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Clinical Biomechanics 18 (2003) 511–517
CLINICAL BIOMECHANICS
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Lecture

Lower extremity stiffness: implications for performance and injury

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Received 20 November 2002; accepted 21 March 2003

Abstract

Background. Lower extremity stiffness is thought to be an important factor in musculoskeletal performance. However, too little or too much stiffness is believed to increase the risk of musculoskeletal injury.

Purpose. To provide a current update of the lower extremity stiffness literature as it pertains to both performance and injury.

Summary. It appears that increased stiffness is beneficial to performance. As well it appears that there may be an optimal amount of stiffness that allows for injury-free performance. There is some evidence that increased stiffness may be related to bony injuries and decreased stiffness may be associated with soft tissue injuries. Further investigations should evaluate the relationship between stiffness and injury prospectively. Initial reports suggest that stiffness can be modified in response to the external environment or verbal cues.

Relevance

A greater understanding of the role of stiffness in both performance and injury will provide a stronger foundation for the development of optimal training intervention programs.
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1. Introduction

Studies of lower extremity stiffness are becoming more prevalent in the biomechanics literature as researchers strive to further understand the complexities of lower extremity mechanics. In its simplest sense, stiffness is the relationship between the deformation of a body and a given force. In terms of the human body, stiffness can be described from the level of a single muscle fiber, to modeling the entire body as a mass and spring. Most biomechanists agree that true stiffness of the human body is the combination of all the individual stiffness values contributed by muscles, tendon, ligaments, cartilage, and bone (Latash and Zatsiorsky, 1993). In particular, sports and clinical biomechanists are typically interested in the role of stiffness as it relates to both performance and injury. While some stiffness may be necessary for performance, either too much or too little stiffness may lead to injury. Therefore, the purpose of this paper is to review the various definitions of stiffness, and to examine the relationship between stiffness, and performance and injury. In addition, we will review studies which provide evidence for the ability to modify stiffness. It is our hope that this paper will lend insight into the current thought about the role of lower extremity stiffness in the areas of performance and injury.

2. Definitions of stiffness

The concept of stiffness has its origin in physics, as part of Hooke's Law. Objects that obey this law are deformable bodies which store and return elastic energy. Hooke's Law, defined as $F = kx$, states that the force (F) required to deform a material is related to a proportionality constant (k) and the distance (x) the material is deformed, provided that its shape is not permanently

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0268-0033/03/$ - see front matter © 2003 Elsevier Science Ltd. All rights reserved.
doi:10.1016/S0268-0033(03)00071-8

changed. The proportionality constant, k, is referred to as the spring constant, and it describes the stiffness of an ideal spring and mass system (Fig. 1). An ideal spring is massless, moves in one direction only, and has a stiffness that is independent of time, length, or velocity. In addition, the mass of the system is assumed to be concentrated at a point at one end of the spring.

The leg is often modeled as a spring supporting the mass of the body. However, Latash and Zatsiorsky (1993) suggest that an accurate model must account for all of the components that contribute to stiffness. These components include tendons, ligaments, muscles, cartilage, and bone; as well the model must also be able to describe changes in muscle force as a function of contraction velocity. In addition, viscosity, muscle reflex time delays, and central nervous system control need to be considered. Finally, the model must be able to characterize more than one degree of freedom at the joints, multiple series and parallel elastic components, control by more than two muscles, and bi-articular muscles. Unfortunately, a model that accounts for all of the components that influence motion is very complicated and becomes impractical. This is because accurate mathematical expressions for many of the components have not yet been developed. So, many assumptions would have to be made, and the solution of the equation might not be valid. Thus, biomechanists often return to the simpler mass–spring models for estimating leg stiffness. Latash and Zatsiorsky (1993) denote this measure as "quasi-stiffness", because one value of stiffness is used to represent the behavior of all the previously described components. However, it is in this context that the term "stiffness" will be used for the remainder of this paper.

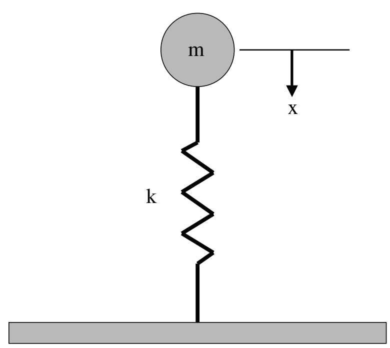

Fig. 1. Ideal spring and mass used for calculating vertical stiffness when the leg is oriented vertically.

