Lower Limb Stiffness Testing in Athletic Performance: A Critical Review

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Abstract

Stiffness describes the resistance of a body to deformation. In regards to athletic performance, a stiffer leg-spring would be expected to augment performance by increasing utilisation of elastic energy. Two-dimensional spring-mass and torsional spring models can be applied to model whole-body (vertical and/or leg stiffness) and joint stiffness. Various tasks have been used to characterise stiffness, including hopping, gait, jumping, sledge ergometry and change of direction tasks. Appropriate levels of reliability have been reported in most tasks, although vary between investigations. Vertical stiffness has demonstrated the strongest reliability across tasks and may be more sensitive to changes in high-velocity running performance than leg stiffness. Joint stiffness demonstrates the weakest reliability, with ankle stiffness more reliable than knee stiffness. Determination of stiffness has typically necessitated force plate analyses, however, validated field-based equations permit determination of whole-body stiffness without force plates. Vertical, leg and joint stiffness measures have all demonstrated relationships with performance measures. Greater stiffness is typically demonstrated with increasing intensity (i.e. running velocity or hopping frequency). Greater stiffness is observed in athletes regularly subjecting the limb to high ground reaction forces (i.e. sprinters). Careful consideration should be given to the most appropriate assessment of stiffness on a team/individual basis.

Running Head: Methods of Lower Limb Stiffness Assessment

Introduction

Stiffness is a concept frequently used to characterise human movement or describe neuromuscular function (Butler, Crowell III, & Davis, 2003; Latash and Zatsiorsky, 1993; Pearson and McMahon, 2012; Serpell, Ball, Scarvell, & Smith, 2012). In a physical context, stiffness describes the ability of an object to resist deformation in response to the application of force (Latash and Zatsiorsky, 1993). The characterisation of stiffness within the human body is important given the viscoelastic, spring-like properties of the musculotendinous unit (Gasser and Hill, 1924; Hill, 1950; Levin and Wyman, 1927). Greater stiffness of the musculotendinous unit would be anticipated to maximise the conversion of potential energy, stored within the elastic components of the lower limb during eccentric lengthening, to kinetic energy released during subsequent contractile shortening (Gasser and Hill, 1924). As such, greater stiffness of the lower limb would be anticipated to enhance athletic performance. The ability to instigate a high level of stiffness within the lower limb is likely to be most beneficial to activities where the ability to transmit a given impulse in a shorter period of time would be advantageous, for example, during maximum velocity running (Bret, Rahmani, Dufour, Messonnier, & Lacour, 2002) or a change of direction (Serpell, Ball, Scarvell, Buttfield, & Smith, 2014). Whilst lower limb stiffness may also be monitored in relation to musculoskeletal injury, for example, it has been postulated that both high and low levels of stiffness can increase the likelihood of injury (Butler, et al., 2003), this review will focus on the measurement of stiffness in relation to athletic performance.

When exploring the relationship between stiffness and athletic performance, three measurements are commonly utilised:

1) *Vertical stiffness* describes the vertical displacement of the centre of mass in response to vertical ground reaction force during a task performed in the sagittal plane (Latash and Zatsiorsky, 1993).
2) *Leg stiffness* describes the compression of the leg spring in response to force in any plane or direction (McMahon and Cheng, 1990).
3) *Joint stiffness* describes the angular displacement of a joint in response to the moment at the joint (Farley, Houdijk, Van Strien, & Louie, 1998).

Although the relationship between lower limb stiffness and athletic performance may seem a logical one, the evidence base is perhaps not as definitive as may be perceived by coaches and practitioners. Indeed, there is currently a great deal of inconsistencies within the literature. For example, investigations have modelled stiffness using different methodologies, sampled a diverse range of performance measures and frequently used specific terms in an incorrect context (i.e. using vertical stiffness and leg stiffness interchangeably). Previous review articles by Brughelli and Cronin (2008) and Serpell, et al. (2012) have sought to outline the different measurements and methods by which to calculate lower limb stiffness. However, the literature has not well considered the advantages and limitations of various assessments for the practitioner seeking to model lower limb stiffness. For example, evaluating whether certain measurements (i.e. vertical, leg or joint stiffness) or movement tasks (i.e. hopping, jumping, etc) may demonstrate stronger reliability or greater sensitivity to change. The aim of this review is therefore to provide a critical overview of the tasks, models and measurements most commonly used to characterise lower limb stiffness. In addition, this review will reflect developments in both technology and in the literature base that have arisen in since the publication of these reviews.

