻¹³

It has been proposed that, during a bout of damaging eccentric exercise, weaker sarcomeres become overextended as the muscle lengthens.¹⁰ Failure to re-interdigitate causes the overextended sarcomeres to become non-functional. As the exercise continues, other weaker sarcomeres become overextended. One of the consequences of EIMD is a change in the joint angle at which peak torque occurs. After EIMD, peak torque often occurs at longer muscle lengths, which results in

Abbreviations: EIMD, exercise induced muscle damage; RAA, relaxed arm angle

a shift of the length-tension curve to the right.¹⁴⁻¹⁶ The greatest decrement in force tends to occur at short muscle length after eccentric exercise.^{12, 13, 17} This has been attributed to the possible shortening of sarcomeres that are adjacent to overextended sarcomeres which have failed to re-interdigitate.

Exposure to a repeated bout of eccentric exercise results in attenuated symptoms of EIMD, suggesting an adaptation in the muscle.¹⁸⁻²¹ This is known as the repeated bout effect. Mechanisms that have been postulated to explain this effect include cellular, neural, or connective tissue processes (see McHugh *et al*²² for a review). The main cellular hypothesis is that after eccentric exercise induced muscle damage, the addition of sarcomeres in series allows more sarcomeres to function at shorter lengths.¹⁰ This corresponds to activity on the ascending limb of the length-tension curve and therefore avoids the possibility of overextension of sarcomeres and damage on subsequent exposure to eccentric exercise.¹⁴⁻¹⁶ While these mechanisms may compensate in the longer term for attenuation of neuromuscular performance capacity associated with EIMD, it would appear also to be biologically advantageous for there to be preservation of neuromuscular performance at longer lengths in specific muscle groups after EIMD. For example, the knee flexor musculature that acts as antagonist to the prime movers is used to control or resist translational and rotational tibiofemoral joint motion by means of eccentric action^{23, 24} at longer muscle lengths and extended joint positions where the anterior cruciate ligament is loaded mechanically and is vulnerable to injury.⁷

Eccentric training (by decline treadmill running) has been associated with a greater number of sarcomeres relative to concentric training (by incline treadmill running) in rat vastus intermedius muscle.^{25, 26} This observation provides some support for the notion that the addition of sarcomeres, as suggested by Morgan,¹⁰ may account for the repeated bout protective effect.

Recent evidence suggests that prior concentric training increases the susceptibility of muscle to EIMD following eccentric exercise in humans.^{27, 28} Whitehead *et al*²⁸ observed a greater rightward shift in the angle at which peak torque occurs after EIMD in concentrically trained triceps surae muscle of men and women. The untrained muscles of the contralateral limb recovered more rapidly than the concentrically trained muscles. They also observed that passive torque in the concentrically trained muscles increased significantly following the concentric training programme. Evidence suggests that passive torque (muscle stiffness) is positively associated with the severity of symptoms of EIMD.²⁹

Ploutz-Snyder *et al*²⁷ observed a greater area of muscle injury, determined by magnetic resonance imaging, and greater reductions in strength after a bout of eccentric exercise of the quadriceps muscle in men after nine weeks of concentric training. Symptoms of EIMD also persisted for longer in the concentrically trained leg than in the untrained leg, which concurs with previous findings.²⁸ Ploutz-Snyder *et al*²⁷ attributed the greater loss of strength in the trained limb to the enhanced strength and subsequent greater force exerted during the isokinetic eccentric exercise bout.

Muscle stiffness is believed to enhance force transmission during concentric and isometric contractions and correlates positively with the rate of force development.^{30, 31} As the contractile component shortens, it is thought that the tendon and series elastic component of the muscle lengthens.³⁰⁻³² Therefore, a stiffer musculotendinous unit is thought to transmit the force generated by the muscle more efficiently to the bone, as less force would be lost taking up stretch in the tendon and series elastic component of the muscle. Based on this notion, it is conceivable that concentric training may induce a reduction in the number of sarcomeres in series, which would increase the amount of muscle stiffness and the efficacy with which the force is transmitted to the bone. Although muscle stiffness appears to favour force transmission, sarcomeres in a stiffer muscle are thought to be longer at any given point in

