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HIGHLIGHTED TOPIC | *Eccentric Exercise*

Eccentric exercise: mechanisms and effects when used as training regime or training adjunct

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Vogt M, Hoppeler HH. Eccentric exercise: mechanisms and effects when used as training regime or training adjunct. *J Appl Physiol* 116: 1446–1454, 2014. First published February 6, 2014; doi:10.1152/jappphysiol.00146.2013.—The aim of the current review is to discuss applications and mechanism of eccentric exercise in training regimes of competitive sports. Eccentric muscle work is important in most sports. Eccentric muscle contractions enhance the performance during the concentric phase of stretch-shortening cycles, which is important in disciplines like sprinting, jumping, throwing, and running. Muscles activated during lengthening movements can also function as shock absorbers, to decelerate during landing tasks or to precisely deal with high external loading in sports like alpine skiing. The few studies available on trained subjects reveal that eccentric training can further enhance maximal muscle strength and power. It can further optimize muscle length for maximal tension development at a greater degree of extension, and has potential to improve muscle coordination during eccentric tasks. In skeletal muscles, these functional adaptations are based on increases in muscle mass, fascicle length, number of sarcomeres, and cross-sectional area of type II fibers. Identified modalities for eccentric loading in athletic populations involve classical isotonic exercises, accentuated jumping exercises, eccentric overloading exercises, and eccentric cycle ergometry. We conclude that eccentric exercise offers a promising training modality to enhance performance and to prevent injuries in athletes. However, further research is necessary to better understand how the neuromuscular system adapts to eccentric loading in athletes.

skeletal muscle; eccentric exercise; skiing; athletes

IN NORMAL HUMAN MOVEMENT, muscles are used to provide both positive and negative external work. Positive work is a consequence of concentric muscle contractions, i.e., contractions in which activated muscles shorten (“shortening contraction”) and thus provide the external work. Concentric muscle activities are dominant in movements or sports like uphill walking, cycling, and swimming. Eccentric contractions are defined as muscle activities that occur when the force applied to the muscle exceeds the momentary force produced by the muscle itself (44). Under these conditions the activated muscle is lengthened (“lengthening contraction”). Eccentric contractions are generally used to decelerate or brake or to absorb energy. This is classically illustrated by downhill walking/running, during which eccentric contractions dissipate the potential energy gained by uphill walking, or by fast and cutting movements like sprinting, running, jumping, or throwing, where absorbed energy is recovered for power enhancement (34). In

alpine skiing eccentric activity of quadriceps muscle is dominant throughout a turning cycle, which is considered to be a unique feature of this sport (Fig. 1) (8).

Proper periodization of training has major implication for success in modern elite sports (32, 66). Accordingly, successful training is characterized by a gradual increase of the training load and by a permanent variation of the training stimuli. Today, for highly trained athletes of most sports, the integration of resistance training has become essential to achieve performance excellence. To maximize the stimuli of resistance training, it is recommended that trained individuals include concentric and isometric as well as eccentric muscle actions during their specific weight training (37). Because of the distinct characteristics of eccentric muscle actions, it is speculated that the integration of this training modality can lead to additional improvements of strength and performance in athletic populations (31).

The aim of the current minireview is to discuss the significance of eccentric muscle actions in competitive sports, and to identify possible applications of eccentric muscle actions in training to improve sports performance.