Methods

This review sought to retrieve original journal articles that had either: 1) evaluated the relationship between measures of lower limb stiffness and athletic performance, and/or 2) reported reliability values for a measure of lower limb stiffness. Only studies which had measures of vertical, leg and joint stiffness were included, isolated measures of tendon stiffness (i.e. Achilles and patella tendon) were not included. Search terms included ‘vertical OR leg OR lower limb OR joint OR ankle OR knee AND stiffness’ and ‘spring mass OR torsional spring AND characteristics OR model’ Material was obtained through electronic searches of the online Science Direct, OVIDSP, Medline (EBSCO) and PubMed databases in addition to searches of Google Scholar, Research Gate and relevant bibliographic hand searches with no limits of language of publication. Where appropriate, review articles and other related literature were included to the elucidate the discussion of lower limb stiffness testing methods. The month of the last search performed was June 2017.

Models Describing Lower Limb Stiffness

The relationship between force and deformation is described by Hooke’s law; shown in Equation 1. Theoretically, stiffness (the proportionality constant) can therefore be modelled wherever force and length change can be determined.

Equation 1: $F = kx$

Where F = force, k = the proportionality constant and x = the distance the material is deformed.

In the human body, stiffness can be approximated with varying degrees of determinism; illustrated in Figure 1. From a practical point of view, the measurement of integrated aspects of stiffness, such as limb or joint stiffness, allows a greater understanding of how global aspects of human stiffness impact on performance and will therefore be the focus of this current review. Moreover, the assessment of muscle-tendon unit and/or sub-component stiffness necessitates a time, monetary and logistical demand that would typically preclude it from utilisation within the athletic training environment.

***** FIGURE 1 NEAR HERE *****

The Spring-Mass Model

***** FIGURE 2 NEAR HERE *****

The stiffness of the body during human movement has been widely approximated using a simple spring-mass model (Arampatzis, Schade, Walsh, & Brüggemann, 2001; Blickhan, 1989; Butler, et al., 2003; Cavagna, Saibene, & Margaria, 1964; Farley, Blickhan, Saito, & Taylor, 1991; Hobara, Kanosue, & Suzuki, 2007; McMahon and Cheng, 1990; Serpell, et al., 2012; Seyfarth, Blickhan, & Van Leeuwen, 2000). In this model (Figure 2), the lower limb is represented as a simple ‘leg-spring’ supporting the mass of the body (Blickhan, 1989; Butler, et al., 2003). This model has been utilised to describe stiffness in tasks such as hopping (Hobara, et al., 2007), walking/running gait (Cavagna, et al., 1964), changes of direction (Serpell, et al., 2014), vertical drop jumping (Arampatzis, et al., 2001) and horizontal jumping

(Seyfarth, et al., 2000). As will be discussed in Section 3, the spring-mass model can be applied to calculate measurements of both vertical stiffness and leg stiffness.

The spring-mass model assumes a linear relationship between centre of mass displacement and ground reaction force, therefore the peak displacement should occur at the instant of peak force (Butler, et al., 2003). The extent to which a task may be appropriately predicted by the spring-mass model can be evaluated through calculation of the correlation coefficient between force and displacement, thus inclusion criteria to be applied to individual trials. Conservative inclusion criteria ($r \geq 0.8$) has been applied in hopping investigations (Granata, Padua, & Wilson, 2002), a task likely to be well described by the model as will be discussed in subsequent sections. However, Clark and Weyand (2014) proposed the use of a higher value ($r^2 \geq 0.9$) when modelling sprinting gait and deviation from the spring-mass model is more likely.

