REVIEW

Motor unit activity after eccentric exercise and muscle damage in humans

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Abstract

It is well known that unaccustomed eccentric exercise leads to muscle damage and soreness, which can produce long-lasting effects on muscle function. How this muscle damage influences muscle activation is poorly understood. The purpose of this brief review is to highlight the effect of eccentric exercise on the activation of muscle by the nervous system, by examining the change in motor unit activity obtained from surface electromyography (EMG) and intramuscular recordings. Previous research shows that eccentric exercise produces unusual changes in the EMG–force relation that influences motor performance during isometric, shortening and lengthening muscle contractions and during fatiguing tasks. When examining the effect of eccentric exercise at the single motor unit level, there are substantial changes in recruitment thresholds, discharge rates, motor unit conduction velocities and synchronization, which can last for up to 1 week after eccentric exercise. Examining the time course of these changes suggests that the increased submaximal EMG after eccentric exercise most likely occurs through a decrease in motor unit conduction velocity and an increase in motor unit activity related to antagonist muscle coactivation and low-frequency fatigue. Furthermore, there is a commonly held view that eccentric exercise produces preferential damage to high-threshold motor units, but the evidence for this in humans is limited. Further research is needed to establish whether there is preferential damage to high-threshold motor units after eccentric exercise in humans, preferably by linking changes in motor unit activity with estimates of motor unit size using selective intramuscular recording techniques.

Keywords eccentric exercise, electromyography, muscle damage, single motor unit.

It is now axiomatic that unaccustomed eccentric exercise involving the repetitive lengthening of active muscle leads to muscle damage and soreness. Since the original observations by Theodore Hough in the early 1900s (Hough 1900, 1902), there have been a large number of studies examining the structural and functional changes in muscle fibres, following muscle damage induced by eccentric contractions. In contrast, much less is known about the adjustments in the neural control of muscle that occurs with eccentric exercise and muscle damage. The purpose of this brief review is to highlight the effect of eccentric exercise and muscle damage on the neural control of movement, by focusing on changes in motor unit activity obtained by surface electromyography (EMG) and intramuscular recordings. Motor units are the smallest

elements of neuromuscular control, and activation of motor units is the final common path for all neural activation strategies. Therefore, studies showing changes in motor unit activity with surface or intramuscular EMG provide compelling evidence for changes in the neural control of force after eccentric exercise.

Eccentric or lengthening contractions are performed regularly in our everyday lives and occur whenever we run downhill, walk downstairs or perform any slowing or braking movements. Although eccentric contractions are known to produce large forces with a low metabolic cost (Abbott *et al.* 1952), the negative consequences of performing these types of contractions are substantial damage to the ultrastructural and cytoskeletal components of muscle fibres (Allen 2001) and an impairment in the process of excitation–contraction coupling (Warren *et al.* 2001). The effects of this exercise-induced muscle damage include a long-lasting decline in muscle strength [for up to 6 weeks; (Sayers *et al.* 1999)], a shift in the optimal length for force generation to longer muscle lengths and an increase in passive muscle tension or stiffness (see reviews by Proske & Morgan 2001, Clarkson & Hubal 2002, Proske & Allen 2005). Muscle pain also develops 1 or 2 days after the exercise, which is thought to reflect an increase in noxious chemicals from the damaged muscle (O'Connor & Cook 1999). This delayed onset muscle soreness is quite unique because it is not discernable at rest, but can be elicited with mechanical stimulation or pressure, stretching or contraction of the damaged muscle (Proske & Morgan 2001), producing effects that can be quite debilitating for motor performance (Cheung *et al.* 2003). Furthermore, the consequences of eccentric muscle damage can involve substantial changes in neuromuscular function, such as impairments in joint position sense (Saxton *et al.* 1995, Brockett *et al.* 1997), electromechanical delay (Howatson 2010), reaction times (Paschalis *et al.* 2007) and submaximal force fluctuations (Semmler *et al.* 2007), suggesting that muscle damaging exercise influences both muscular and neural aspects of motor control.

Eccentric exercise and surface EMG

Despite the extensive knowledge on deficits in motor function after eccentric exercise, little is known about the neural adjustments that accompany these motor deficits, following muscle damage. One classic approach to examine the neural drive to muscle is with the use of surface EMG, with the amplitude and frequency of the signal used as an indicator of the number and population of motor neurones involved in the task.

EMG-force relation

Under normal physiological conditions, the EMG–force relation in different human muscles is either linear, or there is a less-than-proportional increase in EMG at low-force levels (Lawrence & De Luca 1983). However, Komi & Viitasalo (1977) were the first to demonstrate an unusual EMG–force relation after eccentric exercise that was sufficient to induce muscle damage. In this study, they showed that eccentric (but not concentric) exercise of the knee extensor muscles resulted in a change in the EMG–force relation, with a more-than-proportional increase in EMG during low-force isometric contractions when performed immediately after and 2 days after eccentric exercise. This effect has since been confirmed for isometric contractions when performed immediately after eccentric exercise in other muscle groups such as the elbow flexors (Weerakkody *et al.* 2003, Prasartwuth *et al.* 2005, Semmler *et al.* 2007), elbow extensors (Carson *et al.* 2002, Meszaros *et al.* 2010), wrist extensors (Leger & Milner 2001b) and intrinsic hand muscles (Leger & Milner 2001a). Furthermore, we have also shown this effect to be greatest in elbow flexor muscles during shortening contractions compared with isometric and lengthening contractions after eccentric muscle damage (Turner *et al.* 2008). Although the more-than-proportional increase in EMG at low forces is not observed under normal physiological circumstances (Lawrence & De Luca 1983), this EMG–force relation can be produced in computer models of motor unit activation when narrowing the range of motor unit recruitment thresholds in a simulated population of motor units (Fuglevand *et al.* 1993a), suggesting that a change in motor unit activity after eccentric exercise may contribute to this effect.

