Eccentric Exercise as a Training Modality: A Brief Review

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Using barbell weight releasers 5 – 10 repetitions, 75 – 85% concentric 1RM and a releaser load of 40 – 55% may be optimal. Training isokinetically 24 – 30 maximal contractions, three times per week (6 – 10 weeks), may increase hypertrophy and strength.

Abstract

An eccentric muscle action involves the lengthening of a muscle due to an external load and occurs as a result of the mechanical disruption of action and myosin. The mechanical nature of the actin and myosin disruption during eccentric muscle actions is reported to allow for greater force production and requires a different neural activation pattern from a concentric action. As a consequence of these differences it is suggested concentric focused resistance training may not overload the eccentric action sufficiently. Therefore the purpose of this review was to outline a variety of eccentric training modalities and provide the reader with practical recommendations on programming. A search of the literature was conducted for; eccentric; training; methods; cycling; isokinetics; drop jumps; flywheel; exercise induced muscle damage; repeated bout effect. After this search 106 papers were selected to form the basis of this review. When training isokinetically it was reported six to ten weeks of training at $180° s^{-1}$, three times per week and with 24 – 30 maximal contractions per session resulted in improved hypertrophy and eccentric strength. When using dynamic exercises such as the squat and bench press a barbell load of 75 – 85% concentric 1RM with a releaser load of 40 – 55% (5 – 10 repetitions, 45 – 90 seconds between repetitions) may be appropriate. If the eccentric training is submaximal the barbell load has been recommended to be 50 – 65% concentric 1RM with a releaser load of 10 – 25% (15 – 20 repetitions, 15 – 30 seconds between repetitions). In conclusion eccentric training may warrant inclusion as part of an athletes training program.

Key Words: Eccentric, training, cycling, isokinetics

INTRODUCTION

A concentric muscle action occurs when muscles apply force, which results in those muscles shortening whereas an eccentric muscular action involves the lengthening of a muscle due to an external load (1-3). The combination of these two actions is regularly seen in sport and is referred to as the stretch shortening cycle (SSC) (1,4,5). During the SSC muscle is initially lengthened eccentrically, which then facilitates greater force production during the following concentric action (6). This SSC has been suggested to result in a more efficient muscle action and can improve factors which are important in sporting performance such as running economy and jumping (5). Although the combination of eccentric and concentric muscle actions during the SSC is suggested to be desirable the process leading to each is reported to differ. During a concentric muscle action actin and myosin detachment is suggested to be ATP-dependent whilst during an eccentric muscle action the disruption of the action and myosin process is reported to be mechanical in nature (1,6). The mechanical nature of eccentric muscle actions has been suggested to allow for the production of greater force during eccentric actions than is observed in concentric actions (2,3). In addition to the mechanical differences between the two muscle actions neural activation during eccentric muscles actions appears to differ and these differences include; a reduction in muscle activation during maximal eccentric contractions (1), an altered pattern of muscle recruitment with fast-twitch motor units recruited prior to slow-twitch motor units (7), an increased neural drive to agonists and a reduction in antagonist activation (8) and a greater cross education effect (9). Despite research reporting the ability of eccentric muscle actions to produce more force than concentric muscle actions and the unique neural activation associated with this, traditionally during resistance training the intensity of exercises is set according to an athletes concentric strength. Thus although athletes may be working optimally during the concentric phase of an exercise they may not be working optimally eccentrically (4,10-12). This result is supported by the findings that athletes are stronger in the eccentric phase of a lift (13) compared to the concentric phase. Thus it is suggested that traditional training in isolation may not be adequate to maximally enhance eccentric strength which is required in many sporting actions and in particular those that wish to effectively utilise the SSC. Indeed training eccentrically has been reported to resulted in; improvements in total strength, concentric and eccentric strength (3,10,14,15), increased hypertrophy compared to traditional concentric training (16-18), improvements in jumping power (19-21) and reduced risk of injury (22,23). This brief review will outline different eccentric training methods, the use of these training methods to prevent injury or aid the rehabilitation process and provide practical recommendations on the use of eccentric training.

METHOD

A search of the literature was conducted for eccentric exercise modalities, exercise induced muscle damage (EIMD) and the repeated bout effect (RBE). Databases PubMed, CINAHL, Web of Science and SPORTDiscus to February 2015 were searched for terms linked with Boolean operators ("AND", "OR"): eccentric; training; methods; cycling; isokinetics; drop jumps; flywheel; exercise induced muscle damage; repeated bout effect. Papers were selected based on title, then abstract, then text. Only papers, which specifically addressed eccentric training modalities, were included in this review. Once these criteria had been applied 106 papers were selected to form the basis of this review.