The Torsional Spring Model

***** FIGURE 3 NEAR HERE *****

Calculations of vertical stiffness and leg stiffness are based on the premise that the lower limbs function as a global spring-mass system (Blickhan, 1989; Butler, et al., 2003). Such measures do not account for the multiple degrees of freedom within the lower limb, and therefore the relative contribution of the individual joints that determine summative stiffness (Latash and Zatsiorsky, 1993; Pearson and McMahon, 2012). The torsional spring model proposed by Farley, et al. (1998) (Figure 3), deconstructs the lower limb into three torsional springs – the ankle, the knee and the hip – and provides greater depth to the rigid linked-segment model first proposed by (Elftman, 1939). Calculation of individual joint-spring stiffness facilitates a greater level of determinism when it comes to describing stiffness as the relative importance of the three joints to global leg-spring stiffness can be evaluated. Indeed, it has been proposed that the least stiff joint-spring within the system will carry the greatest influence to the overall stiffness of the leg-spring (Kuitunen, Ogiso, & Komi, 2011). The torsional spring model has been used to characterise stiffness in tasks such as hopping (Farley, et al., 1998), vertical drop jumping (Arampatzis, et al., 2001) and walking/running gait (Stefanyshyn and Nigg, 1998).

Limitations of Traditional Models

The spring-mass and torsional spring models are both uniplanar in nature. Whilst this simplicity may be attractive when seeking to model lower limb stiffness, the limitations of such models must be considered. These models appear provide an appropriate representation of stiffness during sagittal plane tasks (i.e. gait, hopping and jumping) and, as will be discussed in subsequent sections of this review, have demonstrated relationships with athletic performance. However, the effectiveness of either model is dependent on the athlete’s ability to stabilise effectively in the frontal and transverse planes. Whilst tasks such as bilateral hopping may provide little threat to multi-planar stability, tasks such as unilateral drop jumps impose an inherently greater challenge. Given the sagittal nature of the spring-mass and torsional spring models, it is rational to question their ability to effectively describe stiffness in multi-planar tasks such as changes of direction or lateral bounding.

Measurements of Lower Limb Stiffness

Vertical Stiffness

Vertical stiffness is proposed as a representative measure of summative lower limb stiffness, approximating the extent to which the whole body deforms in response to ground reaction forces by using inverse dynamics to estimate vertical displacement centre of mass (Butler, et al., 2003). The equation used to calculate vertical stiffness is shown in Equation 2. This measurement assumes the basic Hookean spring-mass model and is typically utilised to describe force-deformation characteristics of the lower limb during a vertical movement task such as a hop or vertical jump (Butler, et al., 2003).

Equation 2: $Kvert = Fmax/\Delta y$

Where *Kvert* = vertical stiffness, *Fmax* = the maximum vertical ground reaction force and *Δy* = the maximum vertical displacement of the centre of mass.

Relative to other approximations of stiffness, vertical stiffness is a quick and easy method by which to estimate the mechanical properties of the lower limb without measuring deformation directly (Butler, et al., 2003). Ground reaction forces can be obtained using a force plate, a tool becoming increasingly common within the athletic training environment, and centre of mass displacement can be estimated from the force trace using principles of inverse mechanics (Cavagna, 1975). However, it is important to acknowledge that the true compression of the leg spring is not being directly measured when determining vertical stiffness in this manner. Movements of the trunk and/or upper limbs would ultimately contribute to stiffness of the leg-spring and are not taken into consideration in this calculation.

Force plates may now be commonplace within larger athletic training environments, but for practitioners and researchers working with limited resources it is necessary to consider alternative methods for the assessment of vertical stiffness. For this reason, Dalleau, Belli, Viale, Lacour, & Bourdin (2004) devised an equation to estimate vertical stiffness during hopping using a simple contact mat (Equation 3).

Equation 3: $Kvert = M \times \pi\left(T_f + T_c\right) \div T_{c^2}\ [(T_f + T_c \div \pi) - (T_c \div 4)]$

Where *Kvert* = vertical stiffness, *M* = body mass, *Tf* = flight time, *Tc* = contact time.

Dalleau, et al. (2004) evaluated the validity of the contact mat method versus the reference force plate method, reporting strong correlations during submaximal, set frequency hopping (r = 0.94; p < 0.001) and maximal hopping (r = 0.98; p < 0.001), together with a maximum difference of ~7% between calculated values. Whilst force plate assessments may offer practitioners greater precision, the contact mat method appears a viable field-based alternative (Lloyd, Oliver, Hughes, & Williams, 2009) and has been utilised in subsequent investigations (i.e. Oliver and Smith (2010)).