The magnitude of the effect of eccentric exercise on biceps and triceps brachii EMG during submaximal isometric contractions of the elbow flexor muscles is shown in Figure 1. These data represent the combined results of four studies involving a total of 36 young subjects (Semmler *et al.* 2007, Dartnall *et al.* 2008, 2009, Dundon *et al.* 2008). Each study involved an eccentric exercise protocol that was designed to induce a reduction in isometric muscle strength of the elbow flexor muscles of approx. 40% of the maximum voluntary contraction (MVC) force. Along with other indicators of muscle damage (muscle stiffness and soreness), this reduction in muscle strength was evident for at least 1 or 2 days after the exercise in each study, which is considered a valid indicator of muscle damage (Warren *et al.* 1999). To obtain the data in Figure 1, the subjects' task was to activate the elbow flexor muscles to produce a short-lasting (approx. 15 s) constant-force isometric contraction that matched a
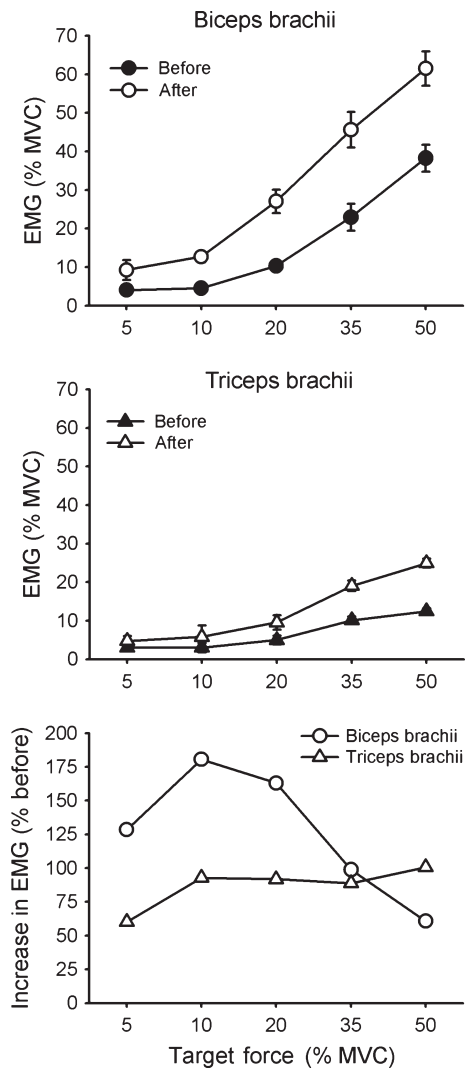
Figure 1 Effect of elbow flexor eccentric exercise on biceps brachii (a) and triceps brachii electromyography (EMG; b) during submaximal isometric contractions. The increase in EMG at each target force is shown in (c). Data were obtained from four studies involving 36 young subjects (Semmler *et al.* 2007, Dartnall *et al.* 2008, 2009, Dundon *et al.* 2008).

target force that was equivalent to 5, 10, 20, 35 or 50% of the most recent MVC obtained before and immediately after exercise. Because eccentric exercise always resulted in a decline in muscle strength, the absolute target force during the submaximal contractions was approx. 40% lower after eccentric exercise. Despite this, the amplitude of the biceps brachii EMG was consistently higher at submaximal forces after eccentric exercise (Fig. 1a), ranging from 61% greater at 50% MVC to 181% greater at 10% MVC (Fig. 1c), even though there was no change in maximum EMG after exercise (Semmler *et al.* 2007, Dundon *et al.* 2008). This effect resulted in a larger-

than-proportional increase in EMG at low forces, with the first 50% of force requiring 38% of maximum EMG before exercise and 62% of maximum EMG after exercise. Importantly, the more-than-proportional increase in EMG at low forces is unlikely to be due to short-lasting metabolic fatigue induced by the repetitive lengthening contractions, because the increase in EMG at low forces has been shown to be largest 2 h after eccentric exercise (Dundon *et al.* 2008), fatiguing concentric exercise that produces a decline in strength with minimal muscle damage does not alter the EMG–force relation (Semmler *et al.* 2007), and lengthening contractions are usually characterized by a low metabolic cost that induce minimal fatigue (Abbott *et al.* 1952).

