Lower Extremity Stiffness: Considerations for Testing, Performance Enhancement and Injury Risk

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Abstract

Force-deformation characteristics of the lower limb have been associated with athletic performance and may modulate the risk of injury. In-spite of these known associations, measurements of lower extremity stiffness are not commonly administered by strength and conditioning coaches. This review provides an overview of the available literature pertaining to the effects of lower extremity stiffness on physical performance and injury risk. Practical methods of monitoring and training stiffness are also discussed. The cumulative body of evidence indicates that increases in lower extremity stiffness are associated with heightened performance in athletic tasks such as hopping, jumping, throwing, endurance running, sprinting and changing direction. Relationships with injury are less conclusive as both excessive and insufficient limb stiffness have been postulated to increase risk. Thus, the 'optimal' level of stiffness appears to be dependent on the anthropometry, and physical capabilities of the athlete, in addition to sport-specific activity demands. Training interventions can positively enhance lower extremity stiffness, including isometric, eccentric and isotonic strength training and plyometrics. Complex training also appears to provide a potent stimulus and may be more effective than the use of singular training modes. For plyometric activities, it is recommended that coaches use a developmental sequence of exercises with increasing eccentric demand to provide an appropriate stimulus based on the training age and technical competency of the athlete.

Introduction

Stiffness can be described as the resistance to the deformation of an object in response to an applied force (18,56,78). This resistance requires the complex interaction of muscles, tendons, ligaments, cartilage and bone, each with their own individual deformation profile (16,18). Thus, lower extremity stiffness can be determined at various levels within the leg, including the tendon, muscle fiber, muscle-tendon unit (MTU), joint and leg. Global stiffness characteristics of the lower limb have been shown to influence performance within a range of athletic tasks which are dominant in most sports, such as, hopping, jumping, running and change of direction (1,3,15,16,26,36,41,61,82). A certain amount of lower extremity stiffness is required for effective storage and re-utilization of elastic energy in these stretch-shortening cycle (SSC) activities. An athlete who can demonstrate greater stiffness characteristics will store more elastic energy during the yielding phase of ground contact and generate more concentric force output at push-off; increasing running speed and jump height. Thus, advancing an athletes ability to act like a 'stiff spring' across movement patterns specific to their sport may enhance performance.

It has also been reported that stiffness properties modulate the risk of injury; however, the relationship between lower extremity stiffness and injury is multifaceted and often misunderstood. A cumulative body of evidence indicates that high levels of stiffness leads to heightened injury risk (31,63,74,77,86,88), likely due to increased shock, peak forces and reduced joint motion in the lower extremity (18,31). Similarly, athletes who exhibit low levels of stiffness may increase their likelihood of soft tissue injury due to excessive joint motion (18,31). Thus, including monitoring tools to evaluate an athlete's lower extremity stiffness characteristics within a testing protocol could be considered beneficial for injury management.

In-spite of the potential for increased athletic performance and associations with injury, measurements of lower extremity stiffness are not commonly administered by strength and conditioning coaches (S&C), perhaps due to perceived practical limitations and complexity.

Identifying the appropriate parameter to test for lower extremity stiffness is a challenge in itself; however, global measures of stiffness such as vertical and leg stiffness have been shown to influence athletic performance and injury risk. Due to advances in research and technology these measures are now practically viable for the S&C coach, enabling an important performance variable to be trained and monitored.

Developing an awareness of what lower extremity stiffness is, how it can be measured and how it can be enhanced is an important addition to the 'tool box' of the S&C coach. The aim of this article is firstly, to examine the effects of lower extremity stiffness on athletic performance and injury risk. Secondly, methods of measurement and training will be discussed to provide coaches with evidence-based strategies to utilize with their athletes.