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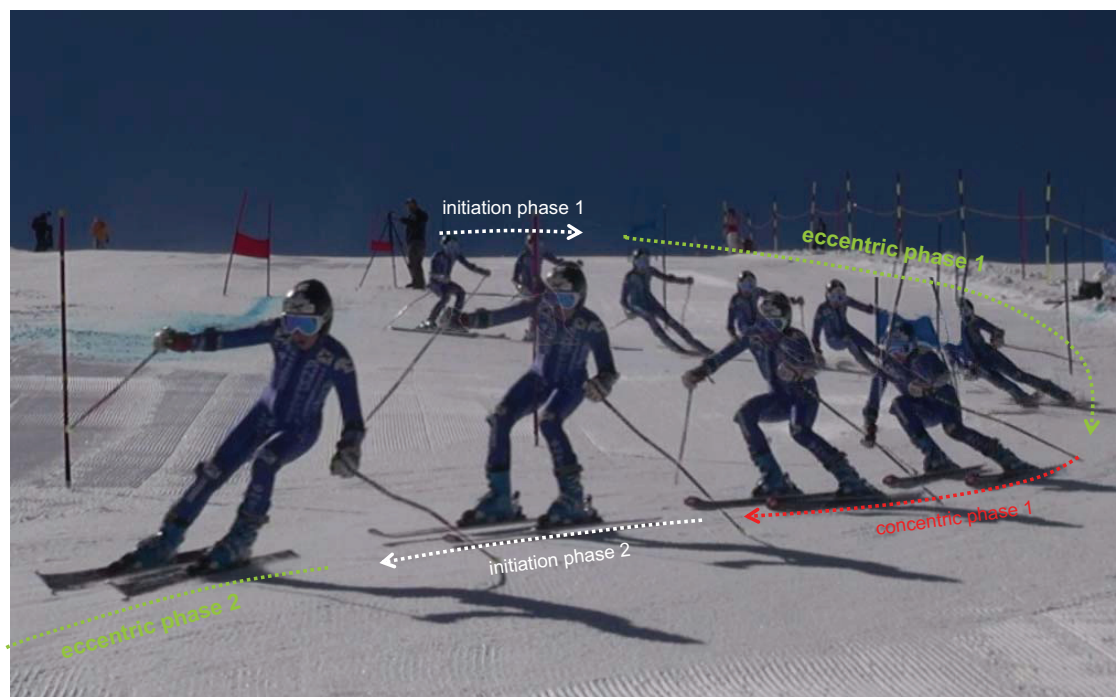


Fig. 1. Motion picture of a giant slalom turn showing initiation, eccentric, and concentric phase. Racer is a 15-yr-old junior skier.

ECCENTRIC MUSCLE ACTION AND PERFORMANCE IN SPORTS

In almost any type sport, movements are characterized by a combination of both concentric and eccentric muscle action (18). During eccentric work the muscular-tendon system is stretched and by that absorbs mechanical energy (43). The absorbed energy can be dissipated as heat. In that situation, the muscle works as a shock absorber, for example while downhill running, skiing, or during landing movements. Alternatively, during fast and cyclic movements, the absorbed energy will temporarily be stored as elastic energy and subsequently recovered during an immediate shortening contraction. By this stretch-shortening cycle (SSC), the muscle acts in a springlike manner (43). Depending on the eccentric-concentric contraction time, fast and slow SSC can be distinguished (53). For example, slow SSC are seen during jumps in basketball and volleyball, when angular displacement is high and ground contact time long (>0.25 s). Fast SSC, as in sprinting, are characterized by smaller angular displacement and ground contact time shorter than 0.25 s. Effective SSC during sports-related movements are characterized by accentuated muscle preactivation before touchdown, a short and fast eccentric phase as well as an immediate transition from the eccentric stretch to the concentric shortening phase during ground contact (36). In very fast movements, preactivation of muscles is observed as an ~ 100 -ms delay between the onset of the electromyographic (EMG) signal and the subsequent limb movement (65). Preactivation immediately increases sensitivity of muscle spindles, leading to improved regulation of reflex potentiation and stiffness throughout the subsequent eccentric phase (38).

There is an important time component in the functioning of SSC. If the coupling between the eccentric and concentric phase during SSC is too long, the elastic energy will be lost as

heat. Wilson et al. (66) showed with bench press exercise that the benefits from the SSC have a half-life of 0.85 s for the coupling time. The effectiveness of SSC on performance also depends on training status and is different between power- and endurance-trained athletes (38, 39, 66). For example during vertical jumping tendomuscular stiffness and the utilization of the elastic energy throughout the concentric phase are enhanced in power athletes. This agrees to some extent with the observation of Bosco and Rusko (11) that enhancement of energy recovery during SSC depends on fiber type distribution and recruitment. Athletes with predominately slow-twitch fiber makeup benefit most from stored energy with longer SSC, as during countermovement jumping, whereas there seems to be no fiber-type-dependent difference on rapid SSC (66). It is assumed that the slower cross-bridge cycling rate in slow-twitch fibers favors elastic energy maintenance through slow SSC to a greater extent than in fast-twitch fibers. Taken together, the degree of benefit from SSC is shown to be influenced by training status, fiber type distribution, and the duration of both eccentric and coupling phases.