the muscle contraction.^{30, 31} This may result in a higher number of sarcomeres contracting at lengths that correspond to the plateau or descending limb of the length-tension curve, rendering them more susceptible to overextension and damage. Thus, during eccentric muscle actions there may be less scope in a stiff musculotendinous unit to extend in order to accommodate the load, which exacerbates the symptoms of EIMD.²⁹ It may be an interesting paradox that, although many contemporary rehabilitation programmes feature concentric muscle actions as a means by which tensile loading of surgically reconstructed ligamentous tissue and shear and compressive loading on joint surfaces may be initially marshalled to protect avascular autogenous grafts and nourish articular cartilage,^{3, 33} this practice may ultimately exacerbate vulnerability to injury.

Although the findings of Whitehead *et al*²⁸ indicate a possible association between concentric training, increased passive muscle stiffness, and susceptibility to EIMD, the training period was only five days and only a slight increase in stiffness was shown. In addition, the triceps surae were studied, and continued ambulation during the course of the study may be a confounding factor. The elbow flexors may represent a better model in which to study the association between concentric training and EIMD because concomitant activity can be better controlled. In addition, the relaxed arm angle can provide an indication of changes in the passive tension of the elbow flexors.³⁴ Therefore the purpose of this study was to investigate the effects of a four week concentric training programme on the severity of EIMD in the elbow flexors.

METHODS

Participants

Four men (mean (SD) age 20.5 (0.74) years, height 177.3 (3.5) cm, mass 74.3 (3.3) kg) and four women (mean (SD) age 21.1 (0.84) years, height 167.3 (3.4) cm, mass 63.5 (5.5) kg) volunteered to participate in the study, which was approved by the school's ethics committee. All participants gave written informed consent and had not been involved in a weight training programme within the preceding six months.

Experimental design

After a one repetition maximum test on both arms to estimate the dynamic concentric strength performance capability of the elbow flexor musculature, this musculature in the non-dominant arm was trained at 60% of one repetition maximum, three times a week for two weeks, increasing to 70% of maximum voluntary strength performance for a further two weeks. Three days later, both arms were subjected to an eccentric exercise protocol designed to stress the elbow flexors.

Concentric training protocol

Concentric training occurred three times a week for four weeks. Participants were required to stand with the elbow fully extended and lift a dumbbell from full elbow extension up to full elbow flexion with the non-dominant arm. The non-dominant arm was selected to maximise the effect of the concentric training programme. It was felt that the dominant arm could be more influenced potentially by concentric and eccentric activities associated with habitual daily physical activities and intrusions associated with the physiological incompatibility of endurance and strength exercises. To ensure that no eccentric training occurred, the dumbbell was removed from the participant at the end of the concentric contraction (full elbow flexion). Each individual performed three sets of 10 repetitions at 60% of one repetition maximum during weeks 1 and 2. This was increased to three sets of 12 repetitions at 70% of one repetition maximum during weeks 3 and 4. Each set was separated by a three minute rest period. There followed a three day rest period to minimise possible symptoms of EIMD.

Eccentric exercise protocol

Three days after performing the concentric training protocol (during which time the possible symptoms of EIMD would be reduced), each participant performed five sets of ten maximal isokinetic eccentric contractions on each arm on a Kin Com isokinetic dynamometer (500H; Chattecx, Chattanooga, Tennessee, USA) to induce muscle damage. After each eccentric contraction, from full flexion to full extension at 60°/s, the investigator returned the arm to elbow flexion so that no concentric exercise occurred. A one minute rest separated each set of 10 contractions and participants were encouraged to exert maximal effort throughout the exercise bouts.

Measurements

Measurements of isometric strength, upper arm circumference, relaxed arm angle (RAA), and muscle soreness were recorded for both the concentrically trained and untrained arm before the concentric training programme, before an eccentric exercise protocol, one hour after exercise and at 24, 48, and 72 hours.

One repetition maximum

At the onset of the study all participants performed a one repetition maximum test on both arms to provide an estimate of dynamic concentric strength performance capability of the elbow flexor musculature that could be used subsequently to regulate the exercise intensity of the concentric training protocol. The participant was asked to stand with the elbow fully extended and lift a dumbbell from full elbow extension to full elbow flexion. The weight of the dumbbell was increased by 2.5 kg until the participant was no longer able to lift the weight. The latter was recorded as the subject's one repetition maximum. A three minute rest separated each repetition in order to minimise fatigue.