Methods

An electronic database search for empirical research studies and review articles was completed utilizing SPORT Discus and PubMed between the 1st September and 31st October 2016. The search strategy combined specific phrases related to lower limb force-deformation characteristics with explicit parameters to ensure relevant articles were extracted. The search terms included "lower extremity stiffness", "lower limb stiffness", "vertical stiffness", "leg stiffness", and "joint stiffness" which were combined with a variety of terms "performance", "injury", "measurement" and "training". Articles were chosen after scanning the title and abstract and then where access to the full text was available from the appropriate publishers. The reference lists of all articles were also examined for eligible studies to ensure no relevant articles were omitted from the search process.

Definitions and Application of Stiffness

The concept of stiffness is based on Hooke's Law; objects that follow this law are deformable bodies, which store and return elastic energy. Hooke's Law is defined as $F=kx$ (18), where F is the force needed to deform an object, k is the proportionality constant (stiffness) and x is

the distance the object is deformed (18). Based on this notion, a simple spring-mass model has been developed to provide an estimate of lower extremity stiffness (1,39,42,69), containing a mass and weightless Hookean spring (Figure 1). Whilst the leg-spring does not represent a true physical spring (69,70), this model is successful in describing features of human movement given principles such as the conservation of momentum in response to reaction forces (12).

********************Figure 1 somewhere near here *****************************

In the human body, the mass represents body mass, and the spring represents the lower extremity. Two types of lower extremity stiffness can be calculated from the spring mass model: vertical stiffness (K_{vert}), which seeks to model the vertical displacement of the center of mass (COM), and leg stiffness (K_{leg}), which seeks to model deformation of the lower limb (16,67). For this reason, the utilization of Kvert may be seen as more applicable to vertical-dominant tasks such as hopping and vertical jumping whereas Kleg may be preferred if seeking to model anterior-posterior or medio-lateral motion, for example, horizontal and lateral jumping and sprinting/steady state running. However, it is important to acknowledge that measurements of Kvert and Kleg have revealed disparate relationships with performance outcomes and/or changes in exercise intensity in running-based investigations (20,37, 69).

Fundamentally, stiffness in the human body portrays its capability to resist deformation in response to the application of ground reaction forces; therefore, many factors can enhance or limit lower extremity stiffness. For example, if one segment such as the Achilles tendon has poor stiffness characteristics this can then affect the whole global system. That said, measuring all the areas in the lower extremity that have their own individual deformation profile, is complex and fundamentally impractical for the S&C coach, especially in a field

environment. Global measures of lower extremity stiffness, notably K_{vert} and K_{leg} are most commonly measured; however, joint stiffness (K_{joint}) is a fundamental measure for all lower extremity tasks as stiffness of the component joints within the system will ultimately impact the global system stiffness (i.e. K_{vert} or K_{leg}) (1,29,40,51). Thus, K_{joint} may also provide S&C coaches with valuable information when examining a range of athletic tasks due to the importance of task specific stiffness. For example, during high frequency movements with short contact times (maximum velocity sprinting, fast jumping/hopping), ankle stiffness is likely to be the main determinant (28,29,41) whereas tasks requiring longer contact time and greater torque outputs (maximum height jumping, slow hopping, acceleration phase of sprinting) place a greater emphasis on knee stiffness (1,40,51). Determination of K_{joint}, where practically viable, should therefore be considered along with K_{vert} and K_{leg}. Key terms defining these lower extremity measures are described in Table 1.

****************Table 1 somewhere near here ****************************

Muscle and Tendon Stiffness and Recovery of Elastic Potential Energy

Before discussing the effects of global measures of lower extremity stiffness (K_{vert} and K_{leg}) on performance, it is important to briefly consider the influence of muscle and tendon stiffness on the return of elastic energy. The inverse to stiffness is compliance, a compliant tissue deforms easily even under the application of a small force. Brughelli and Cronin (16) suggest that more compliance will increase the storage and utilization of elastic energy during the SSC. However, it appears there could be a point of diminishing returns with compliance in muscle and tendon, as when eccentric loading reaches its extreme limits, the following concentric contraction will produce no further increase in force or energy return and could even potentially reduce it. This is probably because too much time is spent in the amortization

phase during the SSC (91). It is therefore important to consider which tissues and structures potentially require more stiffness and which benefit from more compliance.