The SSC is an important feature to improve efficiency and performance of many kinds of movements and sports (43, 44). Compared with pure concentric work, a functioning SSC during a complete movement cycle leads to a higher muscle efficiency (58). The effect on exercise performance is seen, for example, in running, where about 50% of the elastic energy is believed to be recovered, leading to higher running economy (43). In jumping exercises, high and fast muscle activation during the eccentric phase of the take-off improves performance (39). For example, in longjumping, the maximal stretch in fibers of leg extensor muscles is achieved in a very short time of about 15 ms after touch down, leading to an eccentric force enhancement which is greater than the concentrically generated force immediate before the kick-off (54).

In many sports where athletes move on a horizontal surface, the net eccentric muscle work never exceeds that of the net concentric work (8). During alpine skiing, on the other hand, the skier gains speed and kinetic energy while skiing down a slope; to stay on course induces large compressive forces on the skier’s leg muscles. Competitive alpine skiing is therefore a sport where there is particular interest in eccentric exercise (1, 7, 8, 64). During turns in different disciplines (super G, giant slalom, and slalom), eccentric knee extensor muscle activity is dominant and was found to be higher in magnitude and up to twice as long in duration compared with concentric activity (7, 8). In these skiing disciplines, the muscle activity pattern during the eccentric phase is different compared with that found in track and field disciplines like sprinting, jumping, or running. Whereas in those disciplines, there is a substantial delay between the onset of muscle activity of the knee extensors and the subsequent joint movement (54), the EMG signal of knee extensors in alpine skiing is very closely synchronized to the mechanical action and reaches its maximal values toward the end of the eccentric movement (7, 8). Moreover, compared with typical jumping or running, a movement cycle (turn) in giant slalom or slalom is rather long. This is seen in slow knee-joint angular velocities [i.e., 20–70°/s (7, 8) up to 120°/s (authors’ observation in elite and junior skiers 2011 and 2013) compared with about 900°/s during the stance phase of fast running, for example (33)]. Thus movements and activity patterns of important leg muscles during alpine skiing differ from those in explosive sports. That is, they do not fulfill the prerequisites for functioning SSC (high preactivation, short and fast eccentric phase, fast coupling phase) and could be classified between slow SSC and shock absorber functioning (Fig. 2). This is a challenge to the implementation of effective strength training programs for alpine skiers.

EFFECTS OF ECCENTRIC EXERCISE TRAINING

Compared with concentric exercise, eccentric loading has the potential to overload the muscular system at very low

energy cost (31). This makes eccentric training an interesting training adjunct in strength and conditioning programs for performance enhancement or injury prevention purposes in elite sports (42). Despite numerous reports on the effects of eccentric exercise in untrained subjects or clinical trials, there is a lack of investigations on training effects in highly trained athletes. Furthermore, differences in training and testing protocols make it difficult to draw generalized conclusions on the effect of eccentric training on strength and exercise performance.

TRAINING MODALITIES

Extensive reviews on the effect of eccentric exercise training have been published recently (28, 31, 52). From these, different eccentric training modalities can be derived: the eccentric “high intensity-low volume” training approach is characterized by very high load, which can exceed one repetition maximum. Number of repetitions within a set or training session is in general low. Training is performed in a “pure eccentric” or “mixed eccentric-concentric” manner, in which the exercises are “isotonic” or “isokinetic” in most studies (28). Training exercises are generally performed with weight machines, barbells, dynamometers, or one’s own body weight (16, 31). The “low intensity-high volume” approach is characterized by high duration but submaximal exercise intensities. During the last few years, new devices and technology like eccentric arm- and leg-cycle or stepper-like ergometers have been developed (21, 22, 31, 64). Eccentric cycle ergometry is often referred to as “mild” or “chronic” eccentric training.

IMPROVING MAXIMAL AND EXPLOSIVE STRENGTH IN UNTRAINED SUBJECTS

It is well accepted that eccentric resistance training is more effective for improving strength, when measured under concentric or eccentric conditions (16, 28, 31, 37, 43, 50, 52). In their review, Guilhem et al. (28) compared isokinetic and