There are several different calculations of lower extremity stiffness used by biomechanists including vertical, leg, and joint stiffness. Vertical stiffness is often used to describe linear movements that occur in the vertical direction such as hopping and jumping. Vertical stiffness is often calculated by one of three methods. In the first and simplest method, the peak vertical ground reaction force is divided by the maximal vertical displacement of the center of mass during contact with the ground (Table 1, Eq. (1)). The vertical displacement of the center of mass during contact is determined from the

Table 1
Formulas for calculating stiffness

Equation		Reference
VERTICAL STIFFNESS (k_{vert})		
$k_{vert} = F_{max}/\Delta y$	(1)	McMahon and Cheng (1990)
where F_{max} = maximum vertical force; Δy = maximum vertical displacement of the center of mass		
$k_{vert} = m(2\pi/P)^2$	(2)	Cavagna et al. (1988)
where m = mass of the body; P = period of the vertical vibration		
$k_{vert} = m\omega_0^2$	(3)	McMahon et al. (1987)
where m = mass of the body; ω_0 = natural frequency of oscillation		
LEG STIFFNESS (k_{leg})		
$k_{leg} = F_{max}/\Delta L$	(4)	McMahon and Cheng (1990)
where F_{max} = maximum vertical force; ΔL = change in vertical leg length ($\Delta L = \Delta y + L_0(1 - \cos)$ and $\theta = \sin^{-1}(ut_c/2L_0)$); Δy = maximum displacement of the center of mass; L_0 = standing leg length (greater trochanter to floor); θ = half angle of the arc swept by the leg; u = horizontal velocity; t_c = contact time		
TORSIONAL STIFFNESS (k_{joint})		
$k_{joint} = \Delta M/\Delta\theta$	(5)	Farley et al. (1998)
where ΔM = change in joint moment; $\Delta\theta$ = change in joint angle		
$k_{joint} = 2W/\Delta\theta$	(6)	Arampatzis et al. (1999)
where W = negative mechanical work at the joint; $\Delta\theta$ = change in joint angle		

double integration of the vertical force curve as described by Cavagna (1985). This method assumes that the vertical position of the center of mass at foot contact is similar to that at take off, resulting in an integration constant equal to 0. The vertical velocity is then integrated to produce the vertical trajectory of the center of mass. The maximal vertical displacement of the center of mass is determined from the difference between the maximum and minimum values of this curve. Center of mass displacement is typically evaluated using a force platform, but could also be determined from a full body kinematic analysis, requiring the addition of a motion analysis system.

In the second method, the vertical ground reaction force, the mass of the subject, and the period of oscillation are used (Cavagna et al., 1988). The method assumes the vertical force curve to be a sine wave, with a peak occurring at midpoint of the stance phase. With the exception of the impact peak that occurs early in stance, this is a fairly valid assumption. The period of oscillation is then used to determine the time to the midstance peak of the vertical ground reaction force curve. This method is often chosen when the frequency of the activity is constant, as in hopping in time with a metronome. The period of oscillation is then equal to the frequency of the activity. The period of oscillation and the mass of the subject are then used to calculate vertical stiffness as shown in Table 1, Eq. (2).

The third vertical stiffness method uses contact time, and the time in the air between successive foot strikes, to calculate the natural frequency of oscillation (McMahon et al., 1987). The total body mass and frequency of oscillation are then used to determine stiffness (Table 1, Eq. (3)). Although contact time and flight time could be derived from two force plates, it is also possible to obtain these data using foot switches. The use of foot switches is beneficial in smaller laboratory settings where only a treadmill is available.

The three previous methods are used when motion is occurring in the vertical direction. However, during running, the leg contacts the ground at an angle, and the center of mass is not directly over the foot. McMahon and Cheng (1990) developed a method of calculating stiffness for such cases (Table 1, Eq. (4)) which they termed “leg” stiffness. A mass–spring model of this case is shown in Fig. 2. This method takes into account the runner’s horizontal velocity, time of contact, and the resting leg length, as well as peak vertical ground reaction force. Displacement of the center of mass is determined through the double differentiation of the vertical ground reaction force. Finally, the maximum vertical force is divided by the change in the vertical leg length. It is interesting to note that if the mass moves purely in the vertical direction, as in hopping, θ_0 becomes zero. The term $L_0(1 - \cos\theta_0)$ then becomes zero, and leg stiffness becomes identical to vertical stiffness (Eq. (1)).