Most tissues return to their original state when the force that initiated its deformation is reduced or stopped; these tissues are known as 'elastic'. Tendons are elastic tissues, and their shortening can occur at speeds much higher than muscle shortening (11). Also, tendons have been shown to have a high rate and efficiency of energy return during recoil, estimated at 65-90% (57). Although limited data exists on muscle, one study by Best et al. (9) suggests approximately 60% of energy can get returned for mechanical work by the muscles in rabbits. This is due to the viscous effects of muscle ensuring that energy is converted to heat and dissipated; which also slow the rate of muscle shortening during recoil (11). These data indicate that tendons are more efficient in their capacity to store elastic energy. Lai et al. (54,55) have observed that the triceps surae function quasi-isometrically during running gait, with the tendinous structures responsible for length changes in the muscle-tendon unit. When sprinting at 8 m.s^{-1}, the contribution of elastic energy from both the soleus and gastrocnemius was ~75% to the total positive work performed (54). Thus, for optimal elastic energy return during movements that utilize the SSC, it is important to train the muscle to be 'stiffer' than the tendon, as when two springs of differing stiffness are placed in series, more energy is stored in the compliant spring (11). This has important implications for S&C coaches as increasing the force production capacity of muscle is fundamental for increased muscular stiffness. This is not a suggestion that tendons should have excessive compliance, as the research on tendon stiffness is far from conclusive. Arampatzis et al. (5) found that the aponeurosis and tendon of the triceps surae were both stiffer in sprinters than in either endurance runners and untrained participants. The authors suggested that tendon stiffness was associated with the ability to generate high force. However, Lichtwark and Barclay (58) established that more compliant tendons produced greater power outputs, up to 4times higher than muscle could generate alone. Although more clarification is needed on the ideal levels

of tendon stiffness for optimal energy return, what is perhaps more clear is that the muscle should act as a stiff anchor during the SSC to allow for peak energy return from the tendon.

A cautionary note should be added when interpreting research relating to the measurement of muscle and tendon stiffness, both have viscoelastic properties. Therefore, the amount of stretch is not only load but also time dependent. Furthermore, other dependent factors such as joint angle (64) and velocity of movement (3) will affect the measurement of stiffness. Thus, simply measuring force and displacement ignores the intricacies of what is occurring across all the tissues. However, trying to account for all these aspects during physical testing is impractical for field-based measurements; therefore, global measures of stiffness (K_{vert} and K_{leg}) would be more appropriate to give an overall picture of an athlete's stiffness levels due to their ease of implementation.

Effects of Lower Extremity Stiffness on Performance

A certain amount of leg stiffness is essential for efficient storage and re-utilization of elastic energy in SSC activities (18). Higher levels of lower extremity stiffness have been reported with increasing force and speed demands during hopping (26), sprinting (36,37) and endurance running (20,36,37,39,84). Thus, potentially increasing an athlete's lower limb stiffness could facilitate improved performance during activities where the limb is subjected to high ground reaction forces on impact. In vertical jumping and hopping tasks, increased K_{vert} and K_{leg} have been related to increased ground contact frequency (21) and to shorter ground contact times (1,4,26). Further, Arampatzis et al. (4) demonstrated an associated increase in lower extremity stiffness with reduced ground contact times, during a drop-landing task. Greater vertical stiffness has also been positively linked to hopping height (52), jumping (squat, countermovement and drop jump) height (78), takeoff velocity during jumping (2) and track and field throwing performance (13).

