Eccentric muscle actions: Implications for injury prevention and rehabilitation

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Abstract

Many acute muscle strain injuries are thought to occur during the eccentric phase of sudden, forceful muscle actions. Repeated eccentric muscle actions during exercise are also thought to contribute to microscopic muscle and tendon damage, leading to chronic muscle strains, muscle rupture and tendinopathy. Conversely, eccentric training has been demonstrated to have a positive effect in the prevention of muscle damage and injury. The properties of eccentric muscle actions which lead to this protective effect remain to be elucidated but are thought to include cellular, mechanical and neural adaptations. This clinical commentary is an attempt to analyze the potential role that eccentric training may have in both the contribution to and prevention of muscle injury by exploring the effect of various parameters on muscle structure and function. Guidelines as to the appropriate design of eccentric training programmes are also provided.

Keywords: Eccentric muscle actions; Muscle injury; Injury prevention; Rehabilitation

1. Introduction

Strain injuries occur when muscle and tendon fibres cannot maintain the tension placed upon them and are disrupted. These lesions are among the most common sporting injuries and their rate of recurrence is high (Garrett, 1990; Seward, Orchard, Hazard, & Collinson, 1993), suggesting that current prevention and treatment strategies are less than optimal.

Muscle strain injuries range in severity from minor damage with minimal loss of muscle function, to more complicated conditions with total rupture of muscle continuum, marked reductions in muscle strength, severe bruising and swelling, and severely impaired function (Coburn, 2002).

Many explanations for the production of muscle strain injuries have been offered, however it is likely that a number of factors are involved (Garrett, 1990; Worrell, 1994). Lack of flexibility (McHugh, Connolly, Eston, Kremenic, Nicholas, & Gleim, 1999; Witvrouw, Danneels, Asselman, D’Have, & Cambier, 2003), strength deficits (Croisier, Forthomme, Namurois, Vanderthommen, & Crielard, 2002; Dauty, Potiron-Josse, & Rochcongar, 2003; Jonhagen, Németh, & Eriksson (1994); Tyler, Nicholas, Campbell, & McHugh, 2001) fatigue (Croisier, 2004; Mair, Seaber, Glisson, & Garrett, 1996), muscle imbalances (Dauty et al., 2003), inadequate warm-up (Evans, Knight, Draper, & Parcell 2002; Hawkins & Fuller, 1999; Safran, Garrett, Seaber, Glisson, & Ribbeck, 1998; Shellock & Prentice, 1985), altered biomechanics (Croisier, 2004) and previous injury (Jönhagen et al., 1994), are among the commonly cited potential causes.

It has been suggested that muscle strains most frequently occur during the eccentric phase of movement, i.e. when the muscle is acting whilst lengthening...
Proske, 2004). Moreover, exercise that involves eccentric muscle actions is implicated in the causation of exercise-induced muscle damage and soreness (Lieber, Shah, & Friden, 2002). It has been hypothesized that this type of eccentric-induced muscle damage could be a precursor to macroscopic muscle strain injuries (Brockett, Morgan, & Proske, 2004).

Muscle strains most commonly occur in bi-articular muscles such as the hamstrings, rectus femoris and gastrocnemius (Coburn, 2002). During sporting activities such as sprinting, these long, bi-articular muscles have to cope with high internal forces and rapid changes in muscle length and mode of contraction. An elegant example of this is offered via an videographic report of a cricket player’s gastrocnemius being ruptured whilst acting eccentrically to control dorsiflexion of a weight bearing foot (Orchard, Alcott, James, Farhart, Portus, & Waugh, 2002). However, muscle strains have also been reported to occur during slow-lengthening muscle actions such as those performed by ballet dancers (Askling, Tengvar, Saartok, & Thorstensson, 2000).