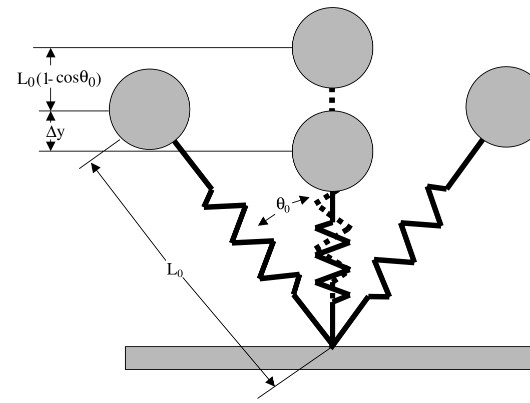

Fig. 2. Leg stiffness model used for calculating leg stiffness when the leg makes contact with the surface in a non-vertical position.

Both vertical and linear stiffness are linear measures. The rotational correlate to these measures, joint stiffness, is used when investigating the role of individual joints in overall lower extremity stiffness. While linear stiffness is defined as linear force per linear displacement, torsional (or joint) stiffness is most often defined as the change in joint moment divided by the change in joint angle (Farley et al., 1998) (Table 1, Eq. (5)). Mean stiffness throughout the entire stance period can be determined by calculating the slope of a regression line through the joint moment versus joint angle data. Alternatively, mean stiffness during specific periods of stance, such as from foot strike to peak knee flexion, can be calculated (Fig. 3). Joint stiffness may also be calculated using a work–energy approach (Arampatzis et al., 1999) (Table 1, Eq. (6)). For example, to assess stiffness during the loading phase of gait, the negative mechanical work at the joint, during the first half of stance, is divided by the change in joint angle during that time.

In summary, stiffness may be calculated in a number of ways depending upon the questions being asked and the laboratory resources available. While vertical stiffness is used to assess hopping and jumping, leg stiffness is most appropriate for analysis of walking and running. When questions are focused at the joint level, torsional

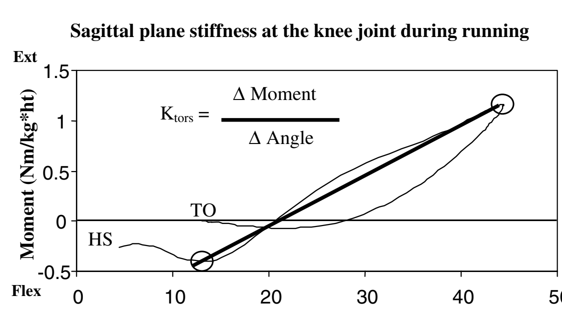

Fig. 3. Torsional stiffness calculation. Stiffness is calculated as the slope of the line through the moment–angle curve from the point of maximum knee flexion moment to maximum knee extension moment.

stiffness should be examined. It should be noted that different methods for calculating stiffness will likely produce different results. Therefore, these methods should be clearly defined, and caution should be exercised when making comparisons between studies using different methods.

3. Stiffness and performance

In terms of performance, some level of stiffness is required for optimal utilization of the stretch-shortening cycle. This results in an efficient utilization of the stored elastic energy in the musculoskeletal system that occurs during the loading portion of movement (Latash and Zatsiorsky, 1993). As greater forces are imparted to the body, greater resistance to movement is needed in order to produce controlled movements. The amount of stiffness required has been reported to increase with the demands of the activity (Arampatzis et al., 1999; Farley et al., 1991; Granata et al., 2001; Arampatzis et al., 2001a,b; Kuitunen et al., 2002; Seyfarth et al., 2002; Stefanyshyn and Nigg, 1998) (Table 2).