A number of studies have observed increases in K_{vert} with increases in running speed (20,37,69); however, K_{leg} appears to be maintained. The difference between these two measures is potentially due to the fact that K_{leg} is mainly determined through the stiffness of the muscle-tendon complex with only small variations in spring stiffness occurring between moderate and high speed activities. Whereas, Kvert is not only reliant on the stiffness of the leg but also on the trunks ability to reduce high impact forces during high speed running; thus, if an athlete has weak trunk musculature this is likely to decrease their running efficiency and reduce $K_{vert.}$

Bret et al. (15) identified that K_{vert} was significantly correlated to the second (30-60m) and third (60-100m) phases of the 100m sprint. Furthermore, ankle K_{joint} was found to markedly increase with rises in running speed. Hobara et al. (39) compared sprint and endurance athletes, reporting that sprinters had greater $K_{leg,,}$ as well as greater knee and ankle K_{joint} during a variety of hopping and drop jump tasks. It was also established that sprinters had longer flight times and shorter ground contact times at both hopping frequencies tested. Although high levels of stiffness appear to be important for sprint athletes, lower extremity stiffness has also been identified as an important factor in endurance running performance. Hobara et al. (41) determined that endurance trained athletes had greater K_{leg}, more specifically greater knee and ankle stiffness than participants from the general population during a maximal hopping task. The authors proposed that these differences were likely due to training-induced adaptations (41), enabling for a more efficient return of strain energy during running. Lower extremity stiffness therefore appears to be influential to running performance, particularly sprint performance, with high levels of ankle K_{joint} being an important determinant.

Lower limb stiffness is also likely to influence the ability to effectively execute change of direction speed (CODS) tasks. Heightened performance in CODS tests have been closely associated with shorter ground contact times resulting in improved CODS (62,81,83)

Moreover, reactive strength index (a measure of an athlete's capacity to utilize fast SSC characteristics) has been highlighted as one of the physical qualities that may underpin CODS performance (23,93,94). It is therefore unsurprising that Maloney et al. (61) reported that K_{vert}, determined during a single leg drop jump, was a strong predictor of CODS performance. A stiffer limb is better able to resist deformation in response to the resultant ground reaction forces at ground contact, thus allowing the impulse required to change direction to be applied in a shorter time period.

Effects of Lower Extremity Stiffness on Injury Risk

Whilst high levels of stiffness may be considered to have a beneficial effect on athletic performance, high levels of stiffness have also been associated with an increased likelihood of lower extremity injury (31,63,77,86,88). This in part may be due to increased peak forces, shock and reduced joint motion in the lower extremity (18,31). For example, a comparison of K_{leg} in high and low arched runners suggested that high arched runners have increased K_{leg} and vertical loading rates, increasing the likelihood of bony injury when compared to low arched and lower Kleg runners (90). Conversely, too little stiffness has also been associated with excessive joint motion which may contribute to injury risk in soft tissue structures (18,31) as has been highlighted in low arched runners (88,89)

Studies on K_{leg} in Australian Rules Football (AFL) players established that bilateral differences were a potential contributor to explain the increased incidence of soft tissue injuries that occurred across a season (77), particularly hamstring strains (87). However, the injured players were significantly older than non-injured players; thus, these findings should be interpreted with caution as age is a known risk factor for increased risk for hamstring injury (71).

Fatigue has also been shown to impact K_{vert}, potentially increasing injury risk. Padua et al. (74) reported that when participants (male and female) were fatigued during hopping tasks at

two different frequencies they adopted an ankle dominant strategy, increasing the recruitment of the gastrocnemius and soleus musculature. Participants also displayed antagonist inhibition, as indicated by a reduction in hamstring and tibialis anterior peak activation and an increase in recruitment of the quadriceps, soleus and gastrocnemius. Both of these strategies can increase the load on the anterior cruciate ligament (ACL) due to increased anterior tibial shear forces (10,32). This antagonist inhibition strategy was more evident in females than in males and could in part explain the greater relative risk associated with ACL injury in females vs. males (76).

