Lower Extremity Stiffness: Effects on Performance and Injury and Implications for Training

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ABSTRACT

THIS ARTICLE REVIEWS RESEARCH TO DATE ON LOWER EXTREMITY STIFFNESS RELATIVE TO ITS EFFECTS ON PERFORMANCE AND INJURY. EVIDENCE SUGGESTS THAT AN OPTIMAL AMOUNT OF LOWER EXTREMITY STIFFNESS IS REQUIRED FOR SUCCESSFUL ATHLETIC PERFORMANCE, AS TOO MUCH OR TOO LITTLE CAN BE DETRIMENTAL AND POSSIBLY INJURY INDUCING. METHODS OF MEASURING LOWER EXTREMITY STIFFNESS AND FAST STRETCH-SHORTENING CYCLE PERFORMANCE ARE SUGGESTED. IN TERMS OF TRAINING, IT IS RECOMMENDED THAT A COMBINATION OF STRENGTH AND PLYOMETRIC TRAINING BE PERFORMED, AS WELL AS CORRECT EXECUTION OF LANDING MECHANICS TO IMPROVE INTERMUSCULAR COORDINATION AND TO AVOID INJURY-PROVOKING DOMINANT AGONIST-TO-ANTAGONIST COACTIVATION RATIOS.

INTRODUCTION

Lower extremity stiffness is considered to be a key attribute in the enhancement of running, jumping, and hopping activities, which are prevalent in most sports (1,4,8,10,19,26,27,32,65). An athlete who can appropriately use greater stiffness characteristics will potentially store more elastic energy at landing and generate more concentric force output at push-off, possibly reducing the onset of fatigue and increasing running speed. Consequently, if a strength and conditioning (S&C) coach is able to advance their athletes' ability to act like a "stiff spring" across an array of sporting movement patterns, performance enhancement may occur.

There are several different classifications and calculations of lower extremity stiffness consisting of joint (K_{joint}), vertical (K_{vert}), and leg (K_{leg}) stiffness (10), as well as muscle and tendon stiffness. The key terms defining lower extremity stiffness are described in Table 1. K_{vert} is generally regarded as the "reference" stiffness gauge; thus, models of K_{leg} and K_{joint} have been established based on this (8,10,53,65). K_{vert} is commonly used to measure jumping and hopping tasks, whereas K_{leg} would be more appropriate when measuring walking and running tasks as the change in leg length can be measured for each stride. Furthermore, K_{joint} is a fundamental measure for all lower extremity tasks, as the stiffness response at the applied joints will have an overall impact on K_{vert} and K_{leg}.

Practical limitations existed in the original techniques used to determine leg stiffness, as the use of a force plate was required. However, subsequent research from Dalleau et al. (15) has reported strong validity with the criterion measure using a jump mat by the calculation of flight time and ground contact time, whereby both submaximal and maximal hopping were significantly correlated

KEY WORDS:
lower extremity stiffness; vertical stiffness; leg stiffness; joint stiffness; compliance; stretch-shortening cycle; plyometrics; intermuscular coordination

Table 1
Classifications and definitions of lower extremity stiffness

Classification of stiffness	Definition	Appropriate term
K_{joint}	The resistance to change in angular displacement for flexion and rotation after implementation of joint moments	Joint stiffness
K_{vert}	The sum of resistance of the human body to vertical displacement after utilization of ground reaction forces	Vertical stiffness
K_{leg}	The resistance to change in leg length after utilization of internal or external forces	Leg stiffness

(r = 0.94 and 0.98). Thus, measurement and monitoring of leg stiffness is now practically viable for the S&C coach. The aim of this article is to review the literature on lower extremity stiffness (K_{vert}, K_{joint}, K_{leg}) and its effect on both performance and injury. This will provide S&C coaches with practical and purposeful methods for enhancing and measuring appropriate levels of lower extremity stiffness within a field environment.

UNDERPINNING SCIENCE

The concept of stiffness is founded on Hooke's law, which asserts that the force required to deform an object is correlated to a proportionality constant (spring) and the extent that object is deformed (8,65). Simply put, stiffness is the relationship between the deformation of an object in response to an applied force. From a practical perspective, for optimal running, jumping, and hopping performance, an appropriate level of lower extremity stiffness is required to absorb ground reaction forces (GRFs), as well as to store and reuse elastic energy (42). Stiffness is measured as the quotient of force to length and in the human body can be quantified from the level of a single muscle fiber to the modeling of the entire body as a mass-spring (8,10). Therefore, stiffness in the human body, or body parts, portrays its capability to withstand displacement once GRFs are applied and can be defined as the ratio between peak GRFs and peak displacement of the center of mass (15,48). This will require the interaction of muscles, tendons, ligaments, cartilage, and bone to oppose deformation to GRF or joint moments (8,10,63,65).

