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REVIEW

Lower Extremity Stiffness Characteristics in Running and Jumping: Methodology and Implications for Athletic Performance

Joong Hyun Ryu

Sports Science Department, Aspire Academy, Doha, Qatar

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Corresponding Author
Joong Hyun Ryu
Sports Biomechanist, Sports Science Department, Aspire Academy, 22287, Doha, Qatar
Tel : +974.5010.2161
Fax : +974.4413.8325
Email : joong.ryu@aspire.qa

Objective: The human body is often modelled as a spring-mass system. Lower extremity stiffness has been considered to be one of key factor in the performance enhancement of running, jumping, and hopping involved sports activities. There are several different classification of lower extremity stiffness consisting of vertical stiffness, leg stiffness, joint stiffness, as well as muscle and tendon stiffness. The primary purpose of this paper was to review the literature and describe different stiffness models and discuss applications of stiffness models while engaging in sports activities. In addition, this paper provided a current update of the lower extremity literature as it investigates the relationships between lower extremity stiffness and both functional performance and injury.

Summary: Because various methods for measuring lower extremity stiffness are existing, measurements should always be accompanied by a detailed description including type of stiffness, testing method and calculation method. Moreover, investigator should be cautious when comparing lower extremity stiffness from different methods. Some evidence highlights that optimal degree of lower extremity stiffness is required for successful athletic performance. However, the actual magnitude of stiffness required to optimize performance is relatively unexplored. Direct relationship between lower extremity stiffness and lower extremity injuries has not clearly been established yet. Overall, high stiffness is potentially associate risk factors of lower extremity injuries although some of the evidence is controversial. Prospective injures studies are necessary to confirm this relationship. Moreover, further biomechanical and physiological investigation is needed to identify the optimal regulation of the lower limb stiffness behavior and its impact on athletic performance and lower limb injuries.

Keywords: Vertical stiffness, Leg stiffness, Joint stiffness, Stretch-shortening cycle, Spring-mass model

INTRODUCTION

The concept of lower extremity stiffness is based on part of Hooke's Law which describes the relationship between a given force and the magnitude of deformation of an object. In its simplest sense the force required to deform an object is related to a proportionality constant and the distance that object is deformed (Butler, Crowell, & Davis, 2003). The proportionality constant is also known as the spring constant, and it describes the stiffness of the spring mass system. During this deformation of the object, the object will store elastic energy and some of this stored energy will be returned and used as the object shortens and returns to its original resting length. Often the human body or body segments are described and modelled as a spring-mass system (Cavagna, Komarek, & Mazzoleni, 1971; McMahon & Cheng, 1990). Therefore, stiffness in the human body and its segments described its ability to resist displacement once ground reaction force (GRF) or moments are applied.

The advantage of the spring-mass system is its simplicity in study the lower extremity neuromuscular behavior during ground contact by using just one spring which represents the elasticity of the entire musculoskeletal system including muscles, tendons, and ligaments. Although the optimal stiffness required for movements such as running and jumping remains a topic of debate for the scientific and sport communities, lower body stiffness has been considered to be one of key factor in the performance enhancement of running, jumping, and hopping involved sports activities. More specific, it is thought that stiffness in the human leg has a major influence on various athletic variables, including rate of force development, elastic energy storage and utilization, and sprint kinematics such contact and flight times, and stride length and frequency (Brughelli & Cronin, 2008). An athlete who can appropriately maintain and utilize optimal amount of lower extremity stiffness will potentially store more elastic energy at landing phase and generate more concentric force output at push-off phase. This mechanism potentially reducing the fatigue and increasing running and jumping performance. Consequently, if sports practitioners such as a sport biomechanist and strength and conditioning coach is able to find optimal technique or to advance athletes' ability to maximize this "optimal spring" effect across sporting movement patterns, sports performance enhancement may occur. For this reason, research in the area of lower extremity stiffness is being published in sports science and sports medicine literature at an escalating rate (Brughelli & Cronin, 2008; Serpell, Ball, Scarvell, & Smith, 2012).