Conversely, other studies have reported reductions in the incidence of muscle injuries and damage following strengthening and exercise programmes based on eccentric contractions (Askling, Karlsson, & Thorstensson, 2003; Nosaka & Newton, 2002). Similarly, there is support for the use of eccentric exercise programmes in the management of tendinopathy (Peers & Lysens, 2005), especially Achilles tendinopathy (Alfredson, 2003; Ohberg, Lorenzo, & Alfredson, 2004). There is also considerable evidence that eccentric contractions might induce some sort of adaptation which would reduce the likelihood of exercise induced muscle damage. This protective effect has been referred to as the repeated bout effect (Nosaka & Clarkson, 1995). Unfortunately the exact mechanisms regulating this adaptive response are not yet well understood (McHugh, 2003).

This article explores the role of eccentric muscle contractions in the production, prevention and rehabilitation of muscular injuries.

2. Eccentric training and muscle stiffness

Eccentric training produces changes in the normal structure of the muscle–tendon unit. This structure becomes less compliant (stiffer) increasing the force required to produce a change in its length (Leger & Milner, 2000).

Several theories have been postulated in order to explain the increased muscle stiffness observed following eccentric exercise. It has been proposed, for example, that the acute decrease in compliance could be due to an increase in Ca\(^{2+}\) released following exercise-induced myofilament disruptions and also as a result of contractures in damaged muscle, i.e. the fibers remaining shortened despite no longer firing impulses are induced (Allen, 2001; Friden & Lieber, 1992; Jones, Allen, Talbot, Morgan, & Proske, 1997; Whitehead, Weerakkody, Gregory, Morgan, & Proske, 2001). In addition, recent studies have shown that repeated eccentric training leads to longer-term increases in muscle stiffness (Lindstedt, Reich, Keim, & LaStayo, 2002) primarily attributable to adaptation of cytoskeletal proteins such as Actin, Desmin, Titin, Actinin and Nebulin in response to micro-injury (Alter, 2004). These proteins seem to be directly involved in the remodelling process of myofilaments disrupted during eccentric contractions. During this process, the muscle–tendon complex is thought to adapt its viscoelastic properties to enable it to absorb and transmit the forces produced during sudden and forceful contractions (Yu, Fürst, & Thornell, 2003).

However, whether this change in the musculo-tendinous stiffness decreases or increases the risk of muscle injury remains a source of controversy (Shrier, 2002). Recent findings suggest that a stiffer structure could improve the capacity of the muscle-tendon unit to absorb elastic energy, thus improving resistance to disruption (LaStayo, Woolf, Lewek, Reich, & Lindstedt, 2003; Lindstedt, LaStayo, & Reich, 2001; Lindstedt et al., 2002; Reich, Lindstedt, LaStayo, & Pierotti, 2000). These results apparently challenge the role of flexibility programmes aimed at preventing muscle injuries.

From a more classical stand point, others claim that increasing tendon stiffness could augment the risk of injury to the relatively compliant muscular component of the musculo-tendinous unit (Lieber, Leonard, & Brown-Maupin 2000). Supporting this last view McHugh et al. reported a positive correlation between hamstring stiffness and muscle damage following bouts of eccentric muscle actions (McHugh et al., 1999). Others, however, have failed to demonstrate a clear relationship between flexibility and muscle strain injury (Andersen, 2005).

New findings seem to indicate that it is possible that long term eccentric training leads to increased range of motion (ROM) measured in passive conditions (Nelson & Bandy, 2004). Although this idea requires further investigation, it could mean that the increase in passive muscle stiffness observed after chronic eccentric training (Leger & Milner, 2000; Lindstedt et al., 2001, 2002; Reich et al., 2000) does not limit per se, the ROM of a given joint and more importantly, that this adaptation might have prophylactic rather than harmful effects.
This might explain why stretching protocols aimed at reducing muscle damage after eccentric training have not been proved effective (Herbert & Gabriel, 2002; Lund, Vestergaard-Poulsen, Kanstrup, & Sejrsen, 1998).

Muscle length may be directly related to the amount of damage produced after eccentric muscle actions as it seems that the longer the sarcomere length, the greater the damage produced after a single eccentric action (Morgan & Proske, 2004). However, eccentric muscle training performed at short muscle lengths provide little or no “repeated bout” protective effect (McHugh & Pastakos, 2004; Nosaka, Newton, Sacco, Chapman, & Lavender, 2005) whilst, eccentric muscle actions performed in the outer range of muscle lengths produce a stronger protective effect (Nosaka et al., 2005).