One of the most obvious reasons for an increase in submaximal EMG after eccentric exercise is an increase in antagonist muscle coactivation, which would require an increase in agonist muscle EMG to maintain the required submaximal target force. Increased antagonist muscle coactivation has been observed during motor skill learning (Bernardi *et al.* 1996) and when the joint or load is unstable (De Serres & Milner 1991), suggesting that it may be used to increase joint stiffness to improve motor performance after eccentric exercise in a damaged muscle (Leger & Milner 2001b). Previous studies have shown an increase in antagonist muscle coactivation after eccentric exercise in several muscle groups involving isometric contractions during wrist extension (Leger & Milner 2001b), knee extension (Vila-Cha *et al.* 2012) and elbow flexion (Semmler *et al.* 2007). Furthermore, increased antagonist muscle coactivation after eccentric exercise has been observed during dynamic contractions of the elbow flexor (Turner *et al.* 2008) and knee extensor muscles (Vila-Cha *et al.* 2012), although the level of coactivation might be lower during movements (Bottas *et al.* 2009) and may depend on the target force level (Vila-Cha *et al.* 2012). Nonetheless, an increase in antagonist muscle coactivation has been a relatively consistent finding during isometric contractions of the elbow flexor muscles (Fig. 1b), with an increase in antagonist EMG activity ranging from 60% at 5% MVC to a 100% increase in antagonist EMG at 50% MVC (Fig. 1c). A similar pattern of change in EMG in agonist and antagonist muscles during recovery after eccentric exercise suggests that increased antagonist muscle coactivation is a likely contributor to the increase in agonist (biceps brachii) EMG during submaximal contractions (Table 1). However, a comparison of the change in EMG of the agonist (biceps brachii) and antagonist (triceps brachii) muscles shows that the pattern of change with increasing target force is dissimilar between the two muscles (Fig. 1c), suggesting that other factors must

Table 1 Time course and magnitude of changes in factors that contribute to increased motor unit activity after eccentric exercise

	Time after eccentric exercise					
	0 h	2 h	1 day	2 days	7 days	References
EMG (agonist)	↑↑↑	↑↑↑	↑			Weerakkody et al. (2003), Semmler et al. (2007), Dundon et al. (2008)
EMG (antagonist)	↑↑	↑↑	↑			Leger & Milner (2001b), Semmler et al. (2007), Vila-Cha et al. (2012)
Low-frequency fatigue	↑↑	↑↑	↑			Dundon et al. (2008)
MU recruitment threshold	↓↓↓		↓↓↓			Dartnall et al. (2009)
MU discharge rate	↑	↑				Dartnall et al. (2009), Piitulainen et al. (2012)
MU synchronization	↑↑		↑↑		↑↑	Dartnall et al. (2008, 2011)
MU conduction velocity	↓	↓	↓	↓		Hedayatpour et al. (2009), Piitulainen et al. (2010)

EMG, electromyography; MU, motor unit. The number of arrows reflects the relative strength of the change. Grey arrows indicate some inconsistency in findings between studies.

also contribute to the increased submaximal EMG in the damaged agonist muscles after eccentric exercise.

Eccentric exercise, EMG and fatigue

One intervention that can drastically modulate motor unit activity and muscle function is a fatiguing contraction, which can be quantified as a decline in the maximum strength of the muscle, and typically results in a reduction in the time to task failure (endurance time) during a sustained isometric contraction. Along with the decline in muscle strength that occurs following eccentric exercise, there is typically an increase in fatigability of the muscle after eccentric exercise (Asp et al. 1998, Doncaster & Twist 2012), but a decrease in fatigability may be observed under some circumstances, such as during a sustained maximal contraction (Byrne & Eston 2002). Although these studies may be confounded by differences in absolute strength after eccentric exercise, an increase in fatigability is still observed even when the target force is matched to the reduced strength of the damaged muscle. For example, Hedayatpour et al. (2008a) found a 40% reduction in endurance time during a sustained submaximal contraction of the knee extensor muscles when performed 24 and 48 h after eccentric exercise. Perhaps, the most intriguing finding of this study was that there was a progressive decrease in EMG amplitude throughout the fatiguing contraction when performed after eccentric exercise. This pattern of muscle activity is opposite to the expected increase in EMG with fatigue during submaximal contractions (Fuglevand et al. 1993b), due at least in part to the recruitment of additional motor units to compensate for the fatigue-related decline in the ability of the active muscle fibres to generate force (Adam & De Luca 2005). This finding suggests that eccentric exercise

alters the neural activation strategies during a fatiguing isometric contraction, which may be due to altered afferent feedback from the injured muscle (Hedayatpour et al. 2008a). Possible candidate afferent pathways that may be influenced by eccentric muscle damage include group III and IV muscle afferents (Mense & Meyer 1988) and altered nociceptor sensitization (Ciubotariu et al. 2004), which may influence primary muscle spindle afferents at the spinal cord level (Weerakkody et al. 2001). However, it has been shown that there is no change in the muscle spindle afferent response, following a series of eccentric contractions in the anesthetized cat (Gregory et al. 2004).

Further support for an exercise-related change in neural activation strategies has been obtained in a recent study involving eccentric exercise of the elbow flexor muscles (Semmler et al. 2013). In this study, EMG activity was recorded from three elbow flexor muscles (biceps brachii, brachialis and brachioradialis) during a submaximal fatiguing isometric contraction performed before, 2 h after and 2 days after eccentric exercise. When the target force was matched to 30% of maximum strength of the muscle obtained in each recording session, there was a 29% reduction in endurance time when performed 2 h after exercise, which had recovered to baseline levels 2 days later. This decrease in endurance time was accompanied by an increase in EMG activity in biceps brachii and brachioradialis muscles throughout the fatiguing contraction when performed 2 h after eccentric exercise, which is in contrast to the decreased EMG observed previously in the knee extensor muscles (Hedayatpour et al. 2008a). However, there was a change in EMG–EMG coherence in specific elbow flexor muscle pairs when the fatiguing contraction was performed after eccentric exercise. Along with the expected increase in EMG–EMG coherence with fatigue (Danna-Dos

Santos *et al.* 2010, Kattla & Lowery 2010), there was a greater increase in EMG–EMG coherence between the biceps brachii and brachialis muscles at the end of the fatiguing contraction when it was performed 2 h after exercise, even though there was no difference in coherence at the start of the fatiguing contraction at any time point (Fig. 2). This finding suggests that there is an increase in common oscillatory inputs to biceps brachii and brachialis muscles after eccentric exercise in the presence of neuromuscular fatigue, which may be a deliberate neural strategy to maintain the target force and optimize endurance or may represent adjustments in the CNS resulting from altered feedback from the fatigued and damaged muscle (Semmler *et al.* 2013).