There are several different classification of lower extremity stiffness consisting of vertical stiffness, leg stiffness, joint stiffness, as well as muscle and tendon stiffness. Vertical stiffness, which is widely regarded as the reference stiffness are described as the sum of resistance of the human body to vertical displacement after utilization of vertical GRF. Leg stiffness is generally regarded as the resistance to change in leg length from internal or external forces utilization. Using the same concept, Joint stiffness can be defined as the resistance to change in angular displacement of lower body segment(s) around joint after implementation of joint moments. Consequently, differences in classification methods for measuring stiffness in the human body exist. However, many studies use the terms synonymously or use the term stiffness in a global sense with little description to the specific applications of the stiffness measure. Therefore, the primary purpose of this paper was to review the literature and describe different stiffness models, and discuss applications of stiffness models while engaging in running, jumping, and hopping involved sports activities. In addition, this paper reviews the relationships between lower extremity stiffness and functional performance.

CALCULATING LOWER EXTREMITY STIFFNESS

1. Vertical stiffness

Vertical stiffness is a measure of resistance of the body to vertical displacement after application of GRF. It is mainly used to describe linear movements that occur in only the vertical direction during activities such as hopping and jumping. There are four widely used methods for calculating vertical stiffness (K_{vert}) during human running and hopping. The McMahon & Cheng's (1990) method is the first and most commonly used method. This method includes two mechanical parameters: maximum vertical GRF (F_{max}) and maximum vertical displacement of the center of mass (Δy). In this method, vertical stiffness is equal to peak vertical GRF divided by the maximum vertical displacement (Eq. 1 and Figure 1). GRF can be directly measured with a force place. In addition, displacement of the center of mass can be derived from vertical GRF (Cavagna, 1975). Because force is equal to mass multiplied by acceleration and body mass remains constant, vertical force can be reflected as vertical acceleration. Then, vertical displacement can be derived from double integration of vertical acceleration. Alternatively, center of mass displacement also can be determined from full body kinematic analysis using video-based systems (Arampatzis, Brüggemann, & Metzler, 1999).

$$K_{vert} = \frac{F_{max}}{\Delta y} \quad \text{(Eq. 1)}$$

The formula of second method for calculating vertical stiffness is vertical stiffness equals mass (m) multiplied by the square of the natural frequency of oscillation (ω) (Eq. 2). Again, a force plate is used to measure vertical GRF and ground contact time. From the force curve, vertical velocity can be calculated by single integration. With contact time and vertical velocity, the natural frequency of oscillation is calculated (McMahon, Valiant, & Frederick, 1987).

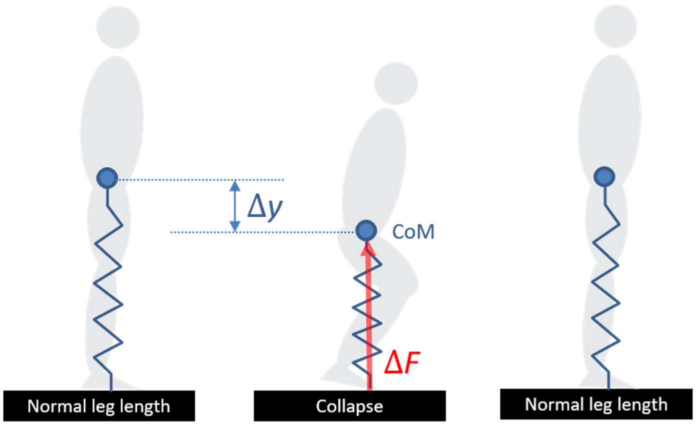

Figure 1. Spring-mass model as it relates to the human body

$$K_{vert} = m\omega^2 \quad \text{(Eq. 2)}$$

Cavagna, Franzetti, Heglund, & Willems (1988) suggested a different method to calculate the natural frequency of oscillation which utilize the effect contact time and period of oscillation (P) (Eq. 3). The effective contact time refers to the duration that vertical GRF is greater than body weight during stance phase and the period of oscillation equals to double of the effective contact time. The natural frequency of oscillation can be calculated from the period of oscillation with $\omega = 2\pi/P$.

$$K_{vert} = m\left(\frac{2\pi}{P}\right)^2 \quad \text{(Eq. 3)}$$

However, beside Cavagna et al. (1988) and McMahon et al. (1987), only few studies have used this method in order to calculate vertical stiffness during human running and jumping.