Advantages

- Seeks to model summative stiffness of the lower limb in a holistic manner.
- Provides the fastest and simplest representation of lower limb stiffness by accounting only for vertical force and deformation characteristics.
- May be determined using minimal equipment (i.e. contact mat) with established validity versus criterion measures (i.e. force plate analyses).

Limitations

- Provides an indirect estimation of centre of mass displacement, not lower limb deformation.

- Does not consider horizontal motion which may influence stiffness during certain tasks (i.e. running gait or horizontal jumping).
- Does not consider the confounding influence of the trunk and upper body.
- Does not consider the relative contribution of each joint to summative stiffness.

Leg Stiffness

Although vertical stiffness aims to approximate stiffness of the lower limb, it is important to note that leg stiffness is a distinct and separate measurement. As such, the terms vertical stiffness and leg stiffness should not be used interchangeably. Measurements of leg stiffness seek to determine compression of the leg-spring (Equation 4) as opposed to vertical stiffness assessing displacement of the body's centre of mass (McMahon and Cheng, 1990).

Equation 4: $Kleg = Fmax/\Delta L$

Where $Kleg$ = leg stiffness, $Fmax$ = the maximum vertical ground reaction force and ΔL = the maximum change in leg length.

Despite the difference between the two terms, numerous investigations have used the term 'leg stiffness' when calculating vertical stiffness (Farley and Morgenroth, 1999; Granata, et al., 2002; Hobara et al., 2008; Padua, Arnold, Carcia, & Granata, 2005). Whilst leg stiffness assumes the basic Hookean spring-mass model as vertical stiffness, the change in leg length is calculated using a greater number of factors (Equation 5).

Equation 5: $\Delta L = \Delta y + L_0(1 - cos\theta_0)\ and\ \theta = sin^{-1}\,(ut_c/2L_0)$

Where ΔL = change in leg length, Δy = maximum displacement of the centre of mass, L_0 = standing leg length, ϑ = half angle of the arc swept by the leg, u = horizontal velocity, t_c = ground contact time.

The calculation of leg stiffness accounts for resting leg length, ground contact time and horizontal velocity, in addition to vertical ground reaction force and calculated centre of mass displacement (McMahon and Cheng, 1990). It is for this reason that the determination of leg stiffness might appear preferable when evaluating movement tasks in which the lower limb contacts the ground in a non-vertical direction (Butler, et al., 2003); for example, during running gait or changes of direction. However, during tasks where the centre of mass moves solely in the vertical direction, such as in-place hopping, the half-angle swept by the leg would be hypothesised to equal zero (Butler, et al., 2003). This would result in calculations of vertical and leg stiffness yielding the same values and may explain the use of the term leg stiffness when it has not been explicitly calculated (Farley and Morgenroth, 1999; Granata, et al., 2002; Hobara, et al., 2008; Padua, et al., 2005).

One limitation of the traditional leg stiffness equation (Equation 4), is that only vertical ground reaction forces are considered. Recent investigations have sought to determine a multiplanar leg stiffness value which also accounts for anterior-posterior and medio-lateral components of ground reaction force. For example, Liew, Morris, Masters, & Netto (2017) compared traditional and multiplanar measurements, reporting that the inclusion of the additional force dimensions resulted in greater deformation of the leg spring and therefore lower values for leg stiffness. Whether the reliability of three-dimensional measures is comparable to the traditional method is yet to be determined, however, multiplanar models would appear to facilitate a more complete picture of force-deformation characteristics given notable contribution from these force components to the overall profile (Cavanagh and Lafortune, 1980).