A number of studies have examined the relationship between stiffness and performance during hopping (Farley et al., 1991; Granata et al., 2001; Arampatzis et al., 2001a,b). Both Farley et al. (1991) and Granata et al. (2001) reported that leg stiffness increased with hopping frequency when subjects hopped in place. Arampatzis et al. (2001a,b) studied subjects rebounding from a drop landing, and reported that as rebound velocity increased, an associated increase in lower extremity stiffness was observed. Farley et al. (1991) observed that vertical stiffness increased with increased velocity as subjects performed one legged hops on a treadmill. These studies suggest that lower extremity stiffness increases as velocity of the activity increases, which may be necessary to resist collapse of the lower extremity during the early phase of landing and allow for maximum energy return during the propulsive phase (Farley et al., 1991; Granata et al., 2001; Arampatzis et al., 2001a,b).

Studies of running have yielded similar results (Arampatzis et al., 1999; Kuitunen et al., 2002; Seyfarth et al., 2002; Stefanyshyn and Nigg, 1998). While Arampatzis et al. (1999) assessed running, and Kuitunen et al. (2002) studied sprinting, both found that leg stiffness increased with increasing speed. In a simulation study of running, Seyfarth et al. (2002) reported a direct relationship between stiffness and running speed. At the joint level, Stefanyshyn and Nigg (1998) noted a significant increase in ankle joint stiffness with increases in running speed. These running studies further support the notion that as the physical demands of the activity increases, stiffness also increases (Arampatzis et al., 1999; Kuitunen et al., 2002; Seyfarth et al., 2002; Stefanyshyn and Nigg, 1998).

Stiffness also appears to be related to stride parameters. It has been shown that, for a given velocity, a longer stride length is associated with lower stiffness (McMahon and Cheng, 1990; Farley and Gonzalez, 1996; Derrick et al., 2000). McMahon and Cheng (1990) found that when subjects ran in a ‘‘groucho running’’ style, characterized by exaggerated knee flexion, stride length increased, and stiffness decreased. During normal running, Farley and Gonzalez (1996) reported subjects who naturally ran with a greater stride length, exhibited decreased leg, and vertical stiffness. In a simulation study using a mass–spring–damper model, Derrick et al. (2000) also reported that stiffness decreased with increasing stride length. Therefore, while increasing the stride length of a runner may be beneficial to performance, it should be understood that this alteration may decrease the vertical stiffness of the runner, which could negatively influence velocity.

Running economy, as measured by oxygen consumption, has also been shown to be related to stiffness (McMahon and Cheng, 1990; Kerdock et al., 2002; Dutto and Smith, 2002; Heise and Martin, 1998). Kerdock et al. (2002) reported that an increase in lower extremity stiffness, induced by having subjects run on softer surfaces, was associated with greater running economy. In addition, McMahon and Cheng (1990)

Table 2
Stiffness and performance

Activity	Result	Reference
Hopping		
Increased lower extremity stiffness	• Increased hopping frequency	Farley et al. (1991), Granata et al. (2001)
	• Landing from increased height	Arampatzis et al. (2001a,b)
Running		
Increased lower extremity stiffness	• Increased running velocity	Arampatzis et al. (1999), Seyfarth et al. (2002), Stefanyshyn and Nigg (1998), Farley and Gonzalez (1996)
	• Decreased stride length	McMahon and Cheng (1990), Derrick et al. (2000), Kerdock et al. (2002)
	• Decreased energy requirement	McMahon and Cheng (1990), Dutto and Smith (2002), Heise and Martin (1998), Farley and Morgenroth (1999)

found that, compared to "groucho" running, normal running was associated with greater stiffness which was also associated with an increase in running economy. In a study of running to exhaustion, Dutto and Smith (2002) reported that as subjects became fatigued both stiffness and running economy decreased. While one study refuted these findings (Heise and Martin, 1998), the majority of the studies suggest that an increase in lower extremity stiffness during running is associated with an increase in economy (McMahon and Cheng, 1990; Kerdock et al., 2002; Dutto and Smith, 2002). It is speculated that increased stiffness in a runner is beneficial in order to utilize the stored elastic energy that occurs during the loading portion of stance (Latash and Zatsiorsky, 1993).