Isometric strength

Isometric strength was assessed using a Kin Com isokinetic dynamometer. The participant was placed on a portable treatment couch (Darley, Lostwithiel, Cornwall, UK) in the supine position. A restraining strap was placed around the body, in line with the point at which the elbow flexed, to prevent any extraneous movement. The elbow was flexed to anatomical 80°, which was identified with a goniometer. A semipermanent marker was used to mark the axis of rotation at the elbow, and points on the humerus and forearm, which were proximal and distal to the axis of rotation. These marks were used to relocate the goniometer position in order to set the anatomical 80° joint angle on subsequent occasions.

After a warm up of three submaximal and two maximal isometric contractions, participants performed two three second maximal isometric contractions separated by a one minute rest. A visual display unit, which displayed force in real time, was used to encourage maximal efforts.³⁵ The mean of the two three second isometric contractions was taken to be representative of the force production capability. Lower coefficients of variation and higher intraclass correlations have been reported for mean torque.³⁶ Strength was reported as a percentage of baseline values in order to remove any pretest differences.

Upper arm circumference

Arm circumference was measured with an anthropometric tape measure. Both arms were marked with a semipermanent pen at the mid-belly of the biceps brachii. Provided that the scores lay within a 5 mm range, the mean value of two measures was recorded.

Relaxed arm angle

RAA was assessed with the participant in the standing position with the arm in a relaxed anatomical position by their side, similar to that described by Cleak and Eston.³⁷ A goniometer (Baseline; Physiomed, Chester, UK) was used to measure

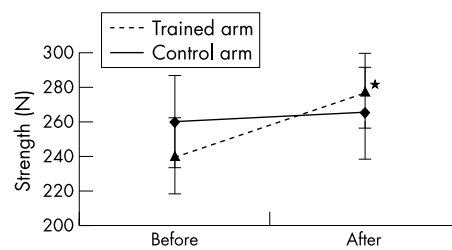


Figure 1 Changes in isometric strength after a four week concentric training programme in the trained arm compared with the control arm. Values are mean (SEM). *Significant difference from baseline value.

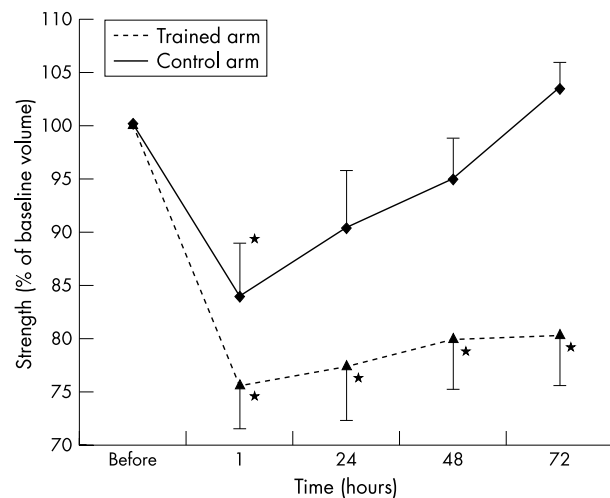


Figure 2 Changes in isometric strength following exercise induced muscle damage in the trained arm compared with the control arm. Values are mean (SEM). *Significant difference from baseline value.

RAA. The RAA at the elbow was subtracted from 180° so that changes in the elbow angle could be expressed relative to the anatomical zero position. In this way, a reduction in resting elbow angle was recorded as a positive change from zero. As described above, marks were placed on the forearm, humerus, and elbow for accurate relocation of these points on subsequent occasions.

Soreness

Soreness was evaluated using a visual analogue scale, which ranged from 0 (no soreness) to 10 (worst soreness ever). Participants rated the level of soreness on the concentrically trained and untrained arm during unassisted active elbow flexion and extension on each arm.