The relationship between lower extremity stiffness and injury is multifaceted; however, it is plausible to suggest that an 'optimal' level of stiffness is required. Too much can lead to high levels of peak forces and magnified loading rates, increasing the risk of bony injuries such as stress fractures and osteoarthritis (18) while low levels have been associated with a greater incidence of soft tissue injury (31). While there is clearly a distinct amount of variability in the determination of an 'optimal' stiffness threshold for a range of individuals, it is likely that this level would be dependent on the specific demands imposed by the sport and the physical profile of the athlete (i.e. body mass, limb length, strength qualities, etc.). However, if an athletic task does require increased stiffness it is very important that the athlete displays the required strength in the relevant musculature has to allow them to handle the increased loading rates and reduce potential injury risk.

Considerations for Coaches in the Field

Measurements of lower extremity stiffness (K_{vert} and K_{leg}) have most commonly been determined during cyclic hopping tasks (43,45,82). Hopping provides the simplest locomotive task by which to assess stiffness and is proposed to provide a strong representation of musculoskeletal stiffness given the efficiency of hopping gait (26). Drop jumps have also been utilized to measure K_{vert} values (59,60,61), as well as K_{vert} asymmetries (59,60,61). These are likely to give distinctly different stiffness measures compared to hopping, due to

greater displacements of the center of mass. Hopping and drop jump tasks have commonly utilized force plates to determine ground reaction forces, as these are considered the gold standard for jump testing (80). This therefore has precluded their use for many S&C coaches working outside of elite-level sport or without links to universities. However, with recent advances in technology S&C coaches can purchase entry level Pasco force plates for ~$650 per plate, making the direct measurement of ground reaction forces a more feasible option.

It is important to consider that the utilization of force places will not be practical in many instances and may not be an option to coaches working with smaller budgets. For this reason, it is important to consider alterative options for the assessment of stiffness. Research from Dalleau et al. (22) has shown that a jump mat can be utilized as a valid and reliable measure of K_{vert} and K_{leg}, therefore increasing their utility for a wider range of S&C coaches. Using the Dalleau et al. (22) method, athletes hop sub-maximally at 2.5hz in time to a metronome, with the flight time and ground contact time being subsequently placed into the following calculation:

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

Where: K_n = leg stiffness, M = body mass, T_c = ground contact time, and T_f = flight time.

The principles outlined by Dalleau et al. (22) were utilized by Morin et al. (69) to develop a simple 'sine wave' method of measuring K_{vert} and K_{leg} during running. Briefly, by assuming that the force-time curve can be fitted by a basic sine function, K_{vert} and K_{leg} can be predicted from a few simple mechanical factors: body mass, leg length, forward velocity, flight time and contact time (69). The original investigation by Morin et al. (60) utilized a treadmill dynamometer which, much like force plates, has practicality and feasibility issues for the S&C coach. However, further research conducted by Pappas et al. (73) has evaluated the reliability of measuring K_{vert} and K_{leg} with the sine-wave method during treadmill running,

utilizing a high speed camera (300 Hz) to measure flight and contact times. Pappas et al. (73) reported high intra- and inter-day reliability (the respective coefficients of variations reported below) for the sine-wave method as an assessment for Kleg (2.6% and 6.0%, respectively) and Kvert (2.1% and 3.0%, respectively). This method therefore becomes much more accessible to the S&C coach who has access to a treadmill and a high-speed camera.