To create a model for lower extremity stiffness that accounts for all the anatomical structures, muscle reflex time delays, and central nervous system control is very complex and becomes impractical (10). Therefore, a much simpler spring-mass model has been developed to provide an estimate of lower extremity stiffness (2,3,21,31–37,53), comprising a mass and a weightless Hookean spring (Figure). In the human body, the mass represents body mass, and the spring represents the lower extremity, with stiffness recorded in the vertical direction (8). If no pressure is applied to the spring, it will accumulate no potential energy and therefore develop zero force. Conversely, if a force is applied to the spring causing a deformation, it will store elastic energy that can then be returned and reused as the spring shortens and returns to its normal resting length (52). The spring-mass model has been used to assess a variety of whole-body movements that involve the stretch-shortening cycle (SSC) including hopping, jumping, and running (8,52,65).

LOWER EXTREMITY STIFFNESS AND PERFORMANCE

The relationship between stiffness (K_{vert}, K_{joint}, K_{leg}) and performance is multifaceted and frequently misinterpreted. Numerous studies report that lower extremity stiffness increases with hopping height (19) and running velocity (26,27). However, it is argued that leg compliance (increased joint range of motion and elongation of muscles, tendons, and soft tissues) should be enhanced to improve running and jumping performance, as K_{leg} has been shown to stay constant (27,53) or even decrease with increasing running speeds (5). Brughelli and Cronin (8) suggest that more compliance will increase the storage and utilization of elastic energy during the SSC, therefore providing more concentric force output at push-off and potentially reducing the onset of fatigue. Consequently, it seems that there is a compromise between stiffness and compliance during athletic tasks.

There is conflicting evidence within the available literature as to how certain joints affect and regulate lower extremity stiffness. Numerous studies have shown that knee joint stiffness plays a significant role (1,3,4,18,36,42,65), several studies have indicated that ankle stiffness is more essential (20,21,54,63), and some were equivocal (26,34). Reported differences arise from the fact that depending on the task and velocity, the ankle and knee joint will vary in their contribution to lower extremity stiffness (65). However, recent research implies that with increases in hopping frequency there is a greater emphasis on ankle stiffness (35,43).

Sufficient leg stiffness is also a key requirement for effective storage and reutilization of elastic energy in SSC actions (10,46). A review by McMahon et al. (52) found that in vertical jumping and hopping tasks, increased K_{vert} and K_{leg} were related to increased vertical GRFs (1,4), increased ground contact

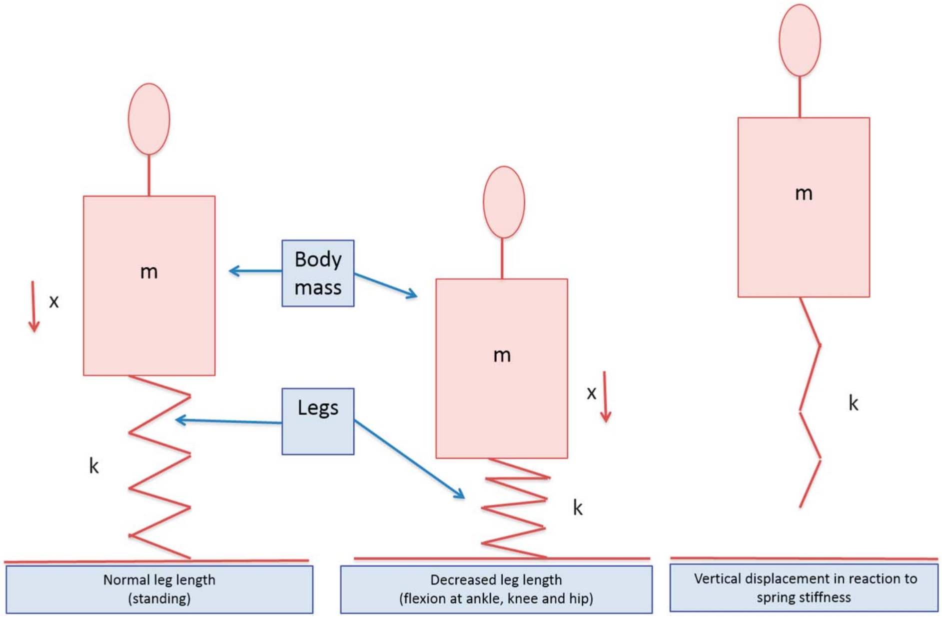

Figure. Spring-mass model behavior in relation to the human body. k = spring stiffness; m = mass; x = downward displacement.