DISCUSSION

Table 1. here

Eccentric Cycling

One method, which has been utilised to allow for eccentric overload, is eccentric cycling. Eccentric cycling involves the athlete resisting the action of the pedals which are being driven in reverse by an electric motor (24) (Eccentric cycling). It has been shown to result in; increases in strength and power, increased muscle cross sectional area (CSA), increased leg spring stiffness and minimal demands for oxygen (24-30) (Table 1). Eccentric cycling it is suggested therefore presents an attractive training method to a wide range of groups including athletes, the elderly, people with cardiovascular disease and those recovering from injury. Although at present most research has been conducted using untrained participants Gross et al. (24) divided trained junior alpine skiers into two groups (concentric and eccentric training groups). The concentric training only group completed 3 lower body weights training sessions per week for 6 weeks which consisted of 4 exercises (5 sets of leg-press and hamstring curls, 4 sets of squats and barbell lunges, all sets consisted of 30 repetitions). The participants in the eccentric training group completed the same exercises but only for 3 sets of 30 repetitions, participants then completed a 20-minute continuous session on the eccentric cycle ergometer. Initially during these eccentric cycle training sessions the workload was constant (200 – 250 watts at a pedalling cadence of 60-80 rpm) however, after week 2 variable wattage was introduced for these sessions. After 6 weeks of training Gross et al. (24) reported that the eccentric cycling group only had improvements in hypertrophy of the lower limb (2.1 ±1.6% and 1.5% ± 1.4% in the right and left legs respectively) and counter movement jump (CMJ) height (6.5%). Although no overall improvement was found in isometric strength it was reported strength increased at longer muscle lengths leading to the suggestion that eccentric cycling promoted the addition of sarcomeres in series (24). The results of this study led the authors to conclude the ability of eccentric cycling to promote hypertrophy and its close dynamic correspondence to alpine skiing made it a beneficial training method. At present research would appear to indicate that eccentric training might be a beneficial training method for untrained participants. However, currently there is not enough research to draw conclusions of its effectiveness on trained athletes and therefore more research is required.

Table 2. here

Isokinetic and Computer Driven Eccentric Training

Another method of training eccentrically that is widely utilised is isokinetic training (table 2). When training isokinetically the load is moved at a constant velocity through the use of an isokinetic dynamometer (31). When utilising isokinetic eccentric training studies have investigated the effects of different training velocities (32-34). Paddon-Jones (33) reported that 10 weeks of eccentric isokinetic training (3 days a week, 24 maximal contractions per session) at 180° s^{-1} resulted in; reduced type I fibre percentage (53.8 – 39.1%), increased type IIb muscle fibre percentage (5.8 – 12.9%), increases in eccentric (29.6 ± 6.4%) and concentric torque (27.4 ± 7.3%) at 180° s^{-1}. These adaptations were not found to be present in the participants who trained eccentrically at 30° s^{-1}. Further studies by Farthing and Chilibek (32) and Shepstone (34) also reported faster speeds resulted in greater strength and hypertrophy. These findings were suggested to be as a result of fast contraction velocities leading to greater protein synthesis, which in turn promoted greater hypertrophy (34).

In addition to the findings on velocity Duncan et al. (35) reported that eccentric isokinetic training is mode specific with eccentric training resulting in the greatest increases in eccentric strength and concentric training resulting in the greatest improvements in concentric strength. In support of the idea of mode specificity Tomberlin et al. (36), Higbie et al. (16), Hortobagyi et al. (37), Seger, Arvidsson and Thorstensson (38) and Seger and Thorstensson (39) also reported that in untrained participants eccentric isokinetic training resulted in the greatest increases in eccentric strength whilst concentric training led to the greatest increases in concentric strength. However, Goddard et al. (40) and Hortobagyi et al. (41) reported training with additional load during the eccentric phase (40-50% concentric load) using a isokinetic dynamometer resulted in similar increases in concentric knee extensor torque and thigh hypertrophy for both concentric and eccentric training groups. When attempting to increase eccentric strength utilising isokinetic training the literature suggests 3 – 4 sets (3 minutes between sets) of 10 maximal eccentric contractions, 3 times a weeks for 6 – 10 weeks utilising fast contraction velocities (~180° s^{-1}) results in optimal adaptations in untrained participants.

As well as the use of traditonal unilateral isokinetic devices studies have also employed novel multijoint isokinetic devices in order to provide an eccentric overload in untrained participants (21,42). Studies by Komsis et al. (42) and Theodosiou et al (21) have reported that 8 weeks (two times per week, 70%+ max eccentric force) of seated leg press eccentric training utlising a multijoint isokinetic machine resulted in; greater concentric and eccentric force production and improvements in drop jump (DJ) height. Therefore the use of multijoint bilateral isokinetic devices is suggested to be an alternative to the unilateral devices currently popular in the literature.

Studies have also utilised specially designed computer driven apparatus to induce eccentric overload (20,43). In Friedmann-Bette et al. (43) study participants completed leg extensions on a computer driven device, which allowed them to overload the eccentric phase of the exercise 2.32-fold higher than in the concentric phase. Results of this study showed an increase in peak torque (5%). It was also suggested that the eccentric overload training resulted in a shift towards a more type II dominant muscle. In a further study trained participants (explosive strength athletes who had completed at least 1-2 strength training sessions per week for on average the last 5 years) performed leg extensions in the eccentric phase at a load 1.9-fold higher than the corresponding concentric load (20). After 6 weeks of training the eccentric overload group were reported to have increased maximal quadriceps strength (~18%), quadriceps CSA (~7%) and a significant increase in jump squat height. Friedmann-Bette et al. (20) suggested these results indicated that eccentric overload training led to a faster gene expression and a shift towards a faster muscle phenotype, resulting in a muscle that was better suited to explosive movements. Thus the results of these studies would be of particular interest to athletes involved in explosive and power based sports where a shift towards a faster muscle phenotype would be beneficial.

The results of the aforementioned studies agree that eccentric training improves eccentric strength to a greater extent than concentric training. However, the results of the effect of eccentric training on concentric strength are equivocal. In a meta-analysis investigating eccentric training Roig et al. (3) concluded that eccentric training leads to greater improvements in eccentric strength than concentric training. Concentric training was reported to show a non-significant trend towards having a greater impact on concentric strength than eccentric training however, given the ability of eccentric training to improve concentric, eccentric and isometric strength Roig et al. (3) concluded that eccentric training was a superior method for increasing total strength. Despite the findings that isokinetic training results in improvements in strength in a review Guilhem et al. (31) reported that isotonic eccentric training led to a greater increase in strength per session than isokinetic training (1.1 ± 1.0% per session vs. 0.6 ± 3.0%). In agreement with this Vogt and Hoppeler (5) also suggested that training eccentrically using isotonic exercise results in greater strength gains than training isokinetically. In addition similarly to eccentric cycling it is also suggested by the author that the majority of S&C coaches, athletes and the general population will not typically have easy access to isokinetic dynamometry. Therefore S&C coaches, athletes and clinicians may be required to come up with novel ways to train eccentrically with athletes.