Design analysis

Data were analysed using separate two factor (arm by time) analyses of variance with repeated measures on both factors. Alpha was set at 0.05. The sphericity assumption was tested using Mauchly's test of sphericity. In the event of any violation of this assumption, Greenhouse-Geisser (ϵ_{GG}) corrections were applied. Significant results were followed up using an adapted Tukey's post hoc analysis for repeated measures.³⁸

RESULTS

Strength

Concentric training of the non-dominant arm resulted in a 14.4 (7.2)% increase ($p < 0.01$) in isometric strength, compared with a non-significant change of 1.8 (8.0)% in the contralateral arm (arm by time $F(1,7) = 12.0$, $p < 0.05$). Figure 1 shows the absolute values.

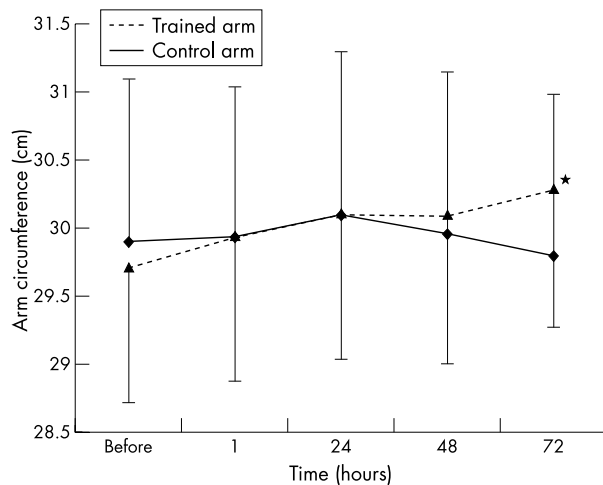


Figure 3 Changes in arm circumference after exercise induced muscle damage in the trained arm compared with the control arm. Values are mean (SEM). *Significant difference from baseline value.

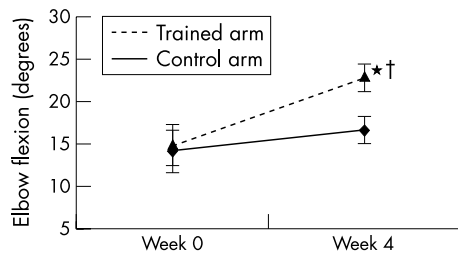


Figure 4 Changes in relaxed arm angle after a four week concentric training programme in the trained arm compared with the control arm. The relaxed arm angle at the elbow was subtracted from 180° so that changes in the elbow angle could be expressed relative to the anatomical zero position (0° = full extension). Values are mean (SEM). *Significant difference from baseline value; †significant difference between arms.

After the eccentric exercise bout there was a greater overall decrease in strength in the concentrically trained arm ($F(1,7) = 19.54, p < 0.01$). A significant arm by time interaction ($F(4,28) = 6.2, p < 0.01$) showed that strength in the concentrically trained arm was significantly lower than baseline at 24, 48, and 72 hours, whereas strength in the untrained arm was significantly lower than baseline at one hour only (fig 2).

Arm circumference

There was no significant change in arm circumference by the end of the four week training programme ($F(1,7) = 0.9, p > 0.05$). After the eccentric exercise bout, there was a significant time by arm interaction on arm circumference ($F(4,28) = 3.4, p < 0.05$). The circumference of the concentrically trained arm was significantly greater than baseline at 48 and 72 hours after eccentric exercise. The concentrically trained arm also had a significantly greater circumference than the control arm 72 hours after eccentric exercise. There were no other differences (fig 3).

Relaxed arm angle

The concentric training programme resulted in a significant reduction in RAA in the concentrically trained arm at the end of the four week training programme, with no changes in RAA of the untrained arm (arm \times time $F(1,7) = 3.4, p < 0.01$) (fig 4).

After eccentric exercise, there was a significant reduction in the RAA across time in both arms ($F(4,28) = 17.1, p = 0.00$), with the highest values being recorded at 24 hours. Although

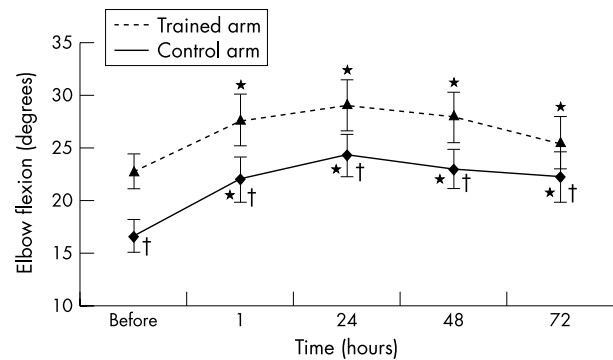


Figure 5 Changes in relaxed arm angle after exercise induced muscle damage in the trained arm compared with the control arm. The relaxed arm angle at the elbow was subtracted from 180° so that changes in the elbow angle could be expressed relative to the anatomical zero position (0° = full extension). Values are mean (SEM). *Significant difference from baseline value; †significant difference between arms.