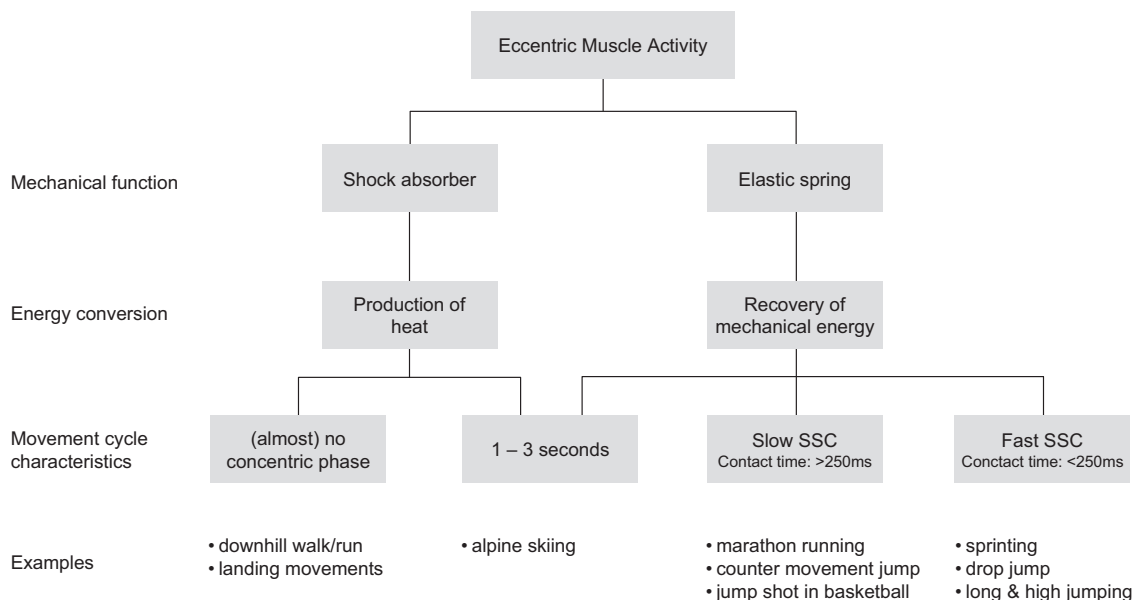


Fig. 2. Classification of eccentric muscle action in sports. SSC, stretch-shortening cycle.

isotonic eccentric forms, mainly from studies on untrained subjects. When focusing on studies examining only eccentric training of knee extensors or flexors (28, 29, 59), it can be calculated that isotonic interventions were on average characterized by 8.2 wk of duration, 2.6 sessions/wk, 3.6 sets, and 7.4 repetitions/set. The average strength gain per session was 2.4% and 1.2% when measured eccentrically and concentrically, respectively. In the isokinetic training studies, subjects trained 10.8 wk, 2.8 sessions/wk, 3.5 sets, and 9.2 repetitions/set. Although average training load (total sessions \times sets \times repetitions) was almost twice as high for isokinetic compared with isotonic training mode in these studies, strength gain was clearly lower for the isokinetic mode. Thus it can be concluded that “high intensity-low volume” eccentric training leads to substantial strength gains, which were higher when tested eccentrically rather than concentrically, and higher when trained isotonicly rather than isokinetically.

Eccentric cycle ergometer training according to the “low intensity-high volume” approach on initially untrained subjects also leads to larger strength gains than concentric training (19, 31, 40, 41, 43, 57). In one study, subjects performed 32 training sessions within an 8-wk period (40). The duration of a training session was between 15 and 30 min. Training load was increased week by week up to a final workload of 489 W. Subjects improved maximal isometric leg strength by 36% (1.1% per session). This increase in strength is similar to that found in the “high intensity-low volume” training studies. In one study the effect of 21 eccentric cycle ergometer training sessions performed within 7 wk on explosive strength was evaluated (20). Both maximal power output during countermovement jumping (+7%) and leg spring stiffness (+10%) were improved to significantly greater extent compared with a control group matched for total work.

IMPROVING MAXIMAL AND EXPLOSIVE STRENGTH IN TRAINED SUBJECTS

Compared with novices, well-trained individuals respond differently to training stimuli. Therefore it is questionable if these results are applicable to training regimes of athletes. To the best of our knowledge, there are only a few studies investigating the effects of eccentric training on strength gain in well-trained athletes. Mjolsnes et al. (46) integrated 27 Nordic hamstring training sessions (isotonic mode) during a 10-wk training period. The well-trained soccer players improved eccentric hamstring torque at slow velocity (60°/s) by 0.4% per session, which was clearly lower compared with that found in untrained subjects. In another study on athletes (from track and field jumps or sprints sports, basketball, volleyball, or judo and with several years of experience in resistance training) the effects of 6 wk of classic concentric/eccentric quadriceps strength training were compared with eccentric overload training (25). Although overloading led to an \sim 1.9 higher loading during the eccentric compared with the concentric phase, both groups improved their concentric one repetition maximum to the same degree. But only eccentric overload training led to improved height in the squat jump. Sheppard et al. (55) investigated jump training exercises three times per week for 5 wk on high-performance male and female volleyball players. Additional loads were applied during the eccentric but not concentric phase of countermovement jumping exer-