Therefore, it could be suggested that passive muscle stiffness is not the main factor regulating muscle damage susceptibility from eccentric training. Moreover, given that during eccentric actions, muscle contracts while being lengthened, it is likely that functional adaptations might explain these apparently conflicting results.

3. Eccentric training and new sarcomere formation

An increase in the number of sarcomeres distributed in series has been observed following intensive periods of eccentric training (Butterfield, Leonard, & Herzog, 2005; Lynn, Talbot, & Morgan, 1998; Yu et al., 2003). This process of ‘sarcomerogenesis’ is not yet fully understood (Butterfield & Herzog, 2006) but has been suggested to have a protective effect on muscle-tendon structure (Friden, 1984; Proske & Morgan, 2001) possibly by allowing a reduced sarcomere length at a specific joint angle (Morgan & Proske, 2004). This, in turn, would increase the optimum torque angle, defined as the joint angle at which maximum muscle force is produced (Brockett, Morgan, & Proske, 2000; Proske & Morgan, 2001).

The relationship between sarcomere shortening and the decreased risk of injury is based on the premise that the lower the joint angle at which maximum force is generated, the greater the range through which the muscle is relatively weak, increasing susceptibility to exercise-induced muscle damage and muscle strain injury (Brockett et al., 2004; Gleeson, Eston, Marginson, & McHugh, 2003; Ploutz-Snyder, Tesch, & Dudley, 1998). Illustrating this, Proske and colleagues analyzed the torque-angle curves for human hamstring muscles, before and after bouts of eccentric exercise (Proske, Morgan, Brocket, & Percival, 2004). Apart from observing the shift in optimum torque angle mentioned above, the authors concluded that eccentric actions may protect muscle integrity by increasing the optimum torque angle as a consequence of the addition of new sarcomeres in series. In a previous study, the same group of researchers reported a reduction of the optimum torque angle in previously injured hamstrings compared with the uninjured muscles (Brockett et al., 2004). Interestingly, in this study, some preliminary data showed that training protocols emphasizing eccentric contractions could significantly reduce the number of hamstring strains injuries.

Interestingly, concentric muscle training appears to reduce the number of muscle sarcomeres in series (Huijing & Jaspers, 2005), which could effectively lower the optimum torque angle. Although controversial (Nosaka, Sakamoto, Newton, & Sacco, 2001), this potential adverse effect of concentric muscle actions should be considered when planning training and rehabilitation programmes.

It seems that not all muscles adapt to training in the same way (Huijing & Jaspers, 2005). Other factors intrinsically related to muscle architecture such as cross-sectional area (CSA), angle of pennation and fibre length could also contribute to varied sarcomere adaptation observed following similar training programmes (Lieber & Fridén, 2000). It is likely that these differences in muscle structure could explain variable susceptibility to injury across muscle groups (Garrett, Nikolaou, Ribbeck, Glisson, & Seaber, 1988) and also equivocal outcomes of eccentric based protocols in the treatment of tendon disorders (Jonsson & Alfredson, 2005; Visnes, Hoksrud, Cook, & Bahr, 2005).

4. Eccentric training and fatigue

There is evidence to suggest that fatigued muscles are less effective in their ability to absorb energy during eccentric contractions (Mair, Seaber, Glisson, & Garrett, 1996). In addition, an epidemiological investigation reported an increased incidence of muscle strain injuries occurring towards the end of either half of football matches (Woods, Hawkins, Maltby, Hulse, Thomas, & Hodson, 2004). Taken together, these findings suggest that fatigued muscles may be predisposed to strain injury.

Surprisingly, eccentric contractions seem to be less influenced by fatigue than other types of muscle actions (Tesch, Dudley, Duvoisin, Hather, & Harris, 1990a). In contrast to concentric muscle actions, fast twitch fibers and high threshold motor units are preferentially recruited during eccentric muscle activity (Nardone, Romanò, & Schieppati, 1989). In addition, levels of motor unit activation are lower during eccentric contractions (Tesch et al., 1990).