The third method for calculating vertical stiffness was suggested by Morin, Dalleau, Kyröläinen, Jeannin, & Belli (2005). This method is distinct from other methods because it does not require to measure GRF. With this method, only contact time (t_c), areal time (t_f), and body mass (m) are necessary for calculating vertical stiffness. Morin et al. (2005) modelled vertical GRF as a sine wave because force of a linear spring-mass model are expected to oscillate in the form of a sine wave. From the sine wave, maximum vertical force and maximum vertical displacement is calculated and thus vertical stiffness can be calculated (Eq. 4 and Eq. 5).

$$F_{max} = mg\frac{\pi}{2}\left(\frac{t_f}{t_c} + 1\right) \quad \text{(Eq. 4)}$$

$$\Delta y = \frac{F_{max}t_c^2}{m\pi^2} + g\frac{t_c^2}{8} \quad \text{(Eq. 5)}$$

Serpell et al. (2012) presented a qualitative analysis of those three calculation methods described and concluded that nor argument can be made regarding which method is better.

Because the majority of research has estimated center of mass displacement by double integration of vertical acceleration, one of key issue for calculating vertical stiffness is determining the integration constant which is the vertical velocity at touch down (Hébert-Losier & Eriksson, 2014). Hébert-Losier & Eriksson (2014) introduced and tested four different methods which estimate initial velocity integration constant. By comparing these four different methods in the same hopping tasks, they found that in double integrations, the choice of the integration constant and mathematical expression considerably affected stiffness values. Therefore, stiffness values should always be accompanied by a detailed description of their evaluation methods and should be cautious when applying different methods to estimate the integration constant.

2. Leg stiffness

Leg stiffness refers to the stiffness of the entire leg which acts as a single linear spring. Vertical stiffness only takes into account the motion in the vertical direction. During running, at initial touchdown the leg contacts the ground at an angle and the center of mass is not directly over the foot. To accommodate this, leg stiffness is specifically used in running activity. The equation for calculating leg stiffness (K_{leg}) was suggested by McMahon & Cheng (1990) which is a measure of resistance to change in leg length (ΔL) after application of GRF (Eq. 6, Figure 2).

$$K_{leg} = \frac{F_{max}}{\Delta L} \qquad \text{(Eq. 6)}$$

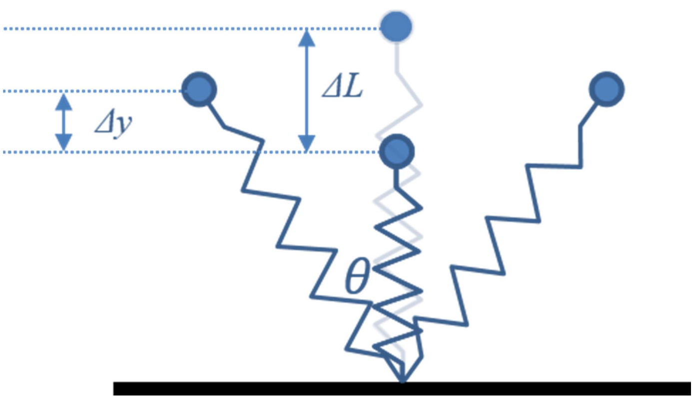

Figure 2. Leg stiffness model during running. Leg stiffness is calculated from maximum vertical ground reaction force and change in 'leg spring' length (ΔL).

Few different methods for measuring the change in leg length has been suggested. In McMahon & Cheng (1990), vertical GRF is measured directly form the force plate. The change in leg length (ΔL) is calculated from running velocity (v), leg length (L_0), half angle of the arc swept by the leg (θ), and vertical displacement of the center of mass (Δy) by following equations (Eq. 7 and Eq. 8).

$$\Delta L = \Delta y + L_0 - \sqrt{L_0^2 - \left(\frac{vt_c}{2}\right)^2} \qquad \text{(Eq. 7)}$$

$$\theta = sin^{-1}\left(\frac{vt_c}{2L_0}\right) \qquad \text{(Eq. 8)}$$

On the other hand, Arampatzis et al. (1999) directly measured the change in leg length with a high-speed video. Morin et al. (2005) utilized the same method suggested by McMahon & Cheng (1990) for calculating the change in leg length. However, maximum vertical force and maximum vertical displacement were estimated from the sine wave model (Eq. 4 and Eq. 5) without the use of force plate. The results of Morin et al. (2005) were compared with that of a reference method (McMahon & Cheng, 1990). Leg stiffness were found to range from 0.67% to 6.93% less than those of McMahon & Cheng (1990) and thus were reported to be acceptable (Brughelli & Cronin, 2008). The advantage of using the Morin et al. (2005) mathematical model is that leg stiffness can be calculated without the use of force plates which is somewhat challenging to use in over ground running condition especially when researchers are interested with multiple steps analysis.