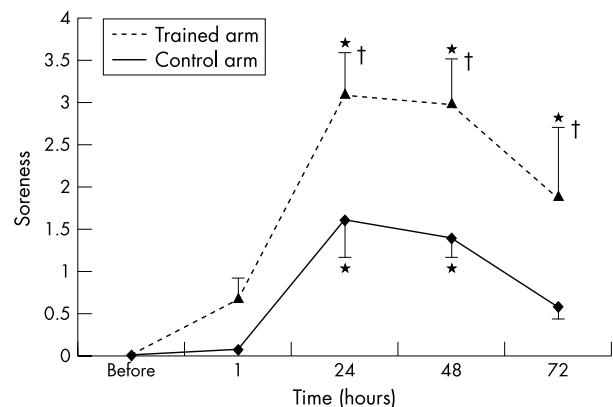


Figure 6 Changes in perceived muscle soreness after exercise induced muscle damage in the trained arm compared with the control arm. Values are mean (SEM). *Significant difference from baseline value; †significant difference between arms.

both conditions illustrated a similar pattern of decrease in RAA, it is notable that the untrained arm had a higher RAA before damage, which remained significantly higher at all times ($F(1,7) = 15.2, p < 0.01$). Signs of recovery were evident in both arms 48 hours after eccentric exercise; however, neither arm had recovered by 72 hours (fig 5).

Soreness

After the eccentric exercise bout, soreness increased significantly in both the control and the concentrically trained arm ($F(1.8,12.5) = 10.05, p < 0.01_{cc}$), with greater soreness being observed in the concentrically trained arm ($F(1,7) = 17.1, p < 0.04$). A significant arm by time interaction ($F(4,28) = 2.8, p < 0.05$) showed that soreness was greater in the concentrically trained arm at 24, 48, and 72 hours. Soreness in the untrained arm was also significantly greater than baseline at 24 and 48 hours with values returning to baseline by 72 hours. However, soreness in the concentrically trained arm was still significantly greater than baseline 72 hours after eccentric exercise (fig 6).

DISCUSSION

The four week concentric training programme resulted in a 15% increase in isometric strength compared with a 1% increase in the untrained arm. No significant changes were observed for arm circumference by week four, which suggests that the increase in strength may have occurred as the result

of a neural adaptation.^{39, 40} RAA and associated elbow flexion in the trained arm increased significantly from baseline to the end of the four week concentric training programme (15.0 (6.9)° v 22.9 (7.2)° respectively). Changes in the untrained arm (14.5 (6.5)° v 16.7 (7.4)° respectively) were not significant and were within 95% confidence limits associated with measurement error.

The mechanical properties of the sarcomere and its surrounding layers of elasticity can be represented by “three-element” models focusing on contractile, series elastic, and parallel elastic elements.⁴¹ The length-force relation of the musculotendinous unit indicates a potential for certain passive structures within muscle, such as connective tissue sheaths—for example, endomysium, perimysium, epimysium, aponeurosis, tendon—and cytoskeletal elements—for example, intermediate filaments, titin, nebulin—to exert a force when unstimulated muscle is stretched, for example by the action of gravity on the mass of the forearm during the assessment of RAA. Any adaptation resulting from the four week concentric training programme, in which there is remodelling and hypertrophy within the connective and cytoskeletal elements and associated changes to the mechanical properties of these parallel elastic elements including greater stiffness, may account for at least some of the reduction in RAA. This would be especially so because the passive mechanical contribution would be expected to be greatest at the longest muscle lengths.⁴²

The increase in maximal voluntary isometric strength following the concentric training programme suggests that, even though it was short in duration and undertaken at moderate levels of intensity (60–70% of isometric strength), it was still sufficient to induce performance improvements despite being unlikely to have activated fully the motor unit pool. It is probable that neural adaptation was the principal mechanism by which increased performance was affected, given that the cross sectional area of muscle was unchanged.^{43, 44} Various mechanisms would be implicated, including concurrent changes to recruitment and discharge rate⁴⁵ at a potentially decreased muscle length (discussed below),⁴⁶ potentiation of reflex responses,⁴⁷ and increased excitability of the alpha-motoneurone pool.^{48, 49} However, such mechanisms of neural adaptation that may underpin the observed changes in strength performance should not have influenced RAA to any great extent given the static and passive nature of the test.