How then is it possible that, in spite of preferential recruitment of low endurance, high threshold motor units, eccentric actions display a greater relative resistance to fatigue? It is likely that the mechanical
advantages of lengthening contractions, such as a greater energy absorption and storage may explain this phenomenon (Lastayo et al., 2003).

Several studies have reported that eccentric muscle activity is more efficient than concentric actions at a given metabolic level, as increases in oxygen consumption during eccentric actions are insignificant in comparison with concentric or isometric actions (Dudley, Tesch, Harris, Golden, & Buchanan, 1991; Hather, Tesch, Buchanan, & Dudley, 1991). These results are consistent with investigations illustrating a relatively low ATP turnover (Ryschon, Fowler, Wysong, Anthony, & Balaban, 1997) and a reduced production of ammonia and lactate during eccentric, compared to concentric, muscle actions (Horstmann, Mayer, Maschmann, Niess, Roecker, & Dickhuth, 2001). These findings support the idea of superior metabolic efficiency of eccentric muscle actions.

However, several studies have reported important strength impairments immediately after eccentric exercise (Clarkson, Nosaka, & Braun, 1992). These deficits have been more evident in upper-limb muscles (Byrne, Twist, & Eston, 2004), in females (Sayers & Clarkson, 2001), at short versus long muscle lengths (Child, Saxton, & Donnelly, 1998), and at higher angular velocities of limb movement (Fridén, Sjöström, & Saxton, & Donnelly, 1998). Moreover, it seems that these force disturbances follow eccentric actions manifest in any type of muscle action (Michaut, Pousson, Babault, & Van Hoecke, 2002). This force reduction has been attributed to several factors such as excitation–contraction coupling impairment, mechanical adaptations within the muscle (sarcormogenesis), an increased susceptibility to damage of fast twitch fibers, and impaired glycogen resynthesis (Byrne et al., 2004).

Given that muscle injuries commonly take place when an athlete is fatigued and during eccentric actions it seems logical to train individuals under these specific conditions in order to reduce the risk of muscle damage. However, the side effects of muscle soreness and force disturbances observed after eccentric actions should be considered when planning training programmes.

5. Eccentric training and neural function

Neural adaptations produced by eccentric muscle actions could also contribute to the protective effect that this type of training may induce (McHugh, 2003). These adaptations seem to be related to a more efficient motor unit recruitment patterns produced by eccentric training (Clarkson & Hubal, 2002; Hortobagyi, Houmard, Fraser, Dudek, Lambert, & Tracy, 1998). Enoka suggested that eccentric muscle actions have a specific neural control pathway probably aimed at preventing muscle injuries (Enoka, 1996). Indeed, the unique neural behavior of eccentric actions has been illustrated in several studies showing: (i) an increased cross-education effect whereby strength gains are produced in the untrained contralateral limb (Enoka, 1996, 1997; Hortobagyi, Lambert, & Hill, 1997); (ii) faster neural adaptation from strength training (Hortobagyi et al., 1996; Hortobagyi, Devita, Money, & Barrier, 2001); (iii) increased cortical activity (Fang, Semionow, Sahgal, Xiong, & Yue, 2001) and (iv) an inverse motor recruitment pattern with preferential recruitment of high threshold motor units at all load levels (Nardone et al., 1989).

It is generally accepted that during eccentric actions there is greater relative force production despite slightly lower surface electromyographic (EMG) activity to comparable concentric muscle actions (Tesch et al., 1990). This fact is likely due to lower relative recruitment and discharge rates of active motor units secondary to the superior mechanical efficiency and energy dissipation of eccentric muscle actions.

Conversely, larger increases in EMG activity have been observed following eccentric, compared to concentric muscle training (Linnamo, Bottas, & Komi, 2000). This muscle activity increase occurs in spite of a decrease in median frequency EMG activity, suggesting that eccentric contractions lead to the enhancement of low-threshold unit activity. In theory, this increased activation of slow muscle fibers after the first bout of eccentric contractions could potentially reduce muscle damage by decreasing the workload on any single muscle fiber (Hortobagyi et al., 1998).