Another characteristic of fatiguing exercise is the emergence of low-frequency fatigue, which is the disproportionate loss of force when motor units are discharging at low compared with high frequencies (Edwards *et al.* 1977). Although low-frequency fatigue occurs after different types of fatiguing exercise, it is typically greatest after eccentric exercise compared with isometric or concentric exercise (Newham *et al.* 1983, Jones *et al.* 1989; see Fig. 3). Furthermore, it has a slow recovery process that can take several days (Edwards *et al.* 1977, Dundon *et al.* 2008; see Table 1), and occurs in the absence of any metabolic disturbance in the muscle (Jones 1996). The mechanism of low-frequency fatigue is thought to involve an impairment of one or more processes of excitation–contraction coupling (Edwards *et al.* 1977) and is likely to produce a decrease in calcium release from the sarcoplasmic reticulum (Westerblad *et al.* 1993). Along with its effect on muscle force, an increase in low-frequency fatigue would be expected to contribute
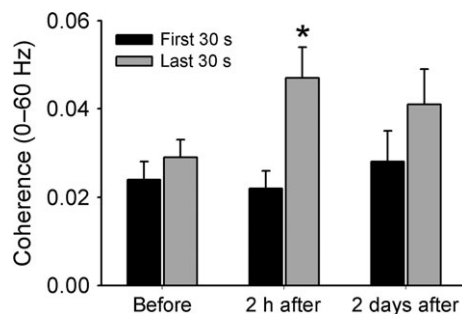
to an increase in EMG at low forces, because single motor units discharging at low rates would no longer be producing an equivalent force, requiring the additional recruitment of higher-threshold motor units to compensate for the force loss. Dundon *et al.* (2008) tested this hypothesis by examining the association between the change in low-frequency fatigue and the change in biceps brachii EMG obtained at contraction intensities ranging from 5 to 60% MVC when performed before, 2 h after and 24 h after concentric and eccentric exercise. In this study, low-frequency fatigue was assessed from the ratio of 20 Hz to 100 Hz force obtained following electrical stimulation of the biceps brachii muscle. From these data, a significant association was found between the change in low-frequency fatigue and the change in biceps brachii EMG before and after eccentric exercise, with the strongest correlations observed at 20% MVC (Fig. 3a). The change in low-frequency fatigue was also weakly associated with the change in isometric force fluctuations of the elbow flexor muscles when performed 2 h after concentric and eccentric exercise (Fig. 3b). These data suggest that the change in motor unit activity with low-frequency fatigue (de Ruiter *et al.* 2005) makes a substantial contribution to the increase in EMG that is observed after exercise, with the greatest effect obtained at low forces (20% MVC).

Single motor unit activity and eccentric exercise

Although the conventional surface EMG approach is simple to use and is useful in some situations, the surface EMG is generally considered a crude indicator of the neural drive to the muscle (Farina *et al.* 2010). As a more direct approach, several studies have used alternative recording techniques to examine the change in single motor unit activity after eccentric exercise (Table 2). These techniques include intramuscular fine-wire electrodes that are inserted into the muscle of interest with a hypodermic needle and provide unambiguous information about the discharge properties of motor neurones due to the high safety factor for action potential transmission at the neuromuscular junction. However, this technique is commonly limited to low-force contractions due to an inability to separate action potential waveforms from multiple motor units that discharge action potentials at similar times, which occurs most often at high forces due to increased motor unit activity. Alternatively, some studies have used surface electrode arrays and a decomposition algorithm to extract single motor unit action potentials from a motor unit population up to near maximum contraction levels. Although the results from surface electrode arrays are impressive,

Figure 2 EMG–EMG coherence from the biceps brachii–brachialis muscle pair obtained in the first and last 30 s of a fatiguing isometric contraction involving the elbow flexor muscles. Data represent the integral of coherence from 0 to 60 Hz and were obtained before, 2 h after and 2 days after eccentric exercise. *$P = 0.003$ compared with first 30 s 2 h after exercise and $P = 0.04$ compared with last 30 s before exercise. Data obtained from Semmler *et al.* 2013.