frequency (19,25) (i.e., they achieved a higher number of hopping contacts), and to shorter ground contact times (1,4,19). Furthermore, Arampatzis et al. (1) identified a concomitant increase in lower extremity stiffness with reduced ground contact times, as demonstrated by a strong correlation (DJ20 cm: $r = -0.82$ and DJ40 cm: $r = -0.89$) during a rebound drop-landing task. Thus, lower extremity stiffness is augmented with increases in drop jump height because of the greater eccentric forces experienced (1,3,4,25,42,66,69).

Conversely, research by Wang (72) found that increased impact loads from drop landings of 40 and 60 cm actually reduced K_{leg} and when impact loads were increased from drop landings of 60–80 cm, K_{leg} did not decrease while knee K_{joint} increased significantly. Wang (72) highlights that the neuromuscular system has a reaction time of 50 milliseconds, and if the human body cannot initiate a reaction time to absorb impact forces before 50 milliseconds, the chances of injury are high. The study (72) found that the time-to-peak vertical GRF from a drop landing of 80 cm was 40 milliseconds, which suggests that modulation by the human body is insufficient to buffer landing impact. Thus, reduced leg stiffness with accumulating impact load may decrease the risk of future injury, particularly knee joint injury. This notion was reinforced by Laffaye et al. (45) as K_{leg} decreased with jumping height, advocating that a more compliant leg approach was beneficial to achieving greater jumping heights and faster ground contact times. As the lower limb joints used a larger range of motion (i.e., more compliant), a greater power output could be produced (45).

EFFECTS ON RUNNING PERFORMANCE

Numerous studies have highlighted that as the speed/force demands of physical activities escalate, there is a concomitant increase in stiffness (3,42,66,69). He et al. (27), Morin et al. (53), and Cavagna et al. (11) found that K_{vert} specifically increased with running speeds while K_{leg} stayed constant. Furthermore, Stefanyshyn and Nigg (69) established that with increases in running speed there was a substantial increase in ankle K_{joint}.

Brughelli and Cronin (8) found comprehensive evidence to suggest that K_{vert} increases with running speed up to moderate intensities and that K_{leg} remains constant. However, as speed increased above moderate intensities (5 m/s to maximum), K_{leg} increased by 60%, potentially suggesting that K_{leg} is important during running at higher velocities. Further evidence by Bret et al. (7) and Souhaiel and Christian (67) found that K_{vert} was interrelated with maximal velocity running, and Bret et al. (7) specifically identified that K_{vert} was significantly correlated with the second and third phases of the 100-m sprint (second phase 30–60 m, third phase 60–100 m) in national level male sprinters ($r = 0.66$, $p < 0.01$).

The enhancement of lower extremity stiffness is also a key factor for improving endurance running performance. This was highlighted by Hobara et al. (34), who showed that endurance-trained athletes had greater K_{leg} and more specifically, greater knee and ankle stiffness than participants from the general population during repeated 5-jump maximal hopping tasks. Furthermore, these results suggest that increases in leg stiffness are likely a result of training-induced adaptations.

LOWER EXTREMITY STIFFNESS AND INJURY

Lower extremity stiffness has been shown to be important for optimal athletic performance (8,10,65); however, there is evidence to suggest that too much stiffness may result in a higher incidence of injury (10,23,51,59,62,72,76). A direct correlation between lower extremity stiffness and lower-body injury has not definitively been established because of a lack of studies. However, extreme levels of lower extremity stiffness have been related to reduced joint motion and increased shock and peak forces in the lower extremity, whereas too low a level of stiffness has been associated with excessive joint motion (10,23).