Recent developments in mobile technology, such as the 240 Hz camera available on the iPhone 6, have enabled the measurement of stiffness from two IOS applications, namely My Jump and Runmatic. The My Jump application is designed to assess jumping capabilities from a number of different tasks, such as squat jumps, countermovement jumps and drop jumps, and can also provide a force-velocity profile for athletes. The application simply requires the input of mass, leg length and leg length at 90 degrees. In regards to stiffness, the drop jump function provides a very simple method of measuring K_{vert} for the S&C coach. The requirements include videoing the jump and then assessing the initial contact point, final take off point and the secondary landing point. This process is also employed for the assessment of K_{leg} during running using the Runmatic application. Take off time and landing are assessed, this data is then analyzed by the application using equations validated in Morin et al. (8,69). However, it is important to consider the potential issues inherent with this technique. Firstly, there are subjective measures of assessment utilized by both these applications such as leg length, and the assessment of take- off and landing which may affect sensitivity compared to a force plate. Secondly, calculations of stiffness appear dependent on the athlete dropping from a pre-determined height. Were the athlete to step down or jump off the box, this would change the drop height and therefore the velocity at which the athlete contacts the mat. Whilst My Jump has been deemed reliable and valid for the assessment of vertical jump height compared to a force plate utilizing countermovement jumps (7), and drop jumps (40cm), countermovement jumps and squat jumps compared to a contact mat (34), the determination of stiffness has not been subject to similar scrutiny. Nonetheless, the ease of use, portability, cost ($9.99) and practicalities of use for field-based assessments offer an attractive alternative

to the recommended gold standards of force plates and 3D motion analysis should these be appropriately validated.

Additional methods of K_{vert} and K_{leg} assessment have employed opto-electronic devices such as the Optojump (68). Optojump utilizes infrared technology to detect interruptions in communication (72), enabling the measurement of contact time and flight time during running and jumping tasks. This data can be used to calculate K_{vert} and K_{leg} using the mathematical model proposed by Morin et al. (69). The Optojump is widely used and has a high degree of validity and reliability compared with force platforms (35). However, in comparison to the two IOS applications My Jump and Runmatic is associated with far greater cost, offers less portability and requires specific computer software. Thus, it is likely that such devices may not be easily accessible to many S&C coaches.

Finally, there is emerging evidence that GPS-embedded accelerometers can be utilized for the measurement of K_{vert} during field based running (17). Buchheit et al. (17) performed a pilot study on a single team sports player and compared accelerometry derived data to that from an instrumented treadmill, finding near perfect correlations for contact time and K_{vert} and large correlations for flight time. Although more replication studies are needed to fully validate this method, the potential to monitor athletes K_{vert} during field based running training could give S&C coaches a valuable insight into determinants of running performance and injury risk, such as lower limb stiffness asymmetries.

Training Effects

Numerous studies have demonstrated augmentations in lower extremity stiffness following a variety of training interventions including; isometric (19), eccentric strength (79), isotonic resistance training (49) and plyometric training (20,49). Specifically, a resistance training protocol including the back squat with loads of 75-90% of 1RM has shown significant increases in K_{vert} and K_{leg} (21) and jump squat training using 0-30% 1RM also enhanced K_{vert}

and K_{leg} (21). Increases in lower extremity tendon stiffness have also been identified after both 8 weeks and 12 weeks of resistance training utilizing loads of 70% 1RM (46, 47). Furthermore, isometric resistance training was shown to increase lower extremity tendon stiffness after 12 weeks utilizing 70% maximal voluntary contractions (MVC) of 15-20s (48,50) and after 14 weeks utilizing 90% MVC for 3s (5,6).

When interpreting the available evidence, it has been suggested the strain magnitude during training should exceed that experienced during usual loading to achieve changes within the tendon (5,6). It should also be noted that resistance training is likely to change the interaction between muscular and tendinous lengthening. For example, McMahon et al. (66) reported that 8 weeks of resistance training reduced lengthening of the medial gastrocnemius muscle fascicles during hopping whilst increasing lengthening of the Achilles tendon. It would therefore appear likely that strength training increases the ability of muscle to function quasi-isometrically and may increase the contribution from the tendon (54,55).

Whilst a number of different training approaches have been used within the available literature (5,6,19,20,21,46,47,48,49,50,66,79), Toumi et al. (85) showed that complex training (i.e. a resistance exercise followed by a plyometric exercise) produced significant increases on K_{vert}/K_{leg}, whereas, resistance training alone had no effect. Hunter and Marshall (44) also utilized a complex training method study design, combining back squats and deadlifts with countermovement jumps and drop jumps respectively. K_{leg} increased during the performance of the counter movement jump (CMJ) but K_{leg} decreased during DJ of 30, 60 and 90cm (44). The authors suggested that the decrease in K_{leg} was potentially due to changes in DJ technique i.e. too much center of mass displacement on landing and increased ground contact times.