When calculating leg stiffness, leg length need to be considered to be the distance between the hip joint center and the distal point of the leg. However, each considered the distal end of the leg at different points: one marked it as a point of the foot (Grimmer, Ernst, Gunther, & Blickhan, 2008), another considered it the point of force application for GRF (Stafilidis & Arampatzis, 2007), or simply the measured distance perpendicular to the ground (Rapoport, Mizrahi, Kimmel, Verbitsky, & Isakov, 2003). Some studies simply estimated leg length by multiplying by a constant value (0.53) and height (Hobara et al., 2008; Morin et al., 2005) or by calculating the vertical distance from the ground to the greater trochanter during standing (Arampatzis et al., 1999; Farley & González, 1996). Potentially, estimating initial leg length by multiplying a constant value poses several problems in sports environment because it is well documented that athletes at the highest level of performance do not possess typical anthropometric profiles and are often considered the extremes of general population (Watts, Coleman, & Nevill, 2012).

3. Joint stiffness

Joint stiffness (K_{joint}) is the stiffness of an individual joint such as knee or ankle and is calculated as the ratio of joint moment (ΔM) to angular displacement of the joint ($\Delta\theta$) (Eq. 9).

$$K_{joint} = \frac{\Delta M}{\Delta \theta} \qquad \text{(Eq. 9)}$$

In general, force plates and high-speed video cameras are used for the kinematic and inverse dynamic analysis in order to calculate angular displacement and joint moment (Gunther & Blickhan, 2002; Kuitunen,

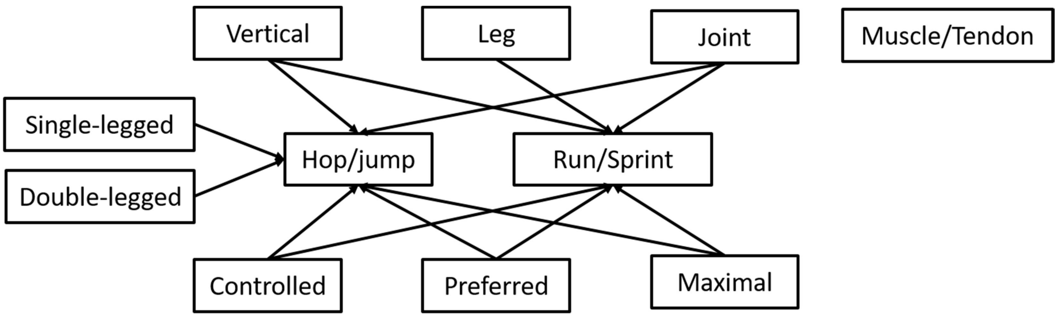

Figure 3. Classification of lower extremity stiffness measurements

Komi, & Kyröläinen, 2002). Arampatzis et al. (1999) suggested a different method for calculating joint stiffness during human running. In their methods, Joint stiffness is calculated as the ratio of negative mechanical work to the change in joint angle, but have been no other studies that have used this method calculate joint stiffness during human running.

4. Musculotendinous and tendon stiffness

These additional forms of stiffness also have been thought to affect lower extremity stiffness during human running (Brughelli & Cronin, 2008a). Musculotendinous stiffness have been examined previously using a free oscillation technique (Wilson, Wood, & Elliott, 1991). The free oscillation technique assesses the stiffness based on the assumption that human muscles and tendons behave like a damped spring system. This assumption suggests that if any perturbation is applied under load, the system will oscillate at a damped natural frequency due to the nature the of the muscle and tendon structures. In this respect, musculotendinous stiffness can be determined by following equation (Eq. 10):

$$K_{mus} = 4mf^2\pi^2 + c^2/4m \qquad \text{(Eq. 10)}$$

Where m is mass of the system, f is damped natural frequency, and c is the damping coefficient. Tendon stiffness has been measured by using ultrasonography (K Kubo, Kawakami, & Fukunaga, 1999; Keitaro Kubo, Ikebukuro, Maki, Yata, & Tsunoda, 2012). Tendon stiffness is calculated as the slope of the force-tendon length curve. Typically, an isokinetic or hand dynamometer have been used to measure muscle force and ultrasonography is used to measure tendon displacement.