In terms of torsional stiffness, a number of studies have examined the relative magnitudes of ankle and knee stiffness in the sagittal plane. Most studies suggest that alterations in joint stiffness may be related, in part, to foot strike pattern during landing (Farley et al., 1998; Arampatzis et al., 1999; Arampatzis et al., 2001b; Seyfarth et al., 2002; Laughton et al., 2003; Hamill et al., 2000). Most studies of forefoot landings (hopping and forefoot strike running) have found that the knee is stiffer than the ankle (Farley et al., 1998; Arampatzis et al., 2001b; Seyfarth et al., 2002; Hamill et al., 2000), conversely, studies on rearfoot landings have reported that the ankle is stiffer than the knee (Arampatzis et al., 1999; Laughton et al., 2003; Hamill et al., 2000). For example, Laughton et al. (2003) compared the relative joint stiffness of the knee and ankle in subjects running with a rearfoot strike and a forefoot strike patterns. These authors found that, compared to a rearfoot strike pattern, knee stiffness was greater and ankle stiffness was lower in the forefoot strike pattern. Laughton et al. (2003) attributed the changes in joint stiffness to the decrease in knee excursion and increase in ankle excursion in the forefoot strike compared to the rearfoot strike.

The contributions of ankle and knee stiffness to increasing velocity has also been studied. However, the nature of these relationships may be dependent on the activity being assessed. Farley and Morgenroth (1999) found that increasing velocity in hopping was associated with greater ankle stiffness. During sprinting, which typically has a forefoot strike pattern, Kuitunen et al. (2002) reported increasing velocity was associated with increases in knee stiffness. While Arampatzis et al. (1999) reported that during rearfoot strike running that increased velocity was associated with greater increases in knee stiffness with respect to ankle stiffness. Further investigations which assess the relationship between, footstrike pattern, stiffness, and changes in velocity are needed in order to clarify joint contributions to changes in velocity.

Overall, lower extremity stiffness increases with the demands of the activity as increased hopping frequency, hopping or jumping height, and running speed are all associated with increased stiffness. In addition, increased stiffness is associated with greater economy of motion. The relative joint contributions to stiffness during an activity appear to be related in part, to the type of foot landing. Further investigations of the relative contribution of joint stiffness to overall stiffness and velocity are needed.

4. Stiffness and injury

Previous studies suggest that some level of stiffness is needed for optimal performance (McMahon and Cheng, 1990; Arampatzis et al., 1999; Kuitunen et al., 2002; Seyfarth et al., 2002; Stefanyshyn and Nigg, 1998; Kerdock et al., 2002; Dutto and Smith, 2002). However, too much stiffness may result in injury in the following manner. Increased leg stiffness is typically associated with reduced lower extremity excursions and increased peak forces. This combination of factors typically leads to increased loading rates, which have been associated with increased shock to the lower extremity (Hennig and Lafortune, 1991). In addition, increased peak forces, loading rates, and shock are all believed to place one at a greater risk for bony injuries such as knee osteoarthritis and stress fractures (Grimston et al., 1991; Radin et al., 1978; Burr et al., 1985).

The direct relationship between stiffness and injury is not well established, due to a paucity of prospective studies. In one such study, Hewett et al. (1996) assessed baseline kinematic and ground reaction force data in a group of male and female athletes. Injuries that occurred over the next year were recorded. Stiffness was not directly calculated in their study. However, compared to the injured subjects, the uninjured group demonstrated reduced peak vertical ground reaction force values, in the presence of similar knee flexion, suggesting they may have been less stiff. In a retrospective study, Williams et al. (2003, 2001) studied the lower extremity mechanics and injury patterns in high and low arched runners. High arch runners, who exhibited greater leg stiffness and vertical loading rates, sustained a significantly higher incidence of bony injuries compared to low arch runners. In another retrospective study, Grimston et al. (1991) reported that runners who had suffered stress fracture exhibited increased peak ground reaction forces, potentially increasing lower extremity stiffness. Results from animal studies have suggested a direct relationship between loading rate and bony injury (Radin et al., 1978; Burr et al., 1985), further supporting the idea that increased stiffness may lead to trauma. These studies suggest that lower extremity stiffness, or biomechanical variables associated with stiffness, such as peak forces and loading rates, may place one at greater risk for bony injuries.