cises. In total, both intervention and control groups performed 190 jumps within the 5-wk training period, in addition to other strength training exercises. The eccentric accentuated training group improved jump performance by 11% whereas there was no effect (-2%) in the control group. During the preseason period of team-sport athletes, Cook et al. (15) performed four counterbalanced 3-wk training blocks in a crossover design (15). Block focused on either traditional resistance training at 80% one repetition maximum (TRT), eccentric-only resistance training at 120% one repetition maximum (ECC), TRT with overspeed sprint and jump training, or ECC with overspeed sprint and jump training. Greater strength gains were found for the ECC (+5%) modalities. Further, performance increased in countermovement and squat jump more after ECC with overspeed stimuli compared with TRT.

Eccentric cycle ergometer training was assessed in well-trained high school basketball players (44). They trained for 6 wk, three times per week, 30 min per session. During the training period, the eccentric load was gradually increased such that they were working at nearly 500 W during the last 3 wk. A concentric weight training control group was drawn from the same high school basketball team. All eccentrically trained subjects increased their jump height, with an overall mean increase of 8% (+5 cm). In response to eccentric training, hopping frequency as an indicator of leg spring stiffness increased by 11%, suggesting an enhanced capacity for energy storage and recovery. A similar eccentric cycle ergometer training protocol was applied on junior alpine skiers (27). They trained for 20 min on the eccentric cycle ergometer in addition to 40 min of classical concentric weight training during the same session three times per week for 6 wk. Athletes of the eccentric training group improved their maximal isometric strength in the leg press by 10%. This was similar to that found for the concentric training control group. Countermovement jump height increased by 7.9% (+4.1 cm) in the eccentric-trained group only. In an applied study, five world-class alpine skiers were monitored during a 5-wk off-snow period (61, 63). As an adjunct to their classical resistance training regime (weight lifting and core training, no jumping exercises), athletes performed one to two eccentric cycle ergometer interval sessions each week. Within a session, training was switched between 5 min sitting or standing position (Fig. 3). From the second to last session, mean training workload was increased by 140% from 404 to 965 W. Athletes were able to sustain this increase in workload without experiencing muscle soreness. Significant improvement were found for maximal isometric leg strength (+12%), maximal power in countermovement (+8.8%) and squat (+9.2%) jumps as well as eccentric force during a weight loaded (+100% of body weight) countermovement jump (+15.2%). These achievements were much greater compared with the same training periods performed without eccentric loading in the previous years.

In conclusion, available data indicate that by applying eccentric exercise training, maximal strength can be enhanced in already trained athletes. Not all (17, 48) but a good number of studies further indicate that athlete's explosive strength can also be increased by eccentric training. For athletic training practice it is striking to note that jump performance can be improved by eccentric training without performing specific jump exercises.



Fig. 3. Eccentric cycle ergometer for training in a sitting position and standing position.

ECCENTRIC TRAINING TO SHIFT THE OPTIMAL MUSCLE LENGTH

For optimal performance or injury prevention, it is believed that optimal muscle length for tension development should be adapted according to the specific demands of a given sport. In sprinting activities, hamstring strains often occur during maximal muscle activity in the transition from eccentric to concentric phase, perhaps due to inadequate or unbalanced muscle strength (2). In such sports, a shift to longer muscle length can decrease the risk for hamstring injury (13). During competitive alpine skiing, knee flexion angle is between 75° (outside leg) and 115° (inside leg), while highest EMG activity during a giant slalom turn is measured at a knee angle lower than 90° for the outside leg (8). It could therefore be supposed that strength of knee extensor and flexor muscles must be optimized in a movement-specific position. Nevertheless, injuries in skiing occur mainly in unbalanced situations, due to technical errors (6), indicating that adequate muscle functioning should be optimized over the whole range of joint movements.

It has been suggested that eccentric muscle activity is the only training modality for athletes to increase the muscle length for optimal tension development (16). In a first study, a single exhaustive and muscle damaging bout of maximal eccentric exercise was able to shift the optimum angle for tension generation by 7.7° in hamstring muscles (12). This effect persisted for several days, although signs of muscle damage diminished. In another study, professional soccer players were exposed to a 4-wk eccentric training intervention (13). The eccentric training group increased optimal length of hamstrings and quadriceps muscles by 4° and 6.5°, respectively. These results reveal that acute and chronic eccentric exercise training has the potential to shift peak torque toward greater muscle lengths (16, 28).