The principles outlined by Dalleau, et al. (2004) for the field-based assessment of stiffness during hopping were the foundation for Morin, Dalleau, Kyröläinen, Jeannin,

& Belli (2005) to propose a similar method for the assessment of vertical and leg stiffness during running. The ‘sine wave’ method proposed by Morin, et al. (2005) allows for both vertical and leg stiffness to be determined without a force plate using a combination of temporal (forward velocity, flight time and ground contact time) and anthropometric (body mass and leg length) data. The application of this method necessitates the use of a photocell system (i.e. OptoJump) which, although a viable alternative to force plates when working in the field, may not be an affordable option in all circumstances. Morin, et al. (2005) evaluated the validity of the sine wave method versus the reference force plate method during both treadmill and overground running. Regression analyses revealed strong correspondence between methods for both vertical stiffness (treadmill: $r^2 = 0.97$, overground: $r^2 = 0.98$; both $p < 0.01$) and leg stiffness (treadmill: $r^2 = 0.98$, overground: $r^2 = 0.89$; both $p < 0.01$) across a range of running velocities (from 3 m/s to maximal velocity) (Morin, et al., 2005). Moreover, Morin, et al. (2005) reported low biases between methods for vertical stiffness (treadmill: 0.12 ± 0.53%, overground: 2.30 ± 1.63%) and leg stiffness (treadmill: 6.05 ± 3.02%, overground: 2.54 ± 1.16%). The sine wave method has been subsequently utilised in a number of running-based investigations (Coleman, Cannavan, Horne, & Blazevich, 2012; Taylor and Beneke, 2012).

Advantages

- Seeks to model summative stiffness of the lower limb in a holistic manner.
- Seeks to estimate deformation of the lower limb, rather than the centre of mass, and can therefore account for horizontal motion.
- May be determined with minimal equipment (i.e. Optojump) validated against criterion measures.

Limitations

- Typically provides an indirect estimation of lower limb deformation rather than a direct measurement.
- Does not consider the confounding influence of the trunk and upper body.
- Does not consider the relative contribution of each joint to summative stiffness.

Joint Stiffness

The respective stiffness of the ankle, knee and hip joints is most commonly determined through the estimation of net joint moments, determined by principles of inverse mechanics, and by the measurement of joint angular displacement (Equation 6). As it has been noted that the phase shift for the moment-displacement curve of the hip commonly exceeds 10% (Farley and Morgenroth, 1999; Kuitunen, et al., 2011; Maloney, Richards, Nixon, Harvey, & Fletcher, 2017b), previously alluded to as exclusion criteria by Farley, et al. (1998), the determination of hip stiffness may not be appropriate. Given also that Farley, et al. (1998) and Farley and Morgenroth (1999) have observed hip stiffness to be unaffected by changes in vertical stiffness, these findings are likely to explain why hip stiffness is not commonly determined alongside ankle and knee stiffness.

Equation 6: $Kjoint = \Delta M / \Delta \theta$

Where $Kjoint$ = joint stiffness, ΔM = change in joint moment, $\Delta \vartheta$ = change in joint angle.

The accurate determination of angular displacements had previously necessitated the use of expensive two- (or even three-) dimensional motion capture systems. However, given recent advancements in mobile technology, video analysis at an appropriate frame rate (≥200 Hz (Farley, et al., 1998; Kuitunen, et al., 2011)) is now possible for most practitioners. For example, iPhone models post-2014 (models 6 and above) are capable of recording at 240 Hz. Such technological advancements could bring the determination of joint stiffness into the realms of coaches and practitioners working in a gym-based setting if they have the capacity to obtain (i.e. force plates) or estimate (i.e. using equations proposed by Dalleau, et al. (2004)) force measurements and existing motion capture software that will accept the relevant video file format. However, the reliability and validity of such measures is yet to be determined.

Advantages

- Directly measures joint angular displacement.
- Can consider the relative contribution of each joint to summative stiffness.

Limitations

- Necessitates video analysis at a task-appropriate frame rate.
- Requires extra time for kinematic analyses and a deeper knowledge of inverse mechanics.
- Less reliable than global measures of vertical or leg stiffness (to be discussed in the subsequent section).