Table 3. here

Dynamic Eccentric Resistance Training

In addition to the use of isokinetic eccentric interventions and eccentric cycling, studies have investigated the effects of accentuated and supramaximal eccentric loading during dynamic movements more akin to those seen in sport (table 3). In Sheppard et al. (19) study participants were placed into two groups, who then both completed normal resistance training 3 times per week for 5 weeks. The eccentric overload group however, completed counter movement jumps (CMJ) with additional load (males 20 kg and females 10 kg) in the eccentric phase prior to releasing the load and completing the concentric phase of the jump. Sheppard et al. (19) reported that this eccentric overload resulted in gains in peak power (20%), peak velocity (16%) and jump height (11%) characteristics in high performance volleyball players. In contrast Moore et al. (44) found that additional loading during the eccentric phase of a jump squat did not lead to any improvements in force, velocity and power. Moore et al. (44) proposed that this may be due to technical difficulties with the weight release devices or that the initial concentric load (30% 1RM) may not have exceeded the threshold needed for additional eccentric load to lead to improved performance.

A study investigating the effects of lifting an additional eccentric load (additional 5% to concentric 1RM) during the bench press exercise through the use of weight releaser hooks (Eccentric overload bench press with weight releasers) reported an increase in subsequent concentric bench press 1RM (5 – 15 lbs) (11). In a further study investigating dynamic eccentric overload in both the squat and bench press exercise Yarrow et al. (18) reported 5 weeks of eccentric overload training (3 times a week, 3 sets of 6 reps at 40% concentric 1RM and 100%

eccentric 1RM) resulted in increased bench press strength (~10%) and squat (~22%). Although these results were similar to those of the traditional training group in the study it was reported that volume was reduced in the eccentric training group leading to the suggestion that eccentric training may be more efficient. It was also reported that post exercise lactate clearance was improved in the eccentric training group leading to the suggestion that eccentric training promotes a faster post activity recovery. In a further study investigating the effects of additional eccentric loading (20, 30 or 40 kg) using weight releasers whilst completing bench throws Sheppard and Young (45) reported superior peak concentric barbell displacement with all loads compared to the an equal eccentric and concentric bar load. This led the authors to conclude that additional eccentric load can lead to improvements in the bench throw exercise. When using weight releasers it has been suggested that for maximal eccentric isotonic actions a barbell load of 75 – 85% concentric 1RM with a releaser load of 40 – 55% (5 – 10 repetitions, 45 – 90 seconds between reps) may be appropriate. If eccentric training is submaximal the barbell load has been recommended to be 50 – 65% concentric 1RM with a releaser load of 10 - 25% (15 – 20 repetitions, 15 – 30 seconds between repetitions) (6). One potential drawback of this type of training may be the use of weight releasers as there use it is suggested by the author is labour intensive and requires spotters to reattach the additional load each time a repetition is complete. This type of training also requires a degree of skill on behalf of the lifter to ensure the bar path is smooth and the additional load is released simultaneously on both sides. In addition the use of only single repetitions rather than a series of repetitions may potentially make this a time consuming training modality especially in a team sport environment.

Studies have also utilised accentuated or supramaximal eccentric loads to train the elbow flexors and extensors. In Brandenburg and Docherty (10) study participants performed preacher curls to eccentrically train the elbow flexors and supine elbow extension to train the elbow extensors. The participants in the eccentric training group trained for nine weeks at 120% of their concentric 1 repetition max (1RM). After 9 weeks the eccentric training group was reported to have greater increases in concentric strength (24 vs. 15%) of the elbow flexors than the concentric group in the elbow extensors. This led the authors to conclude that eccentric overload training may be more effective in improving strength than traditional resistance training alone. In a similar study Vikne et al. (12) reported that an eccentric training group had significant increases in concentric strength (14%), which were very closely matched to the concentric training groups concentric strength results. However, eccentric training resulted in a greater increases in eccentric strength (26%) accompanied with increases in cross sectional area (CSA) of the elbow flexors and type I and type IIa fibres (11%).

Studies have utilised commercially available flywheel devices (YoYo^{tm} Technology Inc, Stockholm, Sweden) to induce eccentric overload (17,46,47). When using these flywheel devices (Eccentric flywheel training with the squat exercise) as the participant completes the concentric phase of the exercise the strap that is attached to the flywheel unwinds and force and energy is transferred to the flywheel (17). Once the concentric phase of the exercise is completed the strap rewinds and it is during this stage that participants resist the action of the strap being pulled in by the flywheel and thus complete the eccentric action (17). In Norrbrand et al. (17) initial study participants performed 5 weeks of unilateral knee extension (2-3 times per week). Upon completion of training maximum voluntary contraction (MVC) was significantly increased in the flywheel-training group compared to the weight stack device-training group. A twofold greater increase in hypertrophy was reported in the eccentric flywheel group in comparison to the weight stack group. A potential explanation for the increase in hypertrophy was reported in Norrbrand et al. (47) study where it was proposed that flywheel training led to greater muscular activation due to increased eccentric loading which in turn resulted in superior protein synthesis and as a consequence a greater hypertrophic response. In a further study participants completed 6 weeks of supine squat flywheel training with the results indicating comparable improvements in strength, power and muscle hypertrophy between men and women upon completion of training (46). As a result of these studies it is suggested that flywheel training may be an appropriate method to induce eccentric overload. However, it should be noted that due to the nature of the devices monitoring and thus programming might prove difficult.