There is also growing evidence that jump and plyometric training is effective in allowing athletes to purposefully modify their lower extremity stiffness levels during ground contact to alter impact forces (4,24,25,95). Kryolainen et al. (53) showed that 4 months of plyometric

training including drop jumps (20-70cm), jump squats (30-60% from maximum), one and two leg hopping and hurdle jumps improved the pre-activation of certain muscles (vastus lateralis, vastus medialis, gastrocnemius, soleus and tibialis anterior) during a jumping task on a specialized sledge apparatus. This led to augmented musculo-tendon stiffness and enhanced intermuscular coordination. Also, the volume of training appears important for changes in stiffness levels, as high volume (~200-600 jumps a session) plyometric training over 14 weeks was shown to increase lower extremity tendon stiffness (33). However, a cautionary note should be added here as a variety of exercises were utilized such as squat jumps, countermovement jumps, drop jumps (40-80 cm) and single leg bounds which all produce differing levels of eccentric loading. Thus, prescribing 600 countermovement jumps versus 600 drop jumps (80cm) would produce very different outcomes. Kubo et al. (49) established that ankle K_{joint} increased 63% after 12 weeks of unilateral hopping and drop jump training. The investigators proposed that plyometric training increased maximal Achilles tendon lengthening and the volume of accumulated elastic energy, leading to enhanced jumping performance through improved utilization of the SSC (49). This proposition has also been advocated more recently by Wu et al. (92). These findings would therefore appear to demonstrate that plyometric training can not only enhance K_{vert}/K_{leg} by improving pre-activation of muscles, increasing ankle K_{joint} and augmenting tendon stiffness, but it is also an effective modality to increase the compliance of the Achilles tendon allowing for more efficient storage and return of elastic energy.

Practical Applications

Training

The cumulative body of evidence contains a variety of differing populations, phenotypes tested and methodological protocols making interpretation complex. Until a consistent body of evidence on highly homogenous groups is created, specific recommendations are inappropriate. That said, it appears that numerous training interventions can positively impact

lower extremity stiffness across a variety of populations, including; isometric, isotonic and plyometric training modalities. Therefore, generic recommendations based around these may be beneficial. It is likely that force dominant training increases the ability of the muscle to function quasi-isometrically, while velocity based SSC training enhances tendon proficiency. Although the mechanisms proposed to elucidate the reported changes differ within the available literature, some fundamental training principles are apparent. To enhance K_{vert}/K_{leg}, multi-joint strength training exercises (i.e squat, deadlift, snatch, clean) utilizing high loads (>75% 1RM) are required to provide a sufficient stimulus for adaptation. Further, emphasis on the power catch position for the clean/snatch may promote greater stiffness capabilities about the knee. Although presently little data exists on eccentric single joint training protocols for enhancing lower extremity stiffness, it is thought that exercises such as eccentric calf raises have the potential to modulate lower extremity stiffness about the ankle joint. Further, lower load, high velocity training may also induce further benefits, specifically, the utilization of jump squats with 0-30% 1RM (21). To develop lower extremity tendon stiffness, isometric training has also been shown to be an effective modality and should be performed for at least 3s per repetition. It appears that plyometric training is the most important modality to incorporate. Developments have been reported in K_{vert}/K_{leg}, K_{joint} and tendon stiffness with plyometric training, and conflictingly findings on tendon compliance have been reported. Plyometric training should be performed using high tendon strain magnitudes that are well above habitual loading (i.e. high drop heights), and drills should also be applicable to the demands imposed in the athlete's sport. A cautionary note should be added that low intensity plyometrics should serve as a pre-requisite to higher intensity modalities to develop the sufficient loading capabilities of the tendon. Guidelines for exercises to develop lower extremity stiffness are shown in table 2.