Tasks to Assess Lower Limb Stiffness

Hopping

Bilateral hopping tasks are the most widely utilised assessments for the determination of vertical stiffness (Hobara, Inoue, Kobayashi, & Ogata, 2014; Joseph, Bradshaw, Kemp, & Clark, 2013), although unilateral hopping tasks have also been employed to determine this characteristic (Hobara, Kobayashi, Kato, & Ogata, 2013). Hopping is recognised to be the most efficient type of gait in regards to energy consumption (Cavagna, et al., 1964), and is perhaps the strongest representation of the simple spring-mass model in action as a consequence (Farley, et al., 1991). Hopping tasks are also a sagittal plane task with limited frontal and transverse plane demands, making them an appropriate tool for the assessment of vertical stiffness.

The reliability of stiffness measures has been evaluated in a number of bilateral (Joseph, et al., 2013; Maloney, Fletcher, & Richards, 2015; McLachlan, Murphy, Watsford, & Rees, 2006; Moresi, Bradshaw, Greene, & Naughton, 2015) and unilateral (Diggin, Anderson, & Harrison, 2016; Joseph, et al., 2013; Pruyn, Watsford, & Murphy, 2016; Pruyn et al., 2013) hopping investigations, outlined in Table 1. Reliability measures obtained during both bilateral and unilateral hopping tasks have differed substantially between investigations. Whilst readers are directed to these manuscripts for more detailed discussion of reliability considerations, reliability may be improved by hopping at faster frequencies (~3.0 Hz) (Diggin, et al., 2016; McLachlan, et al., 2006), applying exclusion criteria for trial selection (i.e. sampling middle trials within 5% of average ground time) (Moresi, et al., 2015) and ensuring adequate athlete familiarisation (Maloney, et al., 2015). Vertical stiffness would appear to be a more reliable measure than ankle stiffness, with knee stiffness measures exhibiting poor reliability (Diggin, et al., 2016; Joseph, et al., 2013). Given the extent of variation between investigations, it is strongly recommended that practitioners evaluate the reliability of their chosen protocol within their own athlete cohort as factors such as participants’ sporting background and training status carry the potential to influence the reliability of measurements. It is also likely that reliability will demonstrate a degree of specificity dependent upon the specific task constraints imposed. As will be discussed below, the relative emphasis on particular joints will be affected by how the hopping task is executed.

*** Table 1 Near Here ***

The literature has shown that vertical stiffness obtained during bilateral hopping is able to differentiate between different athletic groups (Hobara, et al., 2008; Hobara et al., 2010) and is associated with athletic performance in homogenous groups (Bourdin et al., 2010; Bret, et al., 2002; Chelly and Denis, 2001). Hobara, et al. (2008) further reported that joint stiffness during bilateral hopping differentiated endurance and power athletes. In netball athletes, unilateral hopping tasks have been related to jump performance measures (Pruyn, Watsford, & Murphy, 2014) and shown to differentiate between performance levels (i.e. elite vs sub-elite) (Pruyn, Watsford, & Murphy, 2015).

On balance, it appears that lower limb stiffness during hopping demonstrates a greater reliance on ankle stiffness than on knee stiffness (Farley, et al., 1998; Farley and Morgenroth, 1999; Kim et al., 2013; Kuitunen, et al., 2011). For example, Kuitunen, et al. (2011) reported strong correlations ($r = 0.72-0.92$; $p < 0.05$) between vertical and ankle stiffness, but observed no such relationship between vertical and knee stiffness. Kim, et al. (2013) demonstrated that changes in ankle stiffness bore the highest correlation to changes in hopping frequency ($r^2 = 0.83$). In contrast, Hobara et al. (2009) correlated knee ($r = 0.64$; $p = 0.03$) but not ankle ($r = 0.37$; $p = 0.17$) stiffness to vertical stiffness during maximal height hopping. Whilst Kuitunen, et al. (2011) did not correlate knee and vertical stiffness, the investigation reported a significant relationship between knee stiffness and to take-off velocity ($r = 0.56$; $p < 0.001$) and that knee stiffness was increased in response to greater hopping intensities. It is reasonable to suggest knee stiffness, and the role of the knee extensors, is more closely related to mechanical output and hopping intensity. Conversely, ankle stiffness is likely to be more closely related to whole-body stiffness and the modulation of ground contact time during hopping.