On the other hand, it has been suggested (Granata et al., 2001; Williams et al., 2003, 2001) that too little stiffness may allow for excessive joint motion leading to soft tissue injury. Williams et al. (2003, 2001) reported that runners with low arches, and decreased leg stiffness, experienced more soft tissue injuries than their high arched counterparts. Granata et al. (2001) found that females demonstrated less knee stiffness during hopping than males. These authors suggested that this reduced stiffness may provide an explanation for the well documented, higher incidence of knee ligamentous injuries sustained by women (Granata et al., 2001).

In summary, there is a need for additional prospective studies in order to establish a direct relationship between stiffness and injury. However, results from available studies suggest that too much stiffness may be associated with bony injuries, while too little stiffness may be associated with soft tissue injuries (Granata et al., 2001; Williams et al., 2003, 2001). If this is true, there may be an ideal range of stiffness that allows one to optimize performance while minimizing the risk for injury.

5. Modifying stiffness

Leg stiffness has been shown to vary inversely with the stiffness of both footwear and contact surface. In terms of footwear, Smith and Watanatada (2002) reported that vertical stiffness increased when running in a soft shoe compared to a firm shoe. Ferris et al. (1998) reported a similar result when they found that runners exhibited decreases in lower extremity stiffness upon the first step onto an expected, stiffer surface. Thus, it appears that the lower extremity adapts to surface stiffness to possibly maintain an optimal leg-surface overall stiffness during the stance phase of gait.

It has been shown that subjects will automatically alter their leg stiffness in response to different surface stiffnesses. However, studies have also shown that subjects can consciously alter their stiffness during landing to change the forces the body experiences (Devita and Skelly, 1992; Zhang et al., 2000; Dufek and Bates, 1990; Arampatzis et al., 2002). A number of studies have examined lower extremity stiffness during drop landings onto a force plate where subjects were instructed to perform either a hard landing (stiff), a soft landing (compliant), or their normal landing (Devita and Skelly, 1992; Zhang et al., 2000; Dufek and Bates, 1990; Arampatzis et al., 2002). Overall, soft landings resulted in the lowest vertical ground reaction forces, while hard landings resulted in the highest vertical ground reaction forces. While stiffness was not directly measured in these investigations, some inferences can be made with regards to stiffness. Both Zhang et al. (2000) and Devita and Skelly (1992) found small decreases in the knee joint moments, and larger increases in knee joint angles for soft landings compared to hard landings. This will result in a lower slope of the moment–angle curve for indicating a lower knee joint stiffness during softer landings.

If a conscious alteration of lower extremity stiffness can be made by an athlete, interventions may be developed to retrain movement patterns to enhance performance and reduce the incidence of injuries. In a study of volleyball players, Hewett et al. (1996) implemented a jump-training program to examine the alterations of landing mechanics. The program was focused on teaching subjects to land "softer" thereby decreasing their lower extremity stiffness. As a result of the jump-training program, subjects were able to decrease peak vertical ground reaction forces, and reduce knee adduction and abduction moments while exhibiting similar knee flexion during landings. These data suggest that stiffness may be altered through training, and that the alteration can influence the loads experienced by the lower extremity, thereby potentially decreasing the risk of injury.

In another prospective study, Hewett et al. (1999) examined the effect of their jump-training program on the incidence of knee injuries in female basketball, volleyball, and soccer players. In this study, 366 female athletes participated in the training program, while 463 female and 434 male athletes served as a control group. The rate of knee injuries was significantly lower in the female athletes that participated in the jump-training program. Thus, the subjects were able to reduce the incidence of injuries as a result of decreasing the stiffness of their landings. Therefore, it appears that individuals can modify their stiffness and these changes in stiffness may result in a decrease in the incidence of lower extremity injuries.

6. Summary

In summary, lower extremity stiffness has been shown to play a role in both performance and injury. In terms of performance, it appears that increased stiffness is associated with increased velocity, jump height and economy. Several studies suggest that forefoot landings are associated with an increase in knee stiffness and rearfoot landings are associated with increased ankle stiffness. With respect to injury, there are no prospective studies that directly correlate stiffness and injury. However, some retrospective studies suggest that too much stiffness may be associated with bony injuries and too little stiffness may result in soft tissue injuries. Therefore, more prospective studies are needed to validate these findings. Finally, recent studies suggest that athletes may be able to alter their lower extremity stiffness which may reduce the incidence of injury. Further research in this area may lead to the development of optimal training programs to enhance athletic performance and decrease injuries.

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