The findings of these studies into the effects of additional eccentric load on increases in strength and power have been attributed to several possibilities (6). The first of these is the suggestion that the increase in eccentric loading promotes greater numbers of motor units to be recruited (6,19) secondly the elastic properties of muscle allow for a more forceful concentric contraction after the stretch associated with the eccentric contraction (11,19). Another potential explanation is that during eccentric loading the agonist muscle are able to achieve an active state and force as a result of some cross bridges being attached prior the subsequent concentric portion of an exercise (11,45). Finally it is suggested that the eccentric loading allows for greater agonist activation and a reduction in antagonist activation results in greater levels of force production (8,10). Although the exact mechanisms that result in additional eccentric load being able to lead to performance improvements are not yet clear, the methods discussed previously may be of interest to S&C coaches and athlete alike.

Figure 1 here.

Eccentric Training and Injuries

In addition to eccentric training having the ability to increase strength and hypertrophy several studies have reported that the use of eccentric training can; reduce instances of hamstring injuries (22,48-52), strengthen the ankle during rehabilitation to a greater extent than concentric training (53), result in reduced knee pain (54), aid recovery from achilles tendinosis (55) and improve strength in the rotator cuff reducing the chances of injury (56,57). Of particular interest to a strength and conditioning (S&C) coach or athlete may be the findings in relation to hamstring injuries as these are common in a range of sports and also have a high risk or reoccurring (49). It is reported that athletes whose peak tension occurs at shorter lengths are more likely to suffer from muscular strains, which will result in absence both training or matches (4). In a study investigating hamstring strains Brockett et al. (23) reported that optimum length of peak tension was an indicator of hamstring injury risk with shorter lengths more likely to result in injury. Therefore it has been suggested that shifting the optimum length to longer lengths is desirable if the aim is to reduce injury (4,22,23). In a study investigating hamstring eccentric exercise Brockett et al. (22) reported that hamstring lowers (Nordics) (Figure 1.) resulted in a shift in the optimum angle for torque generation to longer lengths (7.7° ± 2.1°) with this suggested to result in protection against subsequent strains. A further study by Potier et al. (58) reported 8 weeks of eccentric hamstring training resulted in increased; hamstring muscle strength and increased fascicle length. It is this increase in fascicle length that confers a protective effect and has been reported to be the result of eccentric exercise leading to the addition of sarcomeres in series that reduce strain during further eccentric contractions (59,60). Thus these finding in conjunction with other studies which have reported eccentric training of the hamstrings results in a reduction in hamstring injuries (48,50-52) appear to make eccentric training an interesting proposition for S&C coaches who either wish to prevent injury or aid return to sport after injury. When programming the Nordic hamstring exercise it is suggested that in preseason athletes should initially complete 2 sets of 5 repetitions once a week progressing to 3 sets of 12, 10 and 8 repetitions three times a week in weeks 5 – 10 (61). In season it is suggested that athletes should complete 1-2 sessions per week of 3 sets (12,10,8 repetitions) (61)

Drop Jumps

A further method, which has been suggested to overload the eccentric portion of a muscle action, is the use of a drop jump (DJ). A DJ is a widely utilised plyometric training method (62,63) and involves an athlete stepping off of a box and then upon making contact with the ground immediately performing an explosive countermovement jump (CMJ) (64). This exercise has been suggested as a method that results in improved utilisation of the SSC (64-67). Therefore improving the ability of an athlete to utilise the SSC may be beneficial, indeed previously studies have reported that DJ training results in; improvements in sprint performance (65,68-70), improvements in jumping performance (71-75), strength (70,76) and agility (69). As a result of the findings of these studies it appears that DJ may represent a useful exercise for a wide range of athletes across a host of sports.

When programming the DJ it has been suggested that S&C coaches use drop height as a determinate of intensity (67). As drop height increases it is reported that ground reaction force also increases upon impact thus resulting in an increase in intensity (77-79). It is widely accepted that initially as drop height increases so does jump height performance however, there comes a point where an increase in DJ will lead to a decrease in performance (63,80,81). The initial increase in performance as drop height increases has been reported to be due to a number of factors including; increased neural activation resulting in greater motor unit activity, post activation potentiation (PAP) of the muscle and reuse of stored elastic energy as result of the initial eccentric muscle action (19,63,66,79,80,82,83). Due to the findings on the effect of drop height when utilising DJ training, programmes need to be individualized due to athletes having differing neuromuscular capacities (82). Thus if drop height is too low for an athlete it may not sufficiently overload the athlete or alternatively if drop height is too high the athlete may not adequately be able to control the eccentric and transition phases (82). Several methods have been proposed as measures of optimal drop jump performance with two suggested as being the most popular. The first termed the maximal jump height (MJH) method involves looking at the jump height achieved upon completion of DJ's from a range of different heights to assess which one results in the best jump height irrespective of ground contact time (82,84). Utilising this method the plyometric box height which corresponds to the greatest MJH for each individual athlete would then be the height which the athlete drops from when completing DJ during a training session. The other most popular method to determine opitimal drop height involves taking jump height and dividing it by ground contact with this termed the reactive strength index (RSI) (66,82,84). Using this method athletes complete drop jumps from a variety of increasing heights. When the RSI is maintained or shows an improvement with increased drop height and ground contact time is considered to result in a fast SSC (see below) it is suggested that athlete can attempt a greater drop height (66). However, there will come a point where the drop height becomes too great and at this point there will be a reduction in the RSI or the ground contact time will indicate that it is no longer a fast SSC action (66). Thus using RSI an S&C will be able to establish the best individual drop heights for each athlete. Typically this may require the use of a contact mat or force platform however it is suggested that if these are not avaliable simply observing the athletes landing may be sufficient (66). Using this method an S&C coach should look at the landing as longer ground contact times are reported to result in the heels hitting the ground (66).