Although there are important differences in the neural control of eccentric versus other types of muscle actions (Enoka, 1996; Bishop, Trimble, Bauer, & Kaminski, 2000), the exact role of the central nervous system in the repeated bout effect is not clear. In fact, some authors have challenged the idea that the protective effect of eccentric training may be explained by neural adaptations. Nosaka and colleagues, for example, showed that the repeated bout effect could also be observed using electrical stimulation, suggesting that the central nervous system is not involved in muscle damage prevention (Nosaka, Newton, & Sacco, 2002a).

6. Eccentric training and proprioception

Proprioception is defined as the capacity of our body to permit the recognition of the position and movements of the limbs in relation with others parts of the body (Gollhofer, 2003). It is thought that proprioception can play an active role in preventing some sporting injuries by enhancing sensory motor control (Verhagen, van der Beek, Twisk, Bouter, Buhr, & van Mechelen, 2004). Proprioceptive information is transmitted by mechanoreceptors mainly located in muscles, tendons, joints and to a lesser extent, in the skin. Whereas position and
movement senses are provided by the muscle spindles, Golgi tendon organs signal changes in the rate of muscle force production (Gollhofer, 2003). It appears that neuromuscular function can be altered by exercise-induced muscle damage (Bottas, Linnamo, Nicol, & Komi, 2005; Byrne et al., 2004; Deschenes, Brewer, Bush, McCoy, Volek, & Kraemer, 2000). The possibility that changes within muscle structure that result from eccentric training may affect the normal function of these mechanoreceptors has been extensively studied (Brockett, Warren, Gregory, Morgan, & Proske, 1997; Fridén & Lieber, 2001).

Brockett et al. investigated the impact that eccentric and concentric training could have on control of limb position and force perception (Brockett et al., 1997). In this study the subjects sensed that their eccentrically trained arms were more flexed than they actually were whilst concentrically trained arms did not show significant alterations in the perception of limb position. Similar proprioceptive alterations were observed when force sense was assessed. It was concluded that peripheral proprioceptive function could be altered by muscle damage induced by eccentric training.

Previously, Saxton, Clarkson, James, Miles, Westerfer, Clark, Donnelly (1995) showed that the more intense the eccentric exercise performed, the greater the alterations found in the accuracy of proprioception. In this study the altered perception of the eccentrically trained arms in terms of both force and position senses lasted up to three days. This means that alterations in the control of force feedback and limb position can not only be explained as a consequence of acute changes such as inflammation (Whitehead et al., 2001), as the time courses for these two processes do not necessarily coincide.

Gregory, Brockett, Morgan, Whitehead, and Proske (2002) examined the variability in Golgi tendon organs responses to passive and active tension after bouts of eccentric muscle actions (Gregory et al., 2002). Surprisingly, although muscle damage and increases in whole-muscle passive tension were observed, the overall sensitivity of Golgi tendon organs remained unaltered. Furthermore, the same group of researchers (Gregory, Morgan, & Proske, 2003) also reported that muscle spindle function was conserved after eccentric muscle actions thus suggesting that these mechanoreceptors are not prone to be damaged under these specific conditions. Supporting these findings, increases in myotatic reflex, thought to be due to increased muscle spindle activation, have been observed in the patella tendon after bouts of eccentric muscle training (Hortobagyi, Hill, Houmard, Fraser, Lambert, & Israel, 1996).

These findings suggest that impaired sensory-motor sensitivity may not be directly linked to the structural damage observed in muscle structures. In addition, the proprioceptive deficits which appear after performing eccentric actions can not be explained solely by dysfunction of the peripheral afferent system. It is also evident that the observed increase in tendon organ signalling must have some implications for motor control and therefore, regulatory efferent mechanisms might be involved in these proprioceptive disturbances (Gregory, Morgan, & Proske, 2004; Proske, Weerakody, Percival, Morgan, Gregory, & Canny, 2003).