***********Table 2 somewhere near here **********************************

Exercise technique and Coaching Cues

During hopping, jumping and running tasks, understanding the optimal technique for increasing lower extremity stiffness is important for S&C coaches. The joint moment relationship is crucial, for example, on touchdown if there is excessive joint flexion at the ankle, knee and hip, the moment arm of the vertical GRF's will increase and therefore, K_{vert}/K_{leg} will decrease. Thus, making athletes aware of minimizing joint flexion, particularly knee flexion at the point of ground contact is fundamental. Arampatzis et al. (3) established that K_{vert}/K_{leg} can be influenced with coaching cues such as "jump as high as you can" and "jump high a little faster (in relation to ground contact time) than your previous jump." Further cues that are likely to be of benefit could include "stiffer knees", or "reduce ground contact time." Thus, S&C coaches can have a positive impact on lower extremity stiffness performance by utilizing effective coaching cues and having an awareness of effective technique. A cautionary note should be added to these recommendations as injury prevention programs advocate 'softer' landings as they decrease peak vertical ground forces (38), and potentially reduce the risk of ACL injury. Therefore, whilst trying to establish 'optimal' stiffness levels that improve performance, consideration of how the likelihood of injury may be decreased must also be considered. The incorporation of 'soft-landing' training is likely to serve as both a beneficial adjunct and precursor to plyometric training. In these instances, coaches would be advised to utilize terms such as "soft", "quiet", "spongy" or "ninja" within their cueing. Moreover, coaches should seek to give the athlete context as to when a stiff versus a soft ground contact should viewed as the appropriate strategy..

A good example of a technical model to improve athlete technique when lower extremity stiffness is required during landing jumping tasks, has been produced by Flanagan and Comyns (30). They provide a theoretical model to improve lower extremity stiffness through a developmental sequence of fast SSC exercises (<0.25s ground contact time) (table 3) (30). The first phase focuses on eccentric landing mechanics where the athlete aims to 'stick' the

landing of a low intensity jump. The aim of this phase is to improve the athlete's ability to withstand the downward velocity and eccentric load of plyometric exercises. The target of the second phase is to reduce ground contact times, thus the utilization of low intensity fast plyometric exercises such as skipping and ankle jumps. Coaches should encourage athletes to stay on the balls of their feet at all times and pre-activate the lower leg muscles before landing to enable a 'stiff spring' response. The third phase introduces height as a parameter, however the main aim in this phase is on minimizing contact time. Athletes are instructed to jump over multiple low hurdles with the focus on minimizing ground contact time and clearing the hurdle. When the athlete can adequately clear the low hurdle height with low contact time the hurdle height can be increased. The final phase focuses on both minimizing ground contact times and maximizing jump height. The reactive strength index (jump height (M)/ground contact time(s)) can be used to provide feedback to the athlete/coach to enhance performance.

****************************Table 3 somewhere near here *********************

Conclusion

Increases in lower extremity stiffness have been associated with heightened performance in athletic tasks such as hopping, jumping, throwing, endurance running, sprinting and changing direction, indicating that development of this physical quality should be targeted in the design of effective strength and conditioning programs. Relationships with injury are less clear as both excessive and insufficient limb stiffness have been associated with increased risk. The 'optimal' level of stiffness for an athlete is likely to be dependent on the activity demands imposed upon them by their sport (i.e. running, jumping, change of direction profiles) and by their physical profile (i.e. anthropometrics, strength qualities). Based on the cumulative body of evidence it appears that a number of training interventions can positively enhance lower extremity stiffness, including: isometric, isotonic and plyometric training methods. Additionally, adopting a developmental sequence of exercises with increasing eccentric

demand is recommended to provide an appropriate stimulus based on the training age and technical competency of the athlete. Finally, targeted coaching cues can be used to ensure safe execution of exercises selected due to their effect on movement mechanics.

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