Williams et al. (74) studied leg stiffness measures between high-arched runners and low-arched runners. High-arched runners were found to have increased leg stiffness and vertical loading rates compared with low-arched runners, potentially leading to the greater incidence of bony injuries compared with low-arched runners (75). Furthermore, earlier research by Williams et al. (75,76) found that runners with low arches and decreased leg stiffness incurred more soft tissue injuries than high-arched runners.

Pruyn et al. (62) studied the bilateral differences in leg stiffness of a professional Australian rules football league (AFL) team across a whole season to see if this was related to lower-body soft tissue injuries. The injured players demonstrated a significantly higher mean bilateral difference in leg stiffness than the noninjured group across the season (p = 0.05). Similarly, Watsford et al. (73) found that there was a propensity for greater bilateral differences in leg stiffness scores for AFL players who went on to suffer hamstring injury during the season compared with noninjured players. However, hamstring stiffness was significantly higher in the noninvolved limb of the injured players. This study may suggest that reduced hamstring stiffness could be associated with increased injury levels, but as the injured players tended to be significantly older than noninjured players, these findings may be contested. Contrary evidence by Granata et al. (25) and Williams et al. (75,76) suggests that too little stiffness allows for extreme joint motion therefore leading to soft tissue injury. Granata et al. (25) reported that females exhibited less knee stiffness than males during hopping, advocating that this reduced stiffness may explain the higher incidence of knee ligament injuries sustained by females. Research by Maquirriain (51) found that athletes who had suffered unilateral Achilles tendinopathy presented significantly reduced leg stiffness even after full symptomatic recovery, highlighting that full recovery of muscle-tendon function only occurred in 25% of athletes tested, so the majority had reduced performance. Therefore, it seems that there is an "optimal" level of lower extremity stiffness. Too much can lead to high levels of peak forces and loading rates, which can contribute to greater risk of bony injuries such as stress fractures and knee osteoarthritis (10), whereas too low levels of stiffness have been associated with possible soft tissue injury (23).

EFFECTS OF FATIGUE

Padua et al. (59) investigated the effects of fatigue on K_{vert} and stiffness control strategies in males and females. K_{vert} was not affected after fatigue; however, several different control strategies were used to maintain K_{vert}. Both males and females used an ankle-dominant strategy where greater reliance was placed on the ankle musculature (increased gastrocnemius and soleus peak activation) than the knee musculature (decreased hamstring peak activation). This increased ankle musculature activation may increase the risk of anterior cruciate ligament (ACL) injury, as the gastrocnemius is an antagonist of the ACL and is capable of increasing ACL strain (24). All subjects also used antagonist inhibition strategies by minimizing antagonist coactivation to maintain K_{vert}, as hamstring and tibialis anterior peak activation was reduced, whereas quadriceps, gastrocnemius, and soleus peak activation was maintained or increased. Thus, a reduction in knee flexor coactivation leads to a quadriceps-dominant strategy and, therefore, increases the load on the ACL due to increased proximal anterior tibial shear forces (6,24,30). This antagonist inhibition strategy was considerably more apparent in females than in males and could go someway to explaining the higher incidence of ACL injuries in females.

Howatson (38) investigated readiness to reperform by measuring electromechanical delay (EMD), which provides information on muscle function changes after exercise interventions. It was reported that after high-volume eccentric training, EMD was significantly greater at 96 hours after exercise and creatine kinase and muscle soreness were significantly elevated, suggesting that optimal recovery had not been achieved and neuromuscular mechanisms could be compromised, leading to altered motor control strategies. This has implications for S&C coaches, particularly in regard to the management of volume load and prescription of training during ballistic and plyometric exercises. Specifically, if the athlete has not fully recovered from periods of high-volume eccentric training, motor control strategies can become altered through a delay in the muscle feedback response, which potentially increases their risk of injury.

TRAINING CONSIDERATIONS FOR LOWER EXTREMITY STIFFNESS

Several papers have stated adaptations in lower extremity stiffness after exercise interventions, such as plyometrics (9,41,68), eccentric strength (61), isometric (9), and general weight (41) training. It has been well established that plyometric training improves sprinting, jumping, and ballistic capabilities (68,70). Plyometric training has also been shown to improve biomechanical technique and neuromuscular control during landing and cutting activities (12,13,29,39,47,55–57), as well as having the potential to reduce lower extremity injuries in team sports (29,49,58,60). There is also evidence to suggest that by performing plyometric training, participants can intentionally alter their stiffness during landing to change the impact forces through the body (4,16,17,78).