Although it is evident that further research is needed to better understand the interactions between eccentric muscle actions and impaired function of the proprioceptive system, in the meantime, the potential for short-term alterations in proprioceptive function should be factored into eccentric training programmes. For example it might be prudent to program (a) low-intensity proprioceptive activities, e.g. single leg balancing and (b) avoid high demand proprioceptive activities e.g. single leg bounding during sessions conducted in the 48 h following eccentric-based training.

7. Eccentric training and muscle strength gains

Many researchers have analyzed the role of eccentric muscle actions in strength training (Dudley, Tesch, Miller, & Buchanan, 1991; Fleck & Kraemer, 2004) however, the effectiveness of this type of training remains controversial (Hortobagyi et al., 2001; Johnson, Adamczy, Tennoe, & Stromme, 1976). When eccentric training is evaluated using protocols aimed at specifically assessing eccentric or even isometric force, it seems clear that the strength gains obtained are greater than those obtained from performing only concentric actions (Hilliard-Robertson, Schneider, Bishop, & Guiliams, 2003; Hortobagyi, Hill et al., 1996; Tesch et al., 1990).

Over one and half times maximal concentric load can be moved using eccentric muscle actions (Enoka, 1996). However, current exercise equipment design means that the eccentric load is often limited by the amount of load that can be lifted during the concentric phase of a movement. Therefore, overloading the eccentric phase becomes problematical and is not easily achieved in all muscle groups.

An interesting solution to this problem is offered via the use of a gravity-independent device designed to enhance strength by reducing muscle atrophy and bone mineral loss whilst improving overall fitness during space travel (Alkner & Tesch, 2004; Berg & Tesch, 1994, 1998; Tesch, Ekberg, Lindquist, & Trieschmann, 2004). This equipment utilizes the inertia produced by a rotating flywheel, permitting work in the absence of a gravitational force and allowing the performance of concentric actions while overloading the eccentric phase of movement. Studies conducted with this equipment have demonstrated strength gains, muscle hypertrophy,
and also reductions in muscle strain injuries in elite soccer players (Askling et al., 2003). Moreover, this type of training is thought to permit enhancement of explosive force in a safe way as it allows the performance of plyometric type jumping exercises, also called stretch-shortening-cycle (SSC) exercises, using relatively low jump heights, thereby possibly reducing the impact forces on joints (Komi, 2002).

Nevertheless, given that eccentric training produces muscle damage in direct proportion to the load used during this contraction, the question regarding the optimal intensity for eccentric programmes is not yet clear. Whereas some authors claim that intensity should be high in order to provide the stimulus necessary to produce further adaptations (Hortobagyi, Hill et al., 1996) others have found that the protective effect of eccentric training may be observed even using light resistances (Paddon-Jones & Abernethy, 2001).

### 8. Relationship between eccentric muscle strength and injury

As force production and magnitude of strain during eccentric muscle actions seem to be directly related to the severity of muscle damage observed after this type of exercise (Armstrong, Warren, & Warren, 1991) many studies have attempted to understand the relationship between strength and injury. Whereas in some studies, the lack of strength has been seen as a possible predictor of strain injuries (Garrett, 1990; Jönghagen et al., 1994; Orchard, Best, & Verrall, 2005; Orchard, Marsden, Lord, & Garlick, 1997), others studies have not found any such correlation (Bennell, WajsWelner, Lew, Schall-Riaucour, Leslie, Plant, 1998; Gaida, Cook, Bass, Austen, & Kiss, 2004) even when strength parameters were evaluated after injury (Worrell, 1994).

Brockett et al. (2004), for example, studied whether reductions in isokinetic optimum torque angle of the knee flexors is predictive of hamstring muscle injury. They found that athletes who suffered hamstring muscle strain had lower pre-existing isokinetic force and also a lower optimum torque angle in the injured leg.

Other authors have attempted to use flexor-extensor isokinetic ratios and bilateral flexor ratios as explanations for strain injuries of the knee musculature. Dauty et al. (2003), for example, analyzed whether isokinetic dysfunctions in elite soccer players could be a detector of previous hamstring injuries and a predictor of new muscle strains. In this study only the ratio of eccentric hamstrings to concentric quadriceps strength was useful in predicting previous hamstring injuries, whilst other combinations of parameters did not show any correlation to either previous or future injuries.