ECCENTRIC TRAINING TO IMPROVE MUSCLE COORDINATION

Eccentric compared with concentric muscle contractions require different activation strategies and programming processes by the central nervous system (23). Electroencephalographic measurements showed that during eccentric tasks,

cortical activation is higher in amplitude and area dimension (28). At the muscular level, similar force developments require substantially lower electromyographic activities during eccentric than concentric contractions (3, 9). This indicates that fewer motor units are recruited to produce the same tension as in concentric contractions, leading to an increased mechanical stress per motor unit. As change of tension per activated motor unit is increased when muscles perform lengthening work, eccentric motor tasks could be supposed to become inherently more difficult to control and coordinate.

Optimization of eccentric muscle coordination could be important in many sports. During SSC, well-coordinated stretch and coupling phases improve storage and release of elastic energy for sprinting and jumping tasks. In competitive alpine skiing, very high external loads must be absorbed by precisely coordinated eccentric contractions over a duration of 0.5–1 s per turn (8, 63). Eccentric muscle coordination was evaluated in 11 elite male skiers from the B-Team and in 5 world-class male skiers of the Swiss National Team (62, 64). They performed a 20-min exercise bout on an eccentric cycle ergometer during which the quality of eccentric muscle force modulation (i.e., the difference between required and delivered torque) was measured. A very good correlation between this quality and world ranking in slalom (B-Team: $r = 0.89$; National Team: $r = 0.93$) but not in downhill was found. This is not surprising when considering the similarities of the acceleration profiles in slalom and the typical force profile recorded during eccentric cycle ergometry (Fig. 4). This suggests that good coordination during eccentric muscle work could be important for elite alpine skiers and that eccentric cycle ergometry can be implemented for evaluating and improving the quality of eccentric muscle action.

MUSCULAR ADAPTATIONS INDUCED BY ECCENTRIC EXERCISE TRAINING

Functional improvements found after eccentric strength training are based on adaptations of the neuronal and muscular-tendon systems. Regarding muscular structural adaptations only, muscle hypertrophy, changes in fiber type-specific characteristics, and sarcomerogenesis can be identified to explain in