Figure 3 Association between the change in low-frequency fatigue (20 : 100 Hz force) and the change in biceps brachii electromyography (a) and force fluctuations (b) at 20% of maximum force obtained before and 2 h after concentric (unfilled symbols) and eccentric (filled symbols) exercise. Data obtained from Dundon *et al.* (2008).
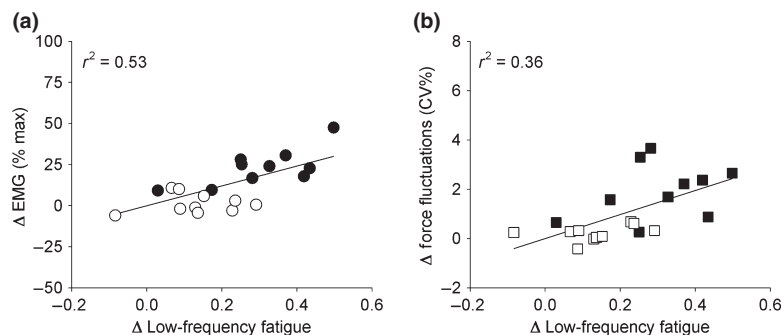
they are limited to superficial motor units that can be identified in the recordings during isometric contractions (Farina *et al.* 2010). There is also some doubt about the accuracy and validity of the decomposition algorithm at high forces (Farina & Enoka 2011), although the accuracy of this method has been defended (De Luca & Nawab 2011).

Correlated motor unit activity

Despite the technical capabilities being available for nearly 100 years (Adrian & Bronk 1929), Dartnall *et al.* (2008) were the first to use intramuscular electrodes to examine single motor unit activity during low-force isometric contractions after eccentric exercise. This study examined correlated motor unit activity from pairs of concurrent activity motor units in the biceps brachii muscle using a synchronization (time domain) and coherence (frequency domain) analysis that was assessed before, immediately after and 24 h after eccentric exercise of the elbow flexor muscles. They found that there was a 20–34% increase in motor unit synchronization and low-frequency (0–10 Hz) coherence immediately after and 24 h after eccentric exercise. Although computer simulation studies have shown that motor unit synchronization can increase the amplitude of the EMG due to action potential summation (Yao *et al.* 2000, Zhou & Rymer 2004), the amplitude of the submaximal EMG largely recovered to baseline levels 24 h after exercise when correlated motor unit activity was still elevated (see Table 1), suggesting that motor unit synchronization and coherence are likely to play only a minor role in the increased EMG after eccentric exercise. Nonetheless, a subsequent study showed that the increased motor unit synchronization (but not coherence) was elevated for at least 7 days after exercise (Dartnall *et al.* 2011), suggesting that a change in motor unit activity could provide a potential mechanism for the reduced muscle damage that is commonly observed with repeated bouts of eccentric exercise (Chen 2003, McHugh 2003, Howatson *et al.* 2007).

As an additional assessment of correlated motor unit activity, a recent study has used a surface electrode array to examine the low-frequency common modulation of mean motor unit discharge rates before and after eccentric exercise of the elbow flexor muscles (Beck *et al.* 2012). This assessment, referred to as common drive, shows that concurrently active motor units share a low-frequency (1–2 Hz) modulation of their discharge rates from a common source, which is thought to free the nervous system from independent control of populations of motor units (De Luca *et al.* 1982). In this study, subjects performed trapezoid isometric contractions of the elbow flexor muscles to 50% of maximum force before and immediately after 60 maximal eccentric contractions, which reduced the maximum strength of the muscle by 20% (Beck *et al.* 2012). From a large number of motor units (approx. 250) in 11 subjects, they found that common drive was not influenced by eccentric exercise. This outcome is surprising, given that a previous study using the conventional intramuscular recording technique showed increased low-frequency coherence immediately after and 24 h after exercise (Dartnall *et al.* 2008), with this low-frequency coherence thought to be quantitatively similar to common drive (Myers *et al.* 2004). The reasons for this discrepancy between the two studies are unclear, but could be related to the magnitude of muscle damage induced in each study. For example, Dartnall *et al.* (2008) performed 60–280 eccentric contractions with a free weight to induce a decline in maximal strength of at least 40% in each subject, with a reduction in strength of 31% obtained 1 day after exercise, a change in relaxed elbow joint angle (reflecting an increase in muscle stiffness) and an increase in muscle soreness 24 h later. In contrast, Beck *et al.* (2012) performed 60 maximal isokinetic eccentric contractions in each subject that only resulted in a 20% decline in strength immediately after exercise, with no indication of whether this decline in strength was long-lasting, and no other indicators of muscle damage (soreness and stiffness) were assessed.

Table 2 Summary of studies examining motor unit activity after eccentric exercise and muscle damage

Study	Muscle	Recording technique	Subject details	No. of contractions	Exercise mode	Decline in strength	MU measurement	Effect
Beck et al. (2012)	Biceps brachii	Surface electrode array	11 men	60	Isokinetic dynamometer	20% (0 h)	Common drive (CD)	No Change in CD
Dartnall et al. (2008)	Biceps brachii	Intramuscular wire electrode	6 men 2 women	60–280	Free weight	46% (0 h) 31% (1 day)	Synchronization (SYN) Coherence (COH)	30% ↑ (0 and 24 h) in SYN; 20% ↑ (0 h) and 34% ↑ (24 h) in COH
Dartnall et al. (2009)	Biceps brachii brachialis	Intramuscular wire electrode	6 men 4 women	30–110	Free weight	42% (0 h) 29% (1 day)	Recruitment threshold (RT) Discharge rate (DR)	41% ↓ in RT (0 h); 39% ↓ in RT (24 h); 11% ↑ in DR (0 h)
Dartnall et al. (2011)	Biceps brachii	Intramuscular wire electrode	4 men 4 women	30–110	Isokinetic dynamometer	42% (0 h) 40% (1 day) 11% (7 days)	Synchronization (SYN) Coherence (COH)	57% ↑ in SYN (7 days); No change in COH (7 days)
Hedayatpour et al. (2009)	Vastus medialis	Surface electrode array and intramuscular wire electrode	10 men	100	Isokinetic dynamometer	26% (1 day) 24% (2 days)	Conduction velocity (CV)	6–10% ↓ in CV (24 and 48 h)
Piitulainen et al. (2010)	Biceps brachii	Surface electrode array	9 subjects	50	Isokinetic dynamometer	21% (2 h) 13% (2 days)	CV	6–7% ↓ in CV (2 h)
Piitulainen et al. 2011,	Biceps brachii	Surface electrode array	24 men	60	Isokinetic dynamometer	30% (0 h) 25% (2 h)	CV	12% ↓ in CV (2 h)
Piitulainen et al. (2012)	Biceps brachii	Surface electrode array	16 men	50	Isokinetic dynamometer	21% (2 h) 13% (1 day)	CV DR	5–7% ↓ in CV[†] 16% ↑ in DR (2 h)*