Hewett et al. (29) instigated a jump-training program that focused on teaching participants to land "softer" (adopting a more flexed knee position to increase hamstring activation and, thus, reduce ACL load). After the 6-week intervention, participants were able to decrease peak vertical GRFs and therefore potentially reduced the risk of injury. Furthermore, Hewett et al. (28) investigated the effect of a jump-training program on knee injury rates in female football, basketball, and volleyball players compared with a control group. The incidence of injury in female athletes who took part in the jump-training program was significantly lower because of their ability to decrease the stiffness (achieve optimal knee flexion) of their landings. Therefore, an athlete's ability to consciously control their lower extremity stiffness can possibly result in a lower chance of injury. Other examples from the literature include the work of Kryolainen et al. (44) who reported that 4 months of plyometric training increased the preactivity of muscles (vastus medialis, vastus lateralis, gastrocnemius, soleus, and tibialis anterior) leading to increased musculotendon stiffness and improved intermuscular coordination. Also, Chimera et al. (13) established that plyometric training might reduce injury rates by improving functional joint stability (K_{joint}) in the lower extremities. Therefore, these results suggest that appropriate jump-landing interventions can elicit favorable changes in neuromuscular control and landing biomechanics, which will subsequently reduce joint loading.

Komi (40) proposed that higher stiffness levels in lower extremity muscles during SSC exercises led to an advantage in terms of the larger amount of stored and reused elastic energy. Kubo et al. (41) added further evidence to this by reporting an increase of 63.4% in ankle K_{joint} assessed during drop jumps. Kubo et al. (41) suggest that plyometric training significantly increased maximal Achilles tendon elongation and the amount of stored elastic energy, which led to improved SSC jumping performance as confirmed by Wu et al. (77). This, therefore, implies that plyometric training and potentially improving ankle K_{joint} also conceivably improve the compliance of the Achilles tendons allowing more elastic energy to be stored and used during athletic performance.

Markovic and Mikili (50) carried out a comprehensive review on the performance adaptations from lower extremity plyometric training, proposing that adaptive changes in neuromuscular function are likely the result of (a) an increased neural drive to the agonist muscles, (b) changes in the muscle activation strategies (i.e., improved intermuscular coordination), (c) changes in the mechanical characteristics of the muscle-tendon complex of plantar flexors, (d) changes in muscle size and/or architecture, and (e) changes in single-fiber mechanics. Therefore, there are numerous mechanisms that plyometric training can affect, which will impact stiffness and compliance performance. In particular, improved intermuscular coordination strategies leading to improved quadriceps-to-hamstring coactivation ratios (50), which could potentially reduce injury rates. Furthermore, there is reported evidence to suggest that short-term plyometric training on nonrigid surfaces (i.e., sand-based or water-based surfaces) can stimulate similar increases in sprinting and jumping performance as traditional plyometric training on rigid surfaces, but with considerably less muscle soreness (50).

Table 2
Guidelines for exercises to develop lower extremity stiffness

Exercise	Aim
Squat and deadlift variations, bilateral and unilateral	Increase knee/hip extension strength and musculotendinous stiffness
Squat clean/snatch, squat jump variations	Increase lower-body power/strength and musculotendinous stiffness. Increase compliance of lower extremity joints
Power clean/snatch	Increase lower-body power and musculotendinous stiffness. Increase lower extremity joint stiffness
Drop lands/drop jumps (≤20 cm) and box jumps—with coaching instruction of stiff leg landing and minimal joint motion	Increase lower extremity stiffness particularly K_{joint}, improve landing mechanics and intermuscular coordination
Drop lands/box jumps and squat jump variations—with coaching instruction of soft landing	Increase compliance and ability to reduce impact forces. Improve landing mechanics and intermuscular coordination
Fast stretch-shortening cycle plyometrics	
Ankling bilateral/unilateral	Increase K_{vert}, K_{joint} particularly ankle K_{joint}, and compliance of Achilles tendon
Drop jumps (≥20 cm)	Increase K_{vert}, K_{joint} particularly knee K_{joint}, and compliance of Achilles tendon
Hopping and bounding variations	Increase K_{vert}, K_{leg}, K_{joint}, and lower-body compliance

This could, therefore, substantially reduce the amount of training stress and potentially aid in the prevention of overtraining.