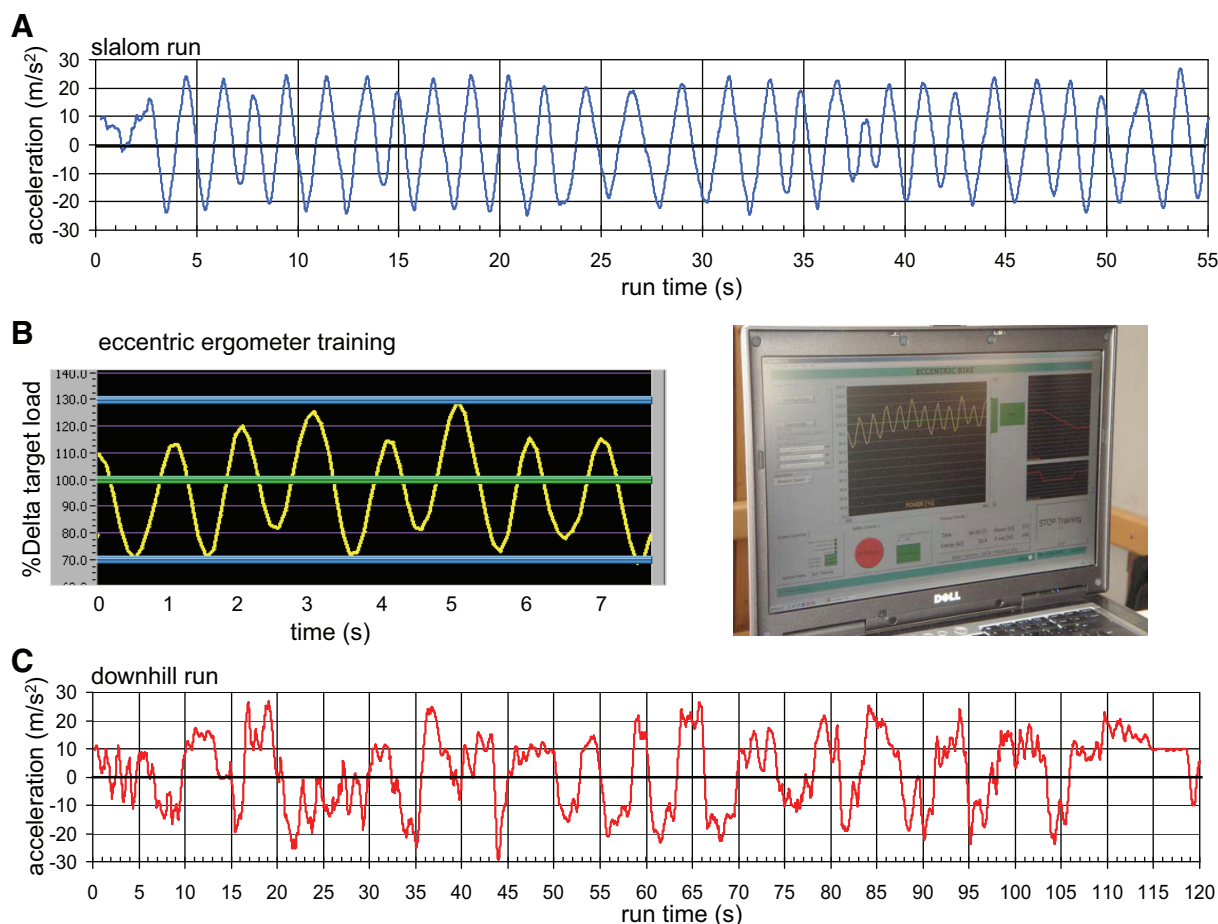


Fig. 4. Acceleration pattern of competitive slalom (A) and downhill (C). Data were recorded by using the activwave cardio sensor (CamNTEch United Kingdom). Positive (turn to the left) and negative (turn to the right) values indicate the direction of the turn. B shows an example of real-time computer feedback, visualizing the difference between the target (set as 100%) and the progression of the instantaneous load (yellow curve) during eccentric cycle ergometry. Area under the curve serves as an indicator to quantify coordination during eccentric work.

some part enhanced functional outcomes of eccentric training in already trained athletes.

Muscle hypertrophy. Maximal muscle strength depends on muscle cross-sectional area and the capacity for well-coordinated motor unit activation. For previously untrained subjects, muscle hypertrophy is enhanced by eccentric strength training (16, 28, 31, 43, 52). Contrary to classical concentric resistance training, which is initially mainly driven by neural adaptations (24), it was recently shown that a muscle mass increase occurred earlier, during the first 4 wk, with eccentric training (5).

In untrained subjects, high intensity-low volume isokinetic eccentric training induces mean muscle hypertrophy of 0.3% per session, which is three times higher than that found after isotonic eccentric training (28). For eccentric cycle ergometry, a 52% increase of muscle fiber cross-sectional area was found after 28 eccentric training sessions performed within 8 wk (40). A similar study employing 24 eccentric cycle ergometer training sessions was unable to reproduce this finding (57). These two studies were different in the training design, meaning that the first study (40) achieved a higher final training workload and applied periodization of the number of weekly training session.

From studies on already trained athletes, few data are available examining the effect of eccentric strength training on muscle hypertrophy. Friedmann-Bette et al. (25) found that 6 wk of classical concentric/eccentric strength training and eccentric overload training had the same anabolic effects, as increases in quadriceps cross-sectional area were similar. Gross et al. (27) showed that well-trained junior alpine skiers increased their leg muscle mass by 1.9% (+242 g), when replacing one-third of the weekly leg press exercises by eccentric cycle ergometer training for a total duration of 6 wk.

Muscle fiber type composition and muscle fiber length. Muscle fiber shortening velocity is determined by muscle fiber type and length (number of sarcomeres in series). Therefore a shift toward a faster muscle phenotype could be one explanation for the increased performance in jumping tasks found after eccentric training in athletes (25). Motor unit activity during eccentric exercise is a controversial topic. While some authors suggest that eccentric contractions are associated with preferential activation of fast and high-threshold motor units, others show a similar recruitment pattern in eccentric and concentric contraction, according to the size principle (28). From training studies, it has been shown that high-intensity or high-volume eccentric training can enhance muscle fiber cross-sectional area

of fast-twitch type IIa and IIx (25, 26, 28, 30, 60). Further, a general shift toward fast type II muscle phenotype is observed after eccentric training, which can be accelerated by fast eccentric contraction velocities (50).