Another factor which an athlete or S&C coach may wish to consider is ground contact time as this has a bearing on the classification of the SSC action (66). Previously it has been suggested that a ground contact time of <0.25 seconds would represent a fast SSC whilst anything over this threshold would be considered a slow SSC (85). Thus athletes who wish to concentrate on simply improving jump height are suggested to benefit from longer contact times (66). Whilst athletes such as sprinters whose contact times during running can be as little as 80-95 milliseconds and whose goal it is to improve speed whilst relying on fast SSC utilisation would benefit from shorter contact times (65). Another consideration may be the knee angle of landing with the suggestion that different sports may require different angles at impact (6). In a study by McNitt-Gray (77) it was reported that gymnasts and recreational athletes had different strategies at the hip, ankle and knee when landing following a DJ whilst Moore and Schilling (6) suggested that an American football lineman would require a smaller knee flexion angle upon impact than a volleyball player due to the demands of the sport. In summary the drop height, ground contact time and control strategies upon landing should be taken into account when considering prescribing DJ's to an athlete.

As previously mentioned DJ intensity is usually dictated by drop height, however, it is also possible to manipulate the mass of an individual to alter DJ intensity (67,78). However, the increase in body mass through the addition of a weighted vest during DJ has been reported to result in no significant improvements in performance (78). During this study however, body mass remained constant for both the eccentric and concentric portion of the exercise. An alternative to this constant additional load approach is the suggestion that dumbbells or elastic bands provide additional load during the eccentric phase of a DJ (6). Thus as an athlete reaches the bottom position of the CMJ following the drop phase of the exercise they either release the dumbbells or the elastic bands are released allowing them to perform the concentric portion of the exercise without any additional load (6). At present only one study has investigated the use of accentuated eccentric loading (AEL) during a DJ. In this study AEL was applied through the eccentric phase by using an elastic device which increased downward force by 20% or 30% of body mass (86). The results of this study indicated that additional eccentric load enhanced eccentric impulse ($p = 0.042$), rate of force development ($p < 0.001$) and resulted in small to moderate effect size increases in iEMG across the eccentric phase (ES = 0.23 - 0.51) however, there was no associated increase in jump height or concentric muscle activation reported (86). These findings led Aboodarda et al. (86) to suggest that the additional eccentric loading could be used as a method to increase DJ intensity without the need to increase drop height. It should be noted however that in the same manner as the weight releasers the use of the elastic bands in the Aboodarda et al. (86) study is currently labour intensive as it requires additional spotters. This method is also reliant on the spotter releasing the bands simultaneously so there is margin for human error. Based on these findings it is suggested more research is required on the using of AEL during the DJ exercise.

In terms of frequency and volume of DJ training it has been previously reported that moderate training frequency and volume of jumps (2 days a week, 840 jumps over 7 weeks) produced similar enhancements in jumping performance but greater efficiency compared with high frequency and volume DJ (4 days per week, 1680 jumps over 7 weeks) (70). The results of this study also supported the notion that DJ training can significantly increase sprint performance and maximal strength in moderately trained athletes (70) Another consideration when programming DJ training for athletes is the influence of rest intervals on performance (83). In a study which investigated this participants completed three sets of 10 DJ with rest intervals of 15, 30 and 60 seconds, the results demonstrated that a 15 second rest period was sufficient for recovery during the performance of DJ (83). In summary it is suggested that three sets of eight to ten jumps, two times per week, for seven to eight weeks with rest periods of 15 seconds between jumps and three minutes between sets may produce optimal results.

Exercise Induced Muscle Damage

Despite the positive adaptations associated with eccentric training the possible negative effect of this type of training is exercised induced muscle damage (EIMD). EIMD is reported to occur as a result of eccentric training being both high in intensity and an activity which athletes are unaccustomed to (87,88). EIMD as a result of eccentric training has been reported to result in acute reductions in muscular strength and power (89), decreases in range of motion, delayed onset muscle soreness (DOMS) and swelling and the leakage of blood proteins including creatine kinase (CK) into the blood (90). A number of mechanisms have been proposed as being responsible for declines in performance following eccentric exercise and these include the popping sarcomere theory (59), failure of the excitation coupling (E-C) process (91), DOMS (92) and increased membrane permeability (93).

The Repeated Bout Effect

Although eccentric exercise has been shown to result in EIMD its effects may be reduced after a bout of similar exercise with this phenomenon termed the repeated bout effect (RBE) (2,94,95). This RBE has been reported to result in; a reduction in ROM deficits, faster recovery of muscular strength and power, reduced swelling and DOMS and smaller increases in blood protein markers (94). As yet the mechanisms responsible for the RBE are unclear but are suggested to be neural (95,96), mechanical (97) or cellular in nature (98). Research has found that a preconditioning bout of maximal (99-101) and submaximal eccentric exercise (102,103) as well as isometric contractions at long lengths (104,105) can confer a protective effect against EIMD. These effects have been reported to last as long as six months after an initial bout of maximal eccentric exercise (101) or as little as three weeks after submaximal eccentric exercise (104). Thus despite the fears of some about the effect of EIMD after a bout of eccentric exercise it is suggested that proper planning can alleviate the effects of EIMD and indeed provide a protective effect against further eccentric induced damage.