Arrows indicate relative increase or decrease after compared with before eccentric exercise.

MVC, maximal voluntary contraction; 1RM, one-repetition maximum; ns, no significant difference after training.

*Only at 50 and 75% MVC (no change at 10, 20, 30, 40% MVC).

[†]Only at 40, 50 and 75% MVC (no change at 10, 20, 30% MVC).

Motor unit recruitment and discharge rate

Motor unit recruitment and rate coding represent the fundamental strategies to regulate the force output of muscle. The recruitment of motor units is based on the size principle, in which small motor neurones are recruited before large motor neurones (Henneman 1957). Although the order of recruitment is relatively consistent, the force level at which motor units are recruited, termed the recruitment threshold, can change depending on the details of the task performed (Desmedt & Godaux 1977, Pasquet *et al.* 2006) and is influenced by acute and chronic interventions such as fatigue and immobilization (Duchateau & Hainaut 1990, Carpentier *et al.* 2001). Furthermore, when a single motor unit is recruited, the rate at which motor units discharge action potentials is an important determinant of contractile force, with its effect determined by the extent of summation of the motor units according to a sigmoidal function known as the force–frequency relation (Bigland & Lippold 1954). As both motor unit recruitment and rate coding represent key features of the neural drive to muscle, any increase in EMG after eccentric exercise is likely to occur due to a change in one or both of these properties of motor unit activation. Accordingly, Dartnall *et al.* (2009) showed an approx. 40% decline in biceps brachii motor unit recruitment threshold immediately after and 24 h after eccentric exercise. This finding suggests that more biceps brachii motor units were active at the same relative force after eccentric exercise, possibly due to increased antagonist muscle activity and/or low-frequency fatigue, contributing to the observed increase in biceps brachii EMG for low-force contractions (Dartnall *et al.* 2009). Interestingly, there was no change in motor unit recruitment thresholds in the brachialis muscle and only a modest (11%) increase in minimum motor unit discharge rates in biceps brachii and brachialis muscles, suggesting that the effects of eccentric exercise on motor unit activity may be muscle dependent. Further insights may be gained by examining the change in motor unit activity during and after eccentric exercise in other upper and lower limb muscles, some of which are less susceptible to damage than others (Chen *et al.* 2011).

Motor unit conduction velocity

The conduction velocity of individual motor units is typically examined using an electrode array placed on the surface of the muscle, by detecting the delay between two and more similar EMG signals obtained in parallel with the muscle fibre orientation (Merletti *et al.* 2008). Motor unit conduction velocity is known to be associated with several characteristics related to the size of the motor unit, such as twitch force (Andreassen & Arendt-Nielsen 1987) and recruitment threshold (Masuda & De Luca 1991), and is influenced by different parameters of muscle activation such as motor unit discharge rate (Nishizono *et al.* 1989) and fatigue (Bigland-Ritchie *et al.* 1981). In addition to these effects, recent studies have shown that eccentric exercise that induces muscle damage results in a decline in motor unit conduction velocity. For example, Hedayatpour *et al.* (2009) were the first to show a decline of 6–10% in vastus medialis motor unit conduction velocity during low-force contractions (10 and 30% MVC) when performed 24 and 48 h after eccentric exercise. This decline was accompanied by an even greater reduction in conduction velocity throughout the low-force sustained (60 s) contractions when performed after eccentric exercise. Additional studies from the biceps brachii muscle obtained 2 h after eccentric exercise have shown that the reduced conduction velocity is greatest at high forces (Piitulainen *et al.* 2010, 2012), with this effect accentuated after eccentric compared with concentric exercise (Piitulainen *et al.* 2011). A decrease in the mean muscle fibre conduction velocity can have a profound effect on the EMG (Bigland-Ritchie *et al.* 1981), because there will be greater overlap of action potentials resulting in increased action potential summation (Keenan *et al.* 2005). Furthermore, this effect would be accentuated in the presence of increased motor unit synchronization (Keenan *et al.* 2006), which has been observed after eccentric exercise (Dartnall *et al.* 2008). These findings suggest that a decrease in motor unit conduction velocity, combined with an increase in motor unit activity (recruitment, discharge rate and synchronization), is likely to have a major contribution to the increase in EMG that is observed 0–2 h after eccentric exercise (Table 1).

Preferential damage to high-threshold motor units in humans?