It appears that some eccentric exercise training protocols using high loads, high movement velocity, or high amplitude can increase muscle fascicle length (4, 10, 16, 28, 29, 49). Increased fascicle length is due to the addition of serial sarcomeres in the muscle fibers (51). In fact, sarcomerogenesis was shown to take place in eccentrically trained animals (14, 45, 47). As a consequence, the mechanical properties of muscle fibers are changed (51). Addition of sarcomeres increases muscle contraction velocity and extensibility, thus allowing more powerful force production at longer muscle lengths. This can potentially influence muscle performance and flexibility or improve the protective effects against muscle damage (51). By affecting muscle shortening velocity, increased number of sarcomeres and fascicle length after eccentric exercise can enhance muscle power, which is important in most sport activities (16, 28).

PRACTICAL APPLICATION

In competitive sports, athletes and coaches are continuously searching for effective training methods to further stimulate physical adaptive processes to enhance performance.

Eccentric exercise training has the potential to massively overload the muscular system at very low energy cost and induce distinct muscular activation patterns. It has been shown that eccentric training modalities can accelerate or optimize improvements to maximal muscular strength, power development, optimal muscle length for strength development, as well as coordination during eccentric movements. We therefore propose that the systematic implementation of eccentric-based training protocols into strength and conditioning programs can improve or optimize performance in most types of sports, and could help prevent injuries as well (16, 42, 43).

From a practical standpoint, eccentric training programs should be specific to the requirements of the sport in mind. Ideally, eccentric exercises should involve multiple muscle groups. Weight lifting or jumping exercises during which the eccentric phase is accentuated or overloaded can fulfill these criteria (16, 55, 56). On the other hand, motor-driven devices like leg press machines or eccentric cycle ergometers, like those constructed for research or training purposes, could be useful (31, 35, 63, 64). By these means, a massive enhancement of total training load per training session is achievable for athletic training purposes. This is illustrated by world-class alpine skiers who trained on an eccentric cycle ergometer at a workload of 1,000–1,200 W for 20 min/session. By measuring pedal reaction force, it can be calculated that athletes resisted a total load of about 240 tons during a single training session (61). This is a magnitude of order higher than the total load possible to apply during a classical weight lifting session.

For the training of athletes, different types of eccentric loads can be applied (16). Depending on the training goal, the programs are varied in intensity, volume, movement velocity, and the length of muscle during eccentric action (16). When intensity is defined as percentage of concentric one repetition maximum, eccentric exercise can be performed at supramaximal, maximal, or submaximal intensities. In general, maximal

or supramaximal eccentric training protocols performed in an isotonic mode are well suited to improve maximal strength and muscle mass, whereas submaximal protocols are adaptable for the enhancement of muscle power and leg stiffness characteristics (16, 28, 31, 43). Training protocols focusing on very fast eccentric movements, such as plyometric exercises, are assumed to be essential for improvements in short SSC, which are mainly driven through neuronal adaptations (16). For this reason, exercises like drop jumps employ fast eccentric muscle action velocities at relative small amplitude of joint movements and at rather short muscle length. Alternatively, eccentric exercises at long muscle length and large amplitude like deep squats, countermovement jumps, Nordic hamstrings, or eccentric cycle ergometry are supposed to improve long SSC, while also inducing a shift in the optimal muscle length for tension development. In this regard, lengthening of muscle fascicles or tendon remodeling is expected to be essential (16, 42).

OUTLOOK

In view of the specific characteristics and promising effects, inclusion of specific eccentric muscle action into training programs is recommended for most competitive sports for performance enhancement or injury prevention. According to the principle of training specificity, regular application of eccentric exercise training is especially well suited for sports in which high loads and/or subtle coordination during eccentric movements are important. Nonetheless, additional well controlled eccentric training studies on trained populations are needed to broaden the understanding of the underlying mechanism and to support athletes, coaches, and physiotherapists. Among others, “optimization and individualization of training protocols” was recently mentioned as a field of further interests (31). This could imply attaining a better understanding of optimal training periodization by studying interactive effects with concurrent training stimuli and recovery time courses when including eccentric loading as a training adjunct in competitive sports.

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author(s).

AUTHOR CONTRIBUTIONS

Author contributions: M.V. and H.H.H. conception and design of research; M.V. performed experiments; M.V. analyzed data; M.V. and H.H.H. interpreted results of experiments; M.V. prepared figures; M.V. drafted manuscript; M.V. and H.H.H. edited and revised manuscript; M.V. and H.H.H. approved final version of manuscript.

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