The decrease in RAA may indicate a degree of muscle shortening, which may be attributable to a decrease in sarcomeres in series, which theoretically could decrease the length of the muscle. A decrease in sarcomere number would also theoretically increase muscle stiffness. Whitehead *et al*²⁸ reported an increase in passive torque after a short concentric training programme, which is consistent with this theory. Transmission of force from the muscle to the bone is facilitated by muscle stiffness,^{30, 31} as this reduces the amount of stretch in the non-contractile component of the muscle as the contractile component shortens and therefore transfers the contractile force to the bone sooner.³² It is therefore conceivable that concentric exercise may shorten a muscle, making it stiffer, thereby enhancing the efficacy with which force can be translated from the muscle to the bone.

After eccentric exercise, symptoms of EIMD were observed in both arms. However, more pronounced symptoms were observed in the concentrically trained arm, which concurs with other findings.^{27, 28} Isometric strength was significantly lower in the concentrically trained arm at 24, 48, and 72 hours after the eccentric exercise bout, whereas isometric strength in the untrained arm had returned to the baseline value by 24 hours.

Arm circumference was significantly greater in the concentrically trained arm at 72 hours, compared with baseline levels in both arms and in comparison with the untrained arm at 72 hours. This is attributed to a greater inflammatory response

involving movement of fluid, plasma proteins, and leucocytes into the damaged tissues,⁵⁰ and is in accordance with previous studies.^{37, 51–53} The results also concur with those of Whitehead *et al*,²⁸ who observed greater swelling (leg volume) in the concentrically trained leg than in the untrained leg after a bout of eccentric exercise.

Soreness was also greater in the concentrically trained arm at 24, 48, and 72 hours. These results differ from those of Whitehead *et al*,²⁸ who reported no difference in soreness between the concentrically trained and untrained ankle plantar flexors after eccentric exercise. The difference in results is most likely due to differences in protocol of the two studies. The RAA decreased significantly in both arms after damage, but was significantly lower at every time point after damage in the concentrically trained arm.

The decrease in RAA in the concentrically trained arm may provide indirect evidence of a reduction in sarcomeres, which would be commensurate with a decrease in muscle compliance after intensive concentric training. This predisposes the muscle to more severe symptoms of muscle damage after eccentric exercise. Passive torque has been used to evaluate muscle stiffness and is positively associated with symptoms of EIMD.^{28, 29} A possible explanation may be that, because of muscle shortening, more sarcomeres have to perform at lengths that correspond to the plateau or descending section of the length-tension curve, where overextension and greater disruption of sarcomeres in series is more likely.^{14–16} It has been suggested that sarcomeres in a stiffer musculotendinous unit are longer at any given point in the muscle contraction,^{30, 31} and it is well documented that EIMD is more severe after eccentric exercise at long muscle length.^{12, 14–16} It is likely therefore that more sarcomeres are overextended in a stiffer musculotendinous unit, which allows less scope for the tendon and series elastic component of the muscle to stretch.²⁹

The plasticity characteristics of muscle are exemplified by the change in sarcomere number after immobilisation of cat soleus muscle in a short or long muscle position.^{54, 55} The reduction in the number of sarcomeres in series that occurs with immobilisation in a shortened position is associated with an increase in passive muscle tension and a shift in the length-tension relation to the left.^{56, 57} If concentric training induces a reduction in the number of sarcomeres, then differences in the length-tension relation of muscle contraction would also be expected. In rats, eccentric training has been associated with a greater number of sarcomeres than concentric training.^{25, 26} Rats that followed an eccentric exercise programme attained peak torque at longer muscle lengths than rats that followed a concentric exercise programme.^{25, 26}