CONCLUSIONS AND PRACTICAL APPLICATIONS

In conclusion it would appear that training eccentrically may be beneficial to a wide ranging population including; athletes who wish to improve performance, those recovery from injury, patients suffering from cardiovascular disease and the general public. The results of studies, which have investigated eccentric training, suggest that it results in; improvements in strength, power and hypertrophy, a reduction in injury risk, improved rehabilitation from injury and additionally has general health benefits.

Based on the finding of studies investigating eccentric cycling it is suggested that training for six weeks, three to five times per week, at an intensity of between 55%-65% heart rate max or 20-55% power max will result in improvements in strength and hypertrophy.

When utilising isokinetic eccentric training results have shown that this can lead to greater improvements in eccentric strength and overall strength. It has also been reported that faster contraction speeds result in greater adaptations with less EIMD suffered by participants. Thus the inclusion of six to ten weeks of isokinetic training at 180° s^{-1}, three times per week and with 24 – 30 maximal contractions per session may result in improved hypertrophy and eccentric strength.

Despite the findings on the effectiveness of isokinetic eccentric training it has been reported that isotonic eccentric training is a more effective eccentric training method. Thus the use of accentuated or supramaximal (greater than concentric 1RM) loads during the eccentric phase of an isotonic movement may enhance the subsequent performance of the concentric phase of a movement. When using weight releasers it has been suggested that when training maximally a barbell load of 75% - 85% concentric 1RM with a releaser load of 40 – 55% (5 – 10 repetitions, 45 – 90 seconds between reps) may be appropriate. If eccentric training is submaximal the barbell load has been recommended to be 50 – 65% concentric 1RM with a releaser load of 10 - 25% (15 – 20 repetitions, 15 – 30 seconds between repetitions)

When using DJ's to provide an eccentric overload it is suggested if the goal is to increase jump height athletes would benefit from longer contact times (>250ms) Whereas sprinter who rely on fast SSC utilisation should try to limit ground contact time. Based on these findings and as a consequence of athletes having differing neuromuscular capabilites there is a need for optimal drop height to be assessed prior to starting DJ training and subsequently individualised. The use of three sets of eight to ten jumps (15 seconds between jumps and 3 minutes between sets), two times per week, for seven to eight weeks is suggested to produce optimal results.

Finally eccentric training has been shown to be a useful tool in both the prevention of injury and in its rehabilitation. Of particular interest is the idea that the inclusion of exercises such as hamstring lowers (Nordics) can result in a shift in optimum length and therefore a reduction in the risk of hamstring injuries. Thus it is suggested that the exercises be included in preseason training when athletes should initially complete 2 sets of 5 repetitions once a week progressing to 3 sets of 12, 10 and 8 repetitions three times a week in weeks 5-10. Whilst once the season has started it is suggested that athletes should complete 1-2 sessions per week of 3 sets (12,10,8 repetitions) In summary eccentric training has been shown to be beneficial in numerous studies and therefore it is suggested may warrant inclusion in a periodised training plan.

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Table 1. Eccentric cycling studies			
Study	**Population**	**Intervention**	**Results**
Elmer et al. (25)	Untrained subjects Eccentric group N = 6 (1 female) Mean age: 25±6 years	Eccentric cycling group trained 3 times per week for a total of 7 weeks. Intensity started at 54% max heart rate and at end of study was 66% of max heart rate	Significant increases in leg stiffness (10 ±3 %) and jumping P_{max} (7 ±2 %) compared to the concentric training group
Gerber et al. (27)	Untrained subjects N = 32 Aged 18-50 years	3 weeks after ACL surgery participants completed a 12 week eccentric cycling program. Intensity was self selected and ranged from 20-40rpm	Quadriceps strength (124.2 Nm – 159.2 Nm) and hopping distance (80.3 – 112.9 cm) significantly increased in the eccentric cycling group compared to traditional training group. Activity level also decreased to lesser extent in the eccentric group.
Gerber et al. (26)	Untrained subjects N = 32 Aged 18-50 years	1 year follow up to the original Gerber et al. study (29)	Significantly greater improvements in quadriceps (1430 ± 426 – 1763 ± 458 cm^3) and gluteus maximus muscle (596 ± 173 – 719 ± 169) volume in eccentric group compared to concentric group. Improvements in quadriceps strength (137 ± 34 – 182 ± 45 Nm) and hopping distance (71 ± 13 – 124 ± 38 cm) were also significantly greater in the eccentric group.
Gross et al. (24)	Trained alpine skiers N = 15 Mean age: 17.6±1.4 years	Eccentric cycling group performed three one hour weights sessions a week (3 sets of leg exercises) followed by 20mins on eccentric ergometer (various workloads) for 6 weeks	Significant increase in lean thigh mass, 6.5% improvement in squat jump height and no significant improvement in isometric force

Study	Population	Intervention	Results
LaStayo et al. (28)	Untrained subjects N = 14 Mean age: 23.9 years	Eccentric cycling group trained for 8 weeks, 2-5 times a week and for 15-30mins at an intensity of 54-65% HR_{peak}	Significant increases in isometric strength (36%) and CSA (52%). No significant changes in concentric training group
LsStayo et al. (29)	Untrained subjects N = 9 Mean age: 21.5 years	Eccentric cycling group trained for 6 weeks, 2-5 times per week, 10-30mins and at an intensity of 50-60rpm	Oxygen demand was less during eccentric cycling compared to concentric cycling despite higher workloads. There was a 33% increase in isometric leg strength in the eccentric group while no significant improvements were recorded in the concentric group.
Leong et al. (30)	Untrained subjects N = 8 (4 males and 4 females) Mean age: 22±2 years	Eccentric cycling 2 times per week, 5-10.5 minutes per session at an intensity of 20-55% P_{max}	Increased RF (24±4%) and VL (13±2%) thickness, increased RF (31±4%) and VL (13±1%) pennation angles. Increased P_{max} 1 week after training (5±1%) and 8 weeks after training (9±2%)