One limitation inherent with hopping tasks is that they are typically performed at set hopping frequencies and stiffness is therefore inherently constrained by the task itself (Hobara, et al., 2014; Joseph, et al., 2013). Such constraints may bare correspondence to other sub-maximal cyclic performances, for example, endurance running. However, it is important to acknowledge that hopping tasks are performed with a forefoot landing strategy, not the rear-mid foot landing strategy which may often be anticipated in submaximal running (i.e. Moore (2016)). As such, hopping tasks may provide a general representation of stiffness properties but do not directly correspond to how the leg-spring is loaded during this type of activity. Measurements of stiffness during gait may therefore provide a more representative profile in running populations. In regard to acyclic maximal performances, such as jumping and changes of direction, typical hopping tasks may not be the best representation of stiffness given discrepancies in how the leg-spring is loaded.

Advantages

- Low requirement for active force contribution and limited frontal/transverse plane demand; may therefore provide the closest representation of a simple spring-mass model.
- Appropriate reliability has been consistently reported for vertical, leg and ankle stiffness.
- Stiffness measures obtained during bilateral and unilateral hopping tasks have demonstrated relationships with athletic performance measures.

Limitations

- Appropriate reliability has not been well demonstrated for knee stiffness.
- Does not replicate how the leg-spring is typically loaded during maximal athletic performance tasks.

Running gait

The spring-mass and torsional spring models have also been applied to describe the mechanics of running gait (Blickhan, 1989; McMahon and Cheng, 1990; Morin, et al., 2005). Naturally, the assessment of stiffness during running gait carries the greatest specificity for running based athletes and can be determined at the most appropriate velocity for the individual. However, it is important to acknowledge that utilisation of the simple, symmetrical spring-mass model may not always be appropriate. Clark and Weyand (2014) demonstrated that elite sprinters applied greater forces in the first half of the stance phase during high-velocity running, therefore deviating from spring-mass model assumptions of a symmetrical sinusoidal reaction force curve, whereas sub-elite and non-sprint athletes applied forces symmetrically across the gait cycle. The spring-mass model may also be inappropriate at slower velocities; Cavagna (2006) reported significant differences between the first (negative) and second (positive) portions of the stance phase at velocities lower than 14 km/hr (3.9 m/s).

As with hopping tasks, the reliability of stiffness measures obtained during gait have also been evaluated (Table 2) (Girard, Brocherie, Morin, & Millet, 2016; Joseph, et al., 2013; Pappas, Dallas, & Paradisis, 2017; Pappas, Paradisis, Tsolakis, Smirniotou, & Morin, 2014). On the whole, vertical and leg stiffness appear reliable measures across a range of velocities with slightly lower coefficients of variation consistently reported for vertical versus leg stiffness. However, Joseph, et al. (2013) reported poor reliability for leg and joint stiffness measures. This investigation differed from the other three noted, in that a slow running velocity was utilised (3.35 m/s) and reaction forces were determined during overground running from a single foot strike on each trial. Importantly for the practitioner, there appears to be little difference in the reliability between measures derived from force data (Girard, et al., 2016) and those derived using the sine wave method (Pappas, et al., 2017; Pappas, et al., 2014). Future studies should seek to determine if the reliability of joint stiffness can be improved by utilising the methodologies which have demonstrated stronger reliability for global stiffness, and if these methodologies demonstrate similar reliability during overground running.

*** Table 2 Near Here ***

Calculations of both vertical and leg stiffness have been reported during gait-based investigations, though these two measurements may yield disparate relationships. Vertical stiffness has been shown to increase with running velocity (Cavagna, Heglund, & Willems, 2005; He, Kram, & McMahon, 1991; Kuitunen, Komi, & Kyröläinen, 2002; Morin, et al., 2005; Morin, Jeannin, Chevallier, & Belli, 2006) and stride frequency (Farley and González, 1996). However, whilst Arampatzis, Brüggemann, & Metzler (1999) reported increases in both vertical and leg stiffness with running velocity, a number of investigations demonstrated that leg stiffness does not increase with running velocity (Cavagna, et al., 2005; He, et al., 1991; Morin, et al., 2005). Such findings may suggest that the measurement of vertical stiffness could be a more sensitive measure than leg stiffness if seeking to explore relationships with running performance. The position is also supported by the findings of further studies. For example, Morin, et al. (2006) reported that fatigue-induced reductions in repeated sprint velocity were mirrored by reductions in vertical stiffness, however, fatigue did not influence leg stiffness. Girard, Millet, & Micallef (2017) reported similar findings during 800-m track running. Nagahara and Zushi (2017) also observed training-induced improvements in vertical stiffness and performance in sprinters, but no change in leg stiffness. However, the reverse may be true in response to slower velocity, longer duration running. Several studies have reported reductions in leg stiffness and minimal change in vertical stiffness following fatiguing protocols (Degache et al., 2016; Hayes and Caplan, 2014; Rabita, Couturier, Dorel, Hausswirth, & Le Meur, 2013; Rabita, Slawinski, Girard, Bignet, & Hausswirth, 2011).