An alternative explanation for the greater severity of symptoms of EIMD in the trained muscle could be that the increases in strength induced by the concentric training programme resulted in greater eccentric forces during the eccentric exercise bout. This could result in more force per fibre during the eccentric loading. Ploutz-Snyder *et al*²⁷ attributed the greater damage and decrease in strength to a greater eccentric loading potential induced by the increase in concentric strength. Although it is beyond the scope of this study to estimate the force per fibre during the exercise bout, it is unlikely that this is the case. Previous research has shown that concentric training has a minimal effect on eccentric increases in strength.^{38, 39} In addition, it is notable that, although the concentrically trained, non-dominant arm increased significantly in strength ($p < 0.01$), there was no significant difference between the two arms before or after the concentric strength training protocol. Respective absolute values for the trained and control arms before the strength training programme were 240.9 (62.3) N and 258.6 (75.9) N, and those after the training programme were 275.5 (60.4) N and 262.6 (79.2) N. The significant interaction of arm by time on strength was due to a greater relative increase in strength in the trained arm compared with the untrained arm. It is therefore difficult to conclude from this study that the more

Take home message

Rehabilitation scientists should be aware that the inclusion of concentric conditioning in rehabilitation programmes will tend to exacerbate the severity of EIMD in subsequent unaccustomed exercise. To minimise these effects, eccentric conditioning should be included in rehabilitation programmes if possible. However, where concentric conditioning is indicated clinically, the net effect of conditioning outcome and EIMD may still confer enhanced strength and capability to protect a joint system.

pronounced symptoms of EIMD were attributable to a greater loading potential in the concentrically trained arm.

The deployment of concentric muscle actions may be appropriate clinically during key phases of physical rehabilitation in order to provide maximum protection for avascular surgically reconstructed tissue while facilitating prevention of fibrosis and muscular atrophy. It may be that in such circumstances the intensity of either rehabilitation or functional activities would be insufficient to induce substantive muscle damage routinely. However, in situations such as intermediate phases of rehabilitation involving accelerated progress towards functionally relevant activities, where the clinician or exercise scientist may be presented with a choice as to the most appropriate intervention strategy, the findings from this study offer several important considerations for optimised rehabilitation practice.

The concentric training regimen used in this study improved this performance capacity by about 15% compared with baseline and the untrained control limb. It is interesting to note that the time course of strength restoration toward baseline levels after the bout of eccentric exercise showed appreciably different patterns for the concentrically trained and untrained limbs. For example, one hour after the bout of eccentric exercise, the net loss of strength performance, taking account of the gains from the concentric training (about 15% compared with the initial baseline) and effects of the eccentric loading (about 24% loss compared with performance after training), was about 9%. This loss of performance compares favourably with a limb that has not undergone training in which the net loss of performance was about 17% (fig 2). In the context of rehabilitation, this point in time after a session involving eccentric muscle actions may be associated with routine daily living and workplace related activities with inherent risks to musculoskeletal integrity. As such, the net effects on strength performance of concentric training before eccentric stresses may still confer biologically significant advantages of increased protection from injury compared with no training. Furthermore, concentric training may facilitate musculoskeletal health by additional means associated with the potentiation of reflex responses, increased excitability of the alpha-motoneurone pool, and a mechanically stiffer system.⁶⁰ The results suggest that net changes to strength performance may be an important consideration for rehabilitation for up to 48 hours after the bout of eccentric exercise. During this time, the strength performance of the concentrically trained arm was at least the equivalent of the untrained arm.

In conclusion, this study extends the understanding of the scope of the effects of prior concentric training in increasing the severity of EIMD to that involving an upper limb exercise model. It provides further evidence, in addition to that presented by Whitehead *et al*²⁸ and Ploutz-Snyder *et al*,²⁷ that the inclusion of concentric conditioning in rehabilitation programmes will tend to exacerbate the severity of EIMD in subsequent unaccustomed exercise. However, where concentric conditioning is indicated clinically, the net effect of condition-

ing outcome and EIMD may still confer an enhanced strength performance and capability to dynamically stabilise a joint system.

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..... COMMENTARY

This research builds on previous work on the topic of exercise induced muscle damage. Its findings have important practical implications, particularly for those working in rehabilitation. The work therefore has the potential to inform good practice and its publication in this journal will facilitate its dissemination to those who can make this difference.

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