Strength and power training has also been shown to affect lower extremity stiffness. As Cormie et al. (14) established that a 10-week back squat training protocol performed at 75–90% of 1 repetition maximum (RM) significantly increased K_{leg} during jump squat performance. Furthermore, it was reported that a comparative training group who performed jump squats using 0–30% 1RM increased K_{leg} during bodyweight jump squat performance. The increased K_{leg} after back squat training was credited to increased strength, whereas the increased K_{leg} after 0–30% 1RM jump squat training was attributed to greater SSC utilization through increased eccentric loading leading to enhanced concentric force output.

The combination of weight training and plyometric training together may have greater potential to advance jumping and sprinting performance through improvements in lower extremity stiffness than plyometric training alone. This was evident in a study by Toumi et al. (70) who identified that when the leg press exercise was combined with a plyometric exercise, K_{leg} assessed during countermovement jump performance was significantly increased after training. This may in part be because of different mechanistic training responses of the 2 modalities as highlighted by Kubo et al. (41) who reported that plyometric training improved concentric and SSC jump performance mostly through changes in mechanical properties of the muscle-tendon complex, whereas weight training produced changes in concentric-only jump performance as a result of increased muscle hypertrophy and neural activation of plantar flexors.

These findings are further substantiated in a recent meta-analysis by Saez-Saez de Villarreal et al. (64) who suggested that the ideal plyometric strategy is to (a) combine weight training and plyometric training, (b) use a training intervention duration of <10 weeks (with >15 sessions), and (c) use high-intensity exercises with >40 jumps per session. However, a precautionary note should be added to the recommendation for >40 jumps per session as the eccentric loading, for example, between 40 drop jumps and 40 ankle jumps is much higher and therefore would need to be accounted for in programming. Thus, although these general guidelines provide some insight, the research is currently equivocal as to effective plyometric program design. Most studies imply that moderate training frequency (2–3 sessions) and short-term interventionist (6–15 weeks) can change the stiffness of various elastic components of the muscle-tendon complex of plantar flexors and improve lower extremity strength, power, and SSC muscle function (50).

FIELD TESTING

A practical way of monitoring lower extremity stiffness levels in athletes in a field environment would be to use a contact mat and measure ground contact time and flight time. Athletes perform submaximal hopping at 2.5 Hz to ensure that movement patterns are reflective of typical spring-mass model behavior (15,48), and a metronome can be used to keep the rhythm of hopping. The contact and flight time data can then be used to calculate leg stiffness (peak GRF/peak displacement of the center of mass) based on the equation proposed by Dalleau et al. (15), which has been established as a valid and reliable measure. Within the following equation, K_n refers to leg stiffness, M is the total body mass, T_c is equal to ground contact time, and T_f represents flight time:

$$\text{Leg stiffness } \big(K_n\big) = \big(M \times \pi[T_f + T_c]\big) \big/ T_c^2\big[T_f + T_c/\pi\big] - \big[T_c/4\big]\big).$$

An easy and practical way of measuring fast SSC contact times (<0.25 seconds) would be to use the reactive strength index. This is calculated by dividing the height jumped by the time in contact with the ground before take off (22). The score can be improved by either increasing height jumped or minimizing time spent in contact

Table 3
Example base conditioning session to enhance lower extremity stiffness

Exercise	Sets	Repetitions	Load	Rest
Hang clean	4	4–6	65–70% 1RM	3 min
A1: Back squat	3	10	75% 1RM	90 s
A2: Drop landings[a]	3	6–8	BW	Perform in rest
B1: Stiff legged deadlift	3	10	75% 1RM	90 s
B2: Squat jumps[b]	3	6–8	BW	Perform in rest
C1: DB lateral lunge	3	10E/L	75% 1RM	90 s
C2: Ankling bilateral (vertical in place)	3	12	BW	Perform in rest

1RM = 1 repetition maximum; DB = dumbbell; BW = bodyweight; E/L = each leg.

[a] Emphasis on stiff landings with minimal joint motion.

[b] Emphasis on soft landings to absorb force and encourage optimal knee flexion.

Table 4
Example strength training session to enhance lower extremity stiffness

Exercise	Sets	Repetitions	Load	Rest
A1: Squat snatch	4	3	80–85% 1RM	3 min
A2: Ankling unilateral	4	20–25 m	BW	Perform in rest
B1: Bench step up	4	4E/L	>85% 1RM	2 min
B2: Drop jumps ≤20 cm[a]	4	4–6	BW	Perform in rest
C1: Deadlift	4	4	>85% 1RM	2 min
C2: Standing long jump	4	4–6	BW	Perform in rest
D: Nordics	3	6–8	BW	90 s

1RM = 1 repetition maximum; BW = bodyweight; E/L = each leg.