Rpm – Revolutions per minute
CSA – Cross sectional area
P_{max} – Power max
HR_{peak} – Peak heart rate
RF – Rectus femoris
VL – Vastus lateralis

Table 2. Isokinetic devices and other machine driven eccentric training modalities			
Study	**Population**	**Intervention**	**Results**
Duncan et al. (35)	Untrained participants N = 48 Mean age: 23.9 years	Eccentric group trained for 6 weeks, 3 times per week, at 180° s^{-1}, 1 set of 10 maximal contractions of the quadriceps	Eccentric group had significantly improved eccentric force (25.1 ± 24.1%) but not concentric force. Eccentric isokinetic training is mode specific
Farthing et al. (32)	Untrained participants N = 36 (13 male and 23 female) Mean age: 21.9±1.5 years (fast group) and 19.6±0.7 years (slow group)	Eccentric and concentric training at two velocities fast 180° s^{-1} and slow 30° s^{-1}. Trained one arm eccentrically for 8 weeks then the other arm concentrically for 8 weeks	Eccentric 180° s^{-1} resulted in greater hypertrophy than all concentric velocities. Eccentric 30° s^{-1} resulted in greater hypertrophy than concentric 180° s^{-1} Eccentric 180° s^{-1} resulted in greatest strength improvements
Friedmann-Bette et al. (20)	Resistance trained participants N = 25 (11 eccentric) Mean age: 24.3±3.7 years	Knee Extension on a specially designed computer driven device, 6 weeks of training, 3 times a week, at an intensity of 5 sets at 8 repetition max (8RM)	Increased max strength (11 – 15 kg), increased quadriceps CSA (5.8 ± 4.3cm^2) and shift towards a faster muscle phenotype
Friedmann-Bette et al. (43)	Untrained participants N = 18	Eccentric group trained on computer driven device, with loads equivalent to 30% 1RM concentric and 30% 1RM eccentric, for 4 weeks, 3 times a week and 3 sets of 25 repetitions per session	Results showed increase in peak torque (5%) and adaptation towards a stronger and faster muscle

Study	Population	Intervention	Results
Goddard et al. (40)	Untrained participants N= 28 (16 women and 12 men) Mean age eccentric group: 22±3.0 years	10 weeks of training, 2 times per week, one set of 8-12 unilateral knee extension with eccentric load 40% greater than the concentric load	Significant improvements in concentric knee extensor torque for both the eccentric (88.0 ± 20.9 – 170.4 ± 32.4 Nm) and concentric (85.8 ± 23.3 to 167.4 ± 35.5 Nm) training groups with no difference between the 2
Higbie et al. (16)	Untrained participants N = 60 Mean age: 20.1±1.1 years	Eccentric group trained for 10 weeks, 3 days per week, 3 sets of 10 repetitions (right leg knee extensions)	Eccentric group showed greatest increases in eccentric strength (36.2%) and concentric in concentric strength (18.4%). Supporting idea of mode specificity in isokinetic training
Hortobagyi et al. (37)	Untrained women N = 30 Mean age: 20.9±1.2 years	Participants in the eccentric overload group completed unilateral knee extensions with an overload of 40-50% during the eccentric contraction for 7 consecutive days	The eccentric training group had on average a two fold increase in strength compared to the standard training group
Hortobagyi et al. (41)	Untrained participants N = 42 Mean age: 21.1±2.38 (eccentric group)	Training involved 824 eccentric quadriceps actions, over 6 weeks, 4 times a week, 4 sets of 6-10 repetitions at 105 rad s^{-1}	Eccentric training increased eccentric (42%) and isometric strength (30%) to a greater degree than concentric training. EMG adaptations were greater with eccentric training
Komsis et al. (42)	Untrained participants N = 16 Mean age: 24±0.5 years	Eccentric training group trained on a custom built multi-joint isokinetic dynamometer, 2 times per week, 3-6 sets, 6-10 reps at an intensity of 70-90%	Significant increase in in eccentric and concentric force and improvement in drop jump height.

Study	Population	Intervention	Results
Paddon-Jones et al. (33)	Untrained participants N = 20 Mean age: 24.2±7.0 years	Two groups completed eccentric training at two different isokinetic velocities fast 3.14 rad s^{-1} and slow 0.52 rad s^{-1}. 10 weeks of training, 3 times a week, 24 maximal contractions (4 sets of six)	Fast group experienced significantly greater increase in; eccentric (29.6 ± 6.4%) and concentric torque (27.4 ± 7.3%) at fast speed and isometric and eccentric torque at slower speed. % type I fibre decreased in fast group (53.8 – 39.1%) while type II increased (5.8 – 12.9%) No significant changes in slow group
Paschalis et al. (44)	Untrained participants N = 20 Mean age: 20±0.3 years	8 weeks, once per week, 5 sets of 15 eccentric or concentric MVC at 60° s^{-1}	Increased; resting energy expenditure (+ 12.7%) and fat oxidation (+12.9%), improved blood lipid profile, reduced resting insulin resistance at week 8
Seger et al. (38)	Untrained participants N = 10 Mean age: 25±1.8 years	Eccentric group trained for 10 weeks, 3 days per week, unilateral knee extension at 90° s^{-1}, 4 sets of 10 maximal efforts	Changes in strength of trained legs revealed more specificity related to velocity and contraction type in eccentric compared to concentric actions
Seger et al. (39)	Untrained participants N = 10 Mean age: 25±2 years	Eccentric group trained for 10 weeks, 3 times per week, at 90° $s^{-1,}$ 4 sets of 10 maximal efforts on left leg followed by same protocol on right leg	Effects of eccentric training on muscle strength were found to be more mode and speed specific than concentric training.
Shepstone et al. (34)	Untrained participants N = 12 Mean age: 23.8±3.4 years	Participants trained one arm at fast velocity 3.66 rad s^{-1} and one arm at slow velocity 0.35 rad s^{-1}, 8 weeks of training, 3 times a week	Type I muscle fibre increased size increased in both arm as did type II but to greater extent in fast arm. Maximum torque generating ability was also greater in fast arm (11.3 ± 10.4 Nm improvement)