In summary, differences in classification (e.g. vertical stiffness, leg stiffness), calculation, and testing methods (e.g. hopping, running, unilateral /bilateral, submaximal/maximal) for measuring lower extremity stiffness are existing (Figure 3). Therefore, lower extremity stiffness measurements should always be accompanied by a detailed description including type of stiffness, testing method and calculation method. Moreover, investigator should be cautious when comparing lower extremity stiffness from different methods.

LOWER EXTREMITY 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 phase of the movement. In general, it has been reported that the amount of stiffness required increase with the demands of the activity. For example, vertical stiffness increased with increased hopping frequency and increased landing height. In addition, increased lower extremity stiffness in running result increased running velocity, decreased stride length, and decreased energy requirement (Brughelli & Cronin, 2008b; Cavagna, Heglund, & Willems, 2005; Stefanyshyn & Nigg, 1998).

1. Effect on sprint performance

A number of studies have examined the relationship between stiffness in vertical hopping test and sprint performance. Overall, these studies have highlighted that the enhancement of lower extremity stiffness is one of a key factor for improving sprint performance.

Chelly & Denis (2001) reported vertical stiffness measured from 2 Hz hopping jump test on a force plate was significantly correlated with the maximal velocity of 40 m sprint. Bret, Rahmani, Dufour, Messonnier, & Lacour (2002) found that the group had greater vertical stiffness in maximal hopping jump test produced higher acceleration between start and 60 m phase in 100 m sprint. Morin, Jeannin, Chevallier, & Belli (2006) reported that changes in vertical stiffness where significantly related to changes mean and maximal running velocity achieved over 100 m. The authors indicated that the change in vertical stiffness was linked with the fatigue effects on performance time during maximal sprint running. Hobara et al. (2010) continuously measured vertical and leg stiffness over an entire 400 m sprint and investigated the relationship between stiffness and running velocity. They found maintaining the higher stride frequency through retaining a higher vertical stiffness is the key factor to keep running velocity at later stage of 400 m sprint. Maloney, Richards, Nixon, Harvey, & Fletcher (2016) investigated potential relationship between stiffness and change of direction speed. They showed that faster athletes in change of direction speed exhibited greater vertical stiffness in drop just test than slower athletes.

Some studies investigated vertical stiffness characteristic in different athlete event groups. Harrison, Keane, & Coglan (2004) compared vertical stiffness measured during rebound and countermovement jumps in sprint and endurance athletes. They showed that sprint athletes performed countermovement jumps and rebound jumps using a significantly stiffer leg spring. Similarly, Hobara et al. (2008) examined the deference in stiffness between sprint-trained athletes and endurance-trained athletes. They found ankle and knee joint stiffness was significantly greater in sprint-trained athletes than the distance runners at 3.0 Hz and 1.5 Hz hopping jump tests respectively.

2. Effect on distance running performance

Few researches have suggested that lower extremity stiffness characteristics may correlate to distance running performance. Dalleau, Belli, Bourdin, & Lacour (1998) found that the energy cost of running on a treadmill at a velocity corresponding to 90% of their maximal aerobic velocity was significantly related to the leg stiffness. Specifically, athletes consumed less energy when they could maintain greater leg stiffness. Ryu & Murray (2016) investigated the relationship between vertical stiffness in the sub-maximal hopping test and middle-distance running performance. They found 3,000 m running performance was significantly correlated with normalized vertical stiffness in 2.2 Hz hopping test. Rogers, Whatman, Pearson, & Kilding (2017) examined relationship between lower extremity stiffness and their associations with running economy in middle-distance runners during submaximal stages run. They found large negative relationship existed between running economy and Achilles tendon and vertical stiffness, and concluded that in well-trained distance athletes, greater tendon and vertical stiffness linked to more economical running.

The research presented above clearly highlights that some degree of lower extremity stiffness is required for successful performance during running. However, the actual magnitude of stiffness required to optimize performance has not been theorized nor tested. In addition, in the majority of the aforementioned research vertical stiffness was determined during vertical hopping test followed by correlational analyses between vertical stiffness and running performance. Although these findings strongly suggest that there is a relationship between vertical stiffness and running performance, cause and effect has not yet been established. Therefore, further research into identifying optimal stiffness for hopping, jumping, and running, performed across a range of intensities, is required to facilitate implication of the coaching process.