Similar studies have reported that athletes who had suffered a muscle strain showed disturbances in force production (Crosier et al., 2002; Dauty et al., 2003; Jönghagen et al., 1994). These muscle disorders varied depending on the velocity at which isokinetic force was recorded; however, a reduction in eccentric hamstring strength was a common feature in all these studies. Although there are obvious limitations in the use of isokinetic devices to imitate natural human movement, it is likely that using eccentric training regimes to conserve, or even increase optimum torque angle (Proske et al., 2004) and to correct forces imbalances (Crosier et al., 2002), might be an appropriate muscle strain prevention strategy.

### 9. Guidelines for the design of eccentric training programs

In general, it appears that eccentric training protocols may be beneficial in the prevention and treatment of muscle damage and injury. However, potential adverse effects of this type of training should be considered (Sayers, Clarkson, Rouzier, & Kamen, 1999). The following recommendations may help to maximize the benefits of eccentric training whilst minimizing potentially harmful side effects:

- Given the greater force production during eccentric actions (Enoka, 1996), whenever possible, the use of equipment specifically designed for eccentric training is advocated as these machines allow eccentric overload without high impact forces (Albert, 1995).
- Training parameters should follow the common guidelines applied to any strength or rehabilitation program (Fleck & Kraemer, 2004). However, the volume and intensity of eccentric training programmes should be gradually progressed in order to minimize the effect of exercise-induced muscle damage and to provide the stimulus necessary to produce ongoing adaptations (Cheung, Hume, & Maxwell, 2003; Friedmann et al., 2004).
- If strength gains are desired, eccentric actions should be overloaded from 20% to 80% beyond the maximal isometric strength (Fleck & Kraemer, 2004). However, we recommend the use of highest intensities only with strength athletes familiarized with this type of training.
- When planning the annual training calendar consideration should be given to avoiding high-intensity eccentric exercise during important competition phases as the side effects of transient muscle soreness and strength deficits may impair performance. In addition, the time course for adaptations from eccentric training should also be considered (Albert, 1995; Nosaka et al., 2001).
- As neuromuscular disturbances have been observed during the initial period of eccentric training,
coordination exercises and very demanding technical actions might be best avoided during this phase of training (Byrne et al., 2004).

- Progressively increasing the length at which muscle groups are trained may also help to minimize initial muscle damage whilst gradually improving outer range muscle strength.

- DOMS, along with indirect muscle damage markers such as Creatine Kinase (CK) or Myoglobin levels have a variable response between individuals (Vincent & Vincent, 1997) and therefore they should not be used as a gold standard when training sessions are planned (Nosaka, Newton, & Sacco, 2002b; Salmons, 1997).

- Eccentric actions should be avoided during the initial stages of rehabilitation (Walsleben, Pearson, & Stymiest, 1986). Eccentric protocols should commence as soon as possible (Mannheimer, 1969), normally during the sub-acute phase post-trauma (Albert, 1995). However, the intensity and volume of eccentric based programs should take into consideration aspects such as the degree of injury, the control of inflammation, and the time course adaptations of connective tissue scar formation (Järvinen, Järvinen, Kääriäinen, Kalimo, & Järvinen, 2005).

10. Conclusions

This clinical commentary has analyzed the potential role that eccentric training may have in both the contribution to and prevention of muscle injury by exploring the effect of various parameters on muscle structure and function. Although the exact mechanisms regulating the protective effect observed after eccentric contractions have not yet been elucidated, the use of strength training protocols incorporating lengthening contractions to protect muscle from strain injuries is a promising area of research. Further experimental studies should focus on the exact origin of “the repeated bout effect” in order to design adequate protocols for rehabilitation and prevention of muscle injuries. We recommend the use of randomized control trials (RCT) to analyze the impact of the different types of contractions on muscle injury prevention and rehabilitation. In addition, the use of well-controlled, long-term follow-up studies might bring about some more data related to the incidence of muscle injuries and the factors involved when they occur.

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