It is a commonly held view that high-threshold (type II) motor units are more susceptible to damage after eccentric exercise. This evidence has been obtained predominantly from animal studies (Lieber & Friden 1988, Friden & Lieber 1992, Vijayan *et al.* 2001), which have shown that fast-twitch glycolytic muscle fibres are preferentially damaged after eccentric exercise, and occurs because of physiological and structural differences between the fibre types that include differences in ATP regeneration and depletion (Friden & Lieber 1992), differences in optimal length–tension characteristics (Brockett *et al.* 2002) and differences in the structural integrity of the sarcomere (Friden *et al.* 1983, Friden & Lieber 1992). Aside from the

functional differences in motor unit and muscle fibre properties between animals and humans (see Bigland-Ritchie *et al.* 1998), these studies in animals have usually used artificial activation of muscle during forced lengthening that is likely to produce a different activation of motor units compared with voluntary contractions (Bergquist *et al.* 2011), and this alternative activation may result in qualitative differences in muscle damage. For example, Crameri *et al.* (2007) examined the effect of 210 maximal eccentric contractions of the knee extensor muscles in humans that were performed voluntarily in one leg and with electrical stimulation in the other leg. Although the extent of muscle soreness was the same between groups, they found a rapid decline in neuromuscular function with voluntary exercise that was not matched by the electrical stimulation exercise. Furthermore, they found differences in the disruption of cytoskeletal proteins (desmin), myogenic growth factors (myogenin), Z-line disruption and satellite cell markers between the two exercise conditions (Crameri *et al.* 2007). The main reasons for these differences are likely to be multifaceted, including changes in the recruitment pattern of motor units (Gregory & Bickel 2005) and differences in the damage induced in synergistic muscles between the voluntary and electrically induced contractions. Nonetheless, these findings suggest that the muscle damage from electrically induced contractions in animals is likely to be different compared with voluntary eccentric exercise in humans, and the translation of results from animals to humans should be treated with caution when different exercise protocols are used to induce muscle damage.

In contrast to the evidence of preferential damage to type II muscle fibres in animal studies, the available evidence for this effect in humans is limited. In one of the most highly cited articles on this topic involving human muscle biopsies, Friden *et al.* (1983) found that 32% (1 h after exercise), 52% (3 days) and 12% (6 days) of the observed vastus lateralis fibres showed focal damage after backwards cycling exercise, but the percentages only corresponded to 1.6, 2.4 and 0.6% of the total fibre area. From the average of all subjects in this study, Z-line disturbances were greater in type II fibres, but this was clearly evident in less than half of their subjects (one of three subjects 1 h after exercise, three of six subjects 3 days after exercise and zero of three subjects 6 days after exercise). Furthermore, from muscle biopsy samples in human gastrocnemius muscle, Jones *et al.* (1986) found greater damage in type II fibres in only one severely affected subject after walking backwards on the treadmill, and this only occurred more than 7 days after the exercise, which is beyond the necessary recovery period for most measures of neuromuscular function. Interest-

ingly, Hortobagyi *et al.* (1998) showed evidence of normal muscle biopsy samples in the vastus lateralis muscle 7 days after exercise, but showed myofibrillar disruption 2 days after a second bout of exercise, despite no effect on neuromuscular function at this time. Aside from the sampling bias inherent with this biopsy technique, the lack of a consistent effect on selective fibre-type damage between subjects suggests that the findings are highly variable and remain unconvincing.

Several studies based on measures of neuromuscular function before and after eccentric exercise have interpreted their findings to support preferential damage to high-threshold motor units, but they are based on indirect evidence that is anecdotal or inconsistent. For example, Byrne & Eston (2002) suggest that there is decreased fatigability during sustained MVCs after eccentric exercise that indicates a greater relative contribution from fatigue-resistant muscle fibres, but an increase in fatigability after eccentric exercise has also been observed on several occasions for maximal (Endoh *et al.* 2005) and submaximal contractions (Hedayatpour *et al.* 2008b, Semmler *et al.* 2013). Furthermore, Kroon & Naeije (1991) showed that the mean frequency of the EMG decreases at a faster rate throughout a fatiguing contraction when performed after eccentric exercise, but this could be due to a greater decrease in conduction velocity of both low- (Hedayatpour *et al.* 2009) and high-threshold motor units (Piitulainen *et al.* 2012), or a greater accumulation of metabolites and shifts in ionic concentrations after eccentric exercise (Hedayatpour *et al.* 2008b). Nonetheless, several studies have shown no difference in the rate of decline of the EMG median frequency during sustained contractions after eccentric exercise (Leger & Milner 2001a, Semmler *et al.* 2013), suggesting that this effect may be dependent on factors other than the preferential damage to high-threshold motor units.

The remaining evidence for preferential damage to high-threshold motor units after eccentric exercise in humans comes from more direct measures of motor unit activity obtained during tasks at different contraction intensities (Table 3). Although there are limited data at high forces due to technical difficulties of recording high-threshold motor units, only one study has shown that motor unit activity is more affected at high contraction intensities compared with low contraction intensities after eccentric exercise. Using a surface electrode array over the biceps brachii muscle, Piitulainen *et al.* (2012) showed an increase in mean motor unit discharge rate and a decrease in motor unit conduction velocity 2 h after eccentric exercise, but only at the highest contraction intensities (50 and 75% MVC) and not at the lowest contraction

Table 3 Effect of contraction intensity on the relative change in motor unit activity after eccentric exercise