LOWER EXTREMITY STIFFNESS AND INJURY

Previous studies suggest that certain level of lower extremity stiffness has been shown to be important for optimal athletic performance. However, too much stiffness may result in lower extremity injuries because increased lower extremity stiffness is typically associated with increased peak forces and loading rates which have been associated with increased shock. Although direct relationship between lower extremity stiffness and lower extremity injuries has not clearly been established yet, Butler et al. (2003) suggested that too much stiffness may be associated with repetitive stress bony Injures, while too little stiffness may be associated with soft tissue Injures due to extreme range of motion. Furthermore, it is plausible that bilateral differences in lower extremity stiffness are also possible determinant of injury risk.

A number of studies have examined the relationship between lower extremity stiffness and injuries. Watsford et al. (2010) prospectively examined the relationship between hamstring stiffness and vertical stiffness with hamstring injury in professional footballers. They found that the players who sustaining a hamstring injury during the season significantly higher mean hamstring stiffness assessed by the oscillation technique and vertical stiffness in 2.2 Hz unilateral hopping test. Considering the injured players, vertical stiffness of the injured limb was significantly higher than uninjured limb. On the other hand, Rodriguez, Watsford, Bower, & Murphy (2017) reported that no significant differences in vertical stiffness in hopping test between non-contact lower extremity soft tissue injured and non-injured netball players. However, they found injured players recorded significantly higher season mean soleus muscle and Achilles tendon stiffness than non-injured players. Pruyn et al. (2012) investigated the relationship between vertical stiffness and its bilateral asymmetries and the incidence of non-contact lower extremity soft tissue injury. The major finding of this study was that the injured football players showed significantly higher bilateral asymmetry in vertical stiffness than uninjured players. Maquirriain (2012) reported that vertical stiffness in vertical hopping test was significantly reduced in the affected limb compared to non-injured limb of patients suffering unilateral Achilles tendinopathy. Dubose et al. (2017) found that hip and knee joint stiffness and vertical stiffness are altered after concussion, providing further evidence of altered neuromuscular function after concussion. Lorimer & Hume (2016) reviewed how risk factors for Achilles tendon injuries influence measures of lower extremity stiffness, and concluded that high stiffness is potentially associate with risk factors of Achilles tendon injuries.

Contradictorily, some studies reported that there is no clear evidence that lower extremity stiffness is risk factor of lower limb injuries. Serpell, Scarvell, Ball, & Smith (2014) found that no significant difference in vertical stiffness between players who suffered lower limb muscle strain and non-injured football players. Moreover, Serpell et al. (2016) reported that vertical stiffness was not associated with anterior cruciate ligament injury in elite rugby players.

Few studies have investigated the link between lower extremity stiffness and lower extremity injuries. Overall, high stiffness is potentially associate risk factors of lower extremity injuries although some of the evidence is controversial. More prospective studies are necessary to confirm this finding in relationship between stiffness and injuries.

IMPLICATIONS AND CONCLUSION

Due to the apparent relationship between lower extremity stiffness measures and running/sprinting performance and potential relationship with lower extremity soft tissue injuries, it is important to explore the possibility of modifying stiffness, in an effort to maximize sports performance and minimize the risk of injury.

Various studied have reported a modification in lower extremity musculotendinous stiffness following exercise interventions. Such interventions included plyometric (Burgess, Connick, Graham-Smith, & Pearson, 2007; Keitaro Kubo et al., 2007; Spurrs, Murphy, & Watsford, 2003), eccentric strength (Pousson, Van Hoecke, & Goubel, 1990), isometric (Burgess et al., 2007), and general weight (Keitaro Kubo et al., 2007) training. Moreover, modification of sports techniques potentially influences lower extremity stiffness and therefore influences sports performance. In the case of hopping, an increase in triceps surae muscle activity in the pre and early post landing phase was reported to be crucial for higher vertical stiffness (Hobara, Kanosue, & Suzuki, 2007). Research has suggested that a higher vertical stiffness could also be reported by adjusting the initial touchdown joint angles (Farley, Houdijk, Van Strien, & Louie, 1998). If the leg is more extended at initial touchdown, GRF will be more closely aligned with each joint, simultaneously decreasing the joint moments while increasing stiffness. McMahon et al. (1987) reported that running with greater knee flexion reduces vertical stiffness.

These studies suggest that athletes may be able to alter their lower extremity stiffness. Therefore, further biomechanical and physiological investigation is needed to identify the optimal regulation of the lower limb stiffness behavior and its impact on athletic performance and lower limb injuries. This may lead to the development of optimal training programs and technical models to enhance athletic performance and decrease injury risks.

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