[a] Emphasis on stiff landings with minimal joint motion and short contact times.

with the ground but ideally both. The data collated from leg stiffness and reactive strength index results will help S&C coaches identify the lower extremity capabilities of their athletes and help in planning a constructive program that should enable sufficient levels of stiffness to be met relative to the athlete's physiological performance needs at tendon, muscle, and joint level.

PRACTICAL APPLICATIONS

It is important that S&C coaches take a progressive approach to developing "optimal" levels of lower extremity stiffness in their athletes. This should be performed through well-structured periodized programming that focuses on developing all the physiological adaptations required for lower extremity stiffness. A further consideration is that a fundamental level of strength is required to develop knee/hip extensor strength and increase tendon stiffness before the more demanding power and high eccentric loading SSC activities are introduced. The development of weightlifting exercises and their derivatives will be fundamental when programming, and an emphasis on the power catch position for the snatch/clean may provide development of stiffness capabilities about the knee.

Table 5
Example power training session to enhance lower extremity stiffness

Exercise	Sets	Repetitions	Load	Rest
A: Power clean and Jerk	4	3	80% 1RM	4 min
B1: Split squat	3	3E/L	90% 1RM	3 min
B2: Drop jumps ≥20 cm[a]	3	3–5	BW	Perform in rest
C: BB jump squats	3	4	20–30% 1RM	3 min
D: SL hops	3	20–25 m E/L	BW	3 min
E1: Snatch pulls	3	3	>80% 1RM	3 min
E2: Hurdle jumps	3	4	BW	Perform in rest

1RM = 1 repetition maximum; BB = barbell; BW = bodyweight; E/L = each leg; SL = single leg.

[a] Emphasis on stiff landings with minimal joint motion, short contact times and maximal height, "jump fast, jump high."

Flanagan and Comyns (22) provide a comprehensive breakdown for optimizing fast SSC training to enhance stiffness responses. They recommend following a 4-step progressive plan: Phase 1: eccentric jumping focusing on landing mechanics, quiet landings, and freezing on contact; phase 2: low-intensity fast plyometrics focusing on ankling/skipping, with short contact times and legs acting like stiff springs; phase 3: hurdle jumping, emphasis on short contact time and some degree of jump height, and contact time is used as a feedback tool; and phase 4: depth jumping, short contact times with maximal jump height, "jump fast, jump high." For a more comprehensive review of developing plyometric exercises, refer to Flanagan and Comyns (22) and Turner and Jeffreys (71). Some general guidelines for exercises that can develop ideal lower extremity stiffness are given in Table 2; Tables 3–5 are examples of base conditioning, strength, and power training sessions to enhance lower extremity stiffness based on the findings from this review. A precautionary note should be added; as these are generic examples that emphasize lower extremity stiffness and have not taken account of specific sporting parameters. The needs, abilities, and sports performance requirements of each athlete should be accounted for when implementing lower extremity stiffness into program design.

CONCLUSIONS

Lower extremity stiffness has been shown to enhance athletic performance through improvements in running, jumping, and hopping tasks (1,4,8,10,19,26,27,32,65), as well as reducing the incidence of soft tissue injuries (10,23). However, there is growing evidence that too much stiffness is injury inducing (10,23,59,62,72,73,76). Thus, the compromise between gaining ample levels of lower extremity stiffness and also the ability to have a compliant range of motion when needed is not simple to train and will require a multifaceted approach from S&C coaches. Concurrent training methods to improve stiffness and compliance should be applied. For example, when coaching landing mechanics, “stiff” leg landings with minimal joint motion should be taught. However, “soft” landings with optimal knee flexion to absorb heavy forces should also be implemented into the program, thus training the athlete to be able to adapt lower extremity stiffness when required. This will develop their intermusclar coordination and thus potentially reduce the chances of noncontact injuries. Once these movement patterns have been mastered and adequate levels of strength gained, progressions to power and high eccentric loading SSC plyometric training can gradually be made, allowing for further developments in lower extremity stiffness but also improved compliance through SSC mechanics.

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