	Force level			
	Low	Intermediate	High	References
Surface EMG	↑↑↑	↑↑	↑	Semmler et al. (2007), Dartnall et al. (2008) (see text for many others)
MU recruitment threshold	↓↓↓	?	?	Dartnall et al. (2009)
MU discharge rate	↑	↑	↑	Dartnall et al. (2009), Piitulainen et al. (2012)
MU synchronization	↑↑	?	?	Dartnall et al. (2008, 2011)
MU conduction velocity	↓	↓	↓↓	Hedayatpour et al. (2009), Piitulainen et al. (2010, 2012)

EMG, electromyography; MU, motor unit. ? indicates that there is no evidence available at this contraction intensity.

intensities (10–40% MVC). Whilst these findings are interesting, they do not provide measures of motor unit recruitment thresholds that provide a reliable indicator of motor unit size (Milner-Brown et al. 1973), so an assumption is made that these effects are caused by the recruitment of larger motor units. Furthermore, it is not clear why the findings from Piitulainen et al. (2012) do not support previous studies that show changes in motor unit conduction velocity (Hedayatpour et al. 2009) and motor unit discharge rates (Dartnall et al. 2009) at low forces. Nonetheless, because the recordings are obtained from the surface of the muscle, they are presumably influenced by swelling and inflammation that occur after eccentric exercise, which is likely to change the geometry between the active muscle fibres and the recording electrodes. This effect may impact on the accuracy of the decomposition technique and influence the maximum number of accurately detected motor units, suggesting that the surface electrode array may not be ideal for examining motor unit activity after muscle damage.

In contrast to the change in motor unit conduction velocity, several other measures of motor unit activity indicate that there are substantial changes in low-threshold motor units after eccentric exercise, which casts some doubt on the notion of preferential damage to high-threshold motor units after eccentric exercise in humans (Table 3). As discussed earlier, the relative increase in EMG after eccentric exercise is greatest at low forces and decreases with increasing contraction intensity (Fig. 1). This increase in EMG is accompanied by a large decrease in motor unit recruitment threshold (Dartnall et al. 2009) and an increase in correlated motor unit activity (Dartnall et al. 2008) at low forces, indicating that more motor units are active at low forces and discharge more action potentials at similar times after eccentric exercise. However, there are no assessments of motor unit recruitment thresholds and motor unit synchronization at intermediate and high forces after eccentric exercise (Table 3), so it is possible that these changes could be greater at higher contraction intensities.

Future motor unit studies that are designed to assess the effect of eccentric exercise on high-threshold motor unit activity must assess motor unit recruitment thresholds to provide a reliable indicator of motor unit size. Furthermore, these studies are likely to require the use of a decomposition technique from intramuscular (Nawab et al. 2008) or subcutaneous electrodes (Gydikov et al. 1986) to avoid the effect of muscle swelling on the action potentials detected from surface electrodes.

Physiological and functional implications

Eccentric contractions have important implications for sports medicine and exercise science as they offer significant advantages for training and rehabilitation because of their potential to produce large forces with a low metabolic cost (Abbott et al. 1952). For example, eccentric exercises have been shown to be effective in reducing muscle strains (Proske et al. 2004), to improve recovery after immobilization (Hortobagyi et al. 2000) and for treating Achilles tendon pain (Silbernagel et al. 2001). However, the consequence of performing unaccustomed eccentric exercise is that it causes significant muscle damage and soreness that negatively impacts neuromuscular function and, under certain conditions, may be responsible for more severe muscle injury (Proske et al. 2004). The challenge is to harness the potential of eccentric exercise to improve neuromuscular function whilst minimizing the negative effects of exercise-induced muscle damage. As single motor units represent the final output pathway of the motor system and are the smallest elements of neuromuscular control, a greater understanding of motor unit behaviour after eccentric exercise is necessary for refining interventions for injury prevention, injury treatment and strength training. For advances to be made in this area, we need to know more about the motor unit activation strategies during lengthening muscle contractions and how they adapt following muscle damage, to determine whether the changes might represent a protective mechanism or be a consequence of the induced muscle damage.

General summary and conclusions

This brief review has summarized the available evidence showing changes in muscle activation after eccentric exercise induced muscle damage in humans. This evidence has largely been inferred from the characteristics of the surface EMG, which shows a more-than-proportional increase in EMG at low forces after eccentric exercise. In contrast, there are relatively few studies examining the neural activation of damaged muscle at the level of the single motor unit, which provides a window into the control of muscle at the spinal motor neurone level. These studies have shown that eccentric exercise results in substantial changes in motor unit recruitment thresholds, discharge rates, motor unit conduction velocities and synchronization, which can last for up to 1 week after muscle damage. When examining the time course of these changes during recovery from eccentric exercise, the increased EMG at low forces most likely occurs through a decrease in motor unit conduction velocity and an increase in motor unit activity. Available evidence suggests that the increase in motor unit activity includes greater recruitment of motor units and an increase in motor unit discharge rates, which may be related to an increase in antagonist muscle coactivation and low-frequency fatigue that accompanies muscle damage. However, due to technical difficulties, there are limited data on the behaviour of motor units at high forces after muscle damage. Animal studies would suggest that there is preferential damage to high-threshold motor units, but the human evidence to support the animal data is not convincing. It is concluded that eccentric exercise that induces muscle damage produces dramatic and long-lasting changes in human motor unit activity, but further work in humans is needed to establish if these effects are greatest at high forces.

Conflict of interest

None.

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