Study	Population	Intervention	Results
Theodosiou et al. (21)	Untrained participants N = 19 Mean age: 21.3±0.9 years	Eccentric group trained using a isokinetic hydraulic leg press, 8 weeks, 2 times per week, 3-6 set, 5-10 repetitions at an intensity of 70-90% max eccentric force	Significant increases in drop jump height (13.6 ± 3.2%) and maximally power (25.8 ± 1.2%), reduction in ground contact time (17.6 ± 2.6%), increased muscle stiffness and increased maximal eccentric and concentric leg press force.
Tomberlin (36)	Untrained participants N = 63 Mean age: 27.1 years	Eccentric group trained for 6 weeks, 3 times a week, at 100° s^{-1}, 3 sets of 10 repetitions (right quadriceps)	Eccentric group showed greatest increases in eccentric work and torque and concentric in concentric work and torque. Supporting idea of mode specificity in isokinetic training

CSA – Cross sectional area
RM – Repetition max
Reps – repetitions
EMG - Electromyography
PLP – Passive leg press
SSC – Stretch shortening cycle

Table 3. Dynamic eccentric training				
Study	**Population**	**Exercise Modality**	**Intervention**	**Results**
Brandenburg et al. (10)	Resistance trained university students N = 23	Preacher curls and supine elbow extension	Eccentric overload group trained for 9 weeks, 2-3 times a week, 3 sets of 10 repetitions with concentric load of 75% 1RM and eccentric load of ~120% concentric 1RM	No significant changes in CSA Eccentric training group produced significantly greater increases in concentric 1RM of elbow extensors (24%) than the concentric training group (15%)
Doan et al. (11)	Untrained athletes N = 10 Mean age: 23.9 years	Bench press	Eccentric overload group completed the eccentric phase of the barbell bench press with a load of 105% of concentric 1RM with weight releasers	The use of additional eccentric load significantly increased subsequent concentric 1RM in the bench press exercise (5 – 15 pounds)
Fernandez-Gonzalo et al. (47)	Untrained N = 32 (16 males and 16 females) Mean age men: 23±1 year Mean age women: 24±1 year	Bilateral flywheel supine squat	6 weeks of training, 2-3 times a week, four sets of 7 repetitions	Increases in strength (20 – 25%), power (3% - 6%) and muscle mass. Changes are comparable between men and women
Moore et al. (45)	Trained men N = 13 Mean age: 22.8±2.9 years	Augmented eccentric jump squat training	2 reps with 30% 1RM concentric load and additional eccentric load on weight releasers of 20,50 and 80% 1RM	No changes in acute force, velocity and power
Norrbrand et al. (17)	Untrained N = 15 Mean age: 39.1±8.1 years	Unilateral knee extensor flywheel training device	5 weeks of training, 2-3 times per week, 4 sets of 7 unilateral concentric-eccentric knee extensions	MVC increased at all angles, increased quadriceps CSA
Norrbrand et al. (48)	Untrained N = 17 Mean age: 38.81±5.0 years	Bilateral knee extensor flywheel training device	5 weeks of training 2-3 sessions per week, 4 sets of 7 repetitions of unilateral knee extensor training of left limb	MVC (8.1 %) and training specific strength increased. Higher EMG activity recorded in eccentric portion of action

Study	Population	Exercise Modality	Intervention	Results
Sheppard et al. (19)	Trained volleyball players N = 16 Mean age: 21.8±4.9 years	Accentuated eccentric load countermovement jumps	Eccentric training group trained for 5 weeks, 3 times per week. During eccentric phase of CMJ males held a 20 kg weight plate and females 10 kg	Significantly greater improvements in displacement, velocity and power in the eccentric group compared to body weight only group
Sheppard et al. (49)	Trained subjects N = 14 Mean age: 22.1±0.8 years	Bench throw	Participants performed the bench throw exercise with an extra eccentric load (20, 30 and 40 kg) in addition to the 40 kg concentric load	Superior concentric peak barbell displacement (0.27 v 0.24 m) were achieved in all eccentric overload conditions
Vikne et al. (12)	Resistance trained men N = 22 Mean age: 26.9±3.4 years	Specially designed elbow flexion apparatus	Eccentric training for 12 weeks, 2-3 times per week, 4-8RM	Eccentric training resulted in similar increase in concentric strength (14%) to concentric training but a greater increase in eccentric strength (26%) CSA of elbow flexors and type I and type II increased (11%) only after eccentric training
Yarrow et al. (18)	Untrained subjects N = 22 Mean age: 22.1±0.8 years	Bench press and squatting	Eccentric training for 5 weeks, 3 times per week, 3 sets of 6 repetitions at 40% concentric 1RM and 100% 1RM eccentric	Similar improvements in bench press and squat strength for both the eccentric and concentric training group Post exercise lactate clearance was greater in the eccentric group

1RM – 1 repetition max
CSA – Cross sectional area
MVC – Maximum voluntary contraction
EMG – Electromyography
CMJ – Countermovement jump