The apparent discrepancies between vertical and leg stiffness measures have not been well considered by the literature. As calculations of leg stiffness consider changes in horizontal velocity (Equation 5), and calculations of vertical stiffness do not (Equation 4), this would explain why changes in running velocity are not reflected in changes in leg stiffness. Nonetheless, whether the vertical force and centre of mass displacement profile may be more important than the summative force and leg-spring deformation profile during high-velocity running, and vice-versa during exhaustive running, is a concept that warrants further investigation. As has been reported during hopping tasks, the emphasis on knee stiffness is likely increased with task intensity. Arampatzis, et al. (1999) and Kuitunen, et al. (2002) reported increases in whole-body and knee stiffness in line with running velocity, but observed little change in ankle stiffness. However, increases in ankle stiffness with running velocity have also been reported (Günther and Blickhan, 2002; Stefanyshyn and Nigg, 1998).

Lower limb stiffness during gait has been evaluated during both high-velocity treadmill running and typical overground running (Morin, et al., 2005). The former facilitates the use of an instrumented treadmill, allowing the direct measurement of ground reaction forces during each step and greater control of running velocity. Of course, the use of a high-velocity treadmill detracts slightly from the ecological validity of the assessment. The direct measurement of ground reaction forces using force plates is the gold standard for assessment during overground running, although such measurements assume that a single ground contact (assuming the use of one force plate) is representative of the mechanical characteristics at a given velocity. Set-ups utilising either multiple force plates or photocell systems offer the advantage of being able to sample data across multiple ground contacts, but are unlikely to be within the realms of most practitioners and researchers.

Advantages

- Models stiffness directly during gait; highly specific for athletes with running requirements in their sport.
- Can be performed at a task-specific velocity.
- Facilitates the determination of vertical and leg stiffness measures.

- Vertical and leg stiffness measures obtained during gait have demonstrated relationships with athletic performance measures.

Limitations

- Assumes a simple spring-mass model and sinusoidal ground reaction force curve that may not be always be appropriate.
- Appropriate reliability of global stiffness measures during overground running is yet to be established.
- Appropriate reliability of joint stiffness measures is yet to be established.

Jumping

Parameters of vertical stiffness may be determined during drop jumping in the same manner as during hopping. Vertical stiffness in drop jump tasks has been shown to differentiate between drop jump intensities (Arampatzis, et al., 2001) and relate to change of direction performance (Maloney, Richards, Nixon, Harvey, & Fletcher, 2017a). Drop jump tasks allow practitioners to obtain a representative measure of stiffness during a maximal and acyclic movement task, thus demonstrating greater correspondence to maximal sporting actions such as jumps and changes of direction. When performing drop jump tasks for the purpose of evaluating stiffness, it is important that the jump is executed in an appropriate manner. Heel contact during the ground contact phase would result in deviation from the symmetrical sinusoidal reaction force curve assumed by the spring-mass model, i.e. a ‘double peak’ will be observed. Practitioners are advised to determine the correlation coefficient between force and displacement, applying inclusion criteria for appropriate trials as has been described for sprinting by Clark and Weyand (2014).

Whilst measurements of stiffness may also be calculated from squat and countermovement jumps (Witmer, Davis, & Moir, 2010), these tasks do not incur impact forces and do not represent how the leg-spring is typically loaded during sporting activities. For example, tasks such as running and changes of direction are dependent upon a flight phase and an initial impact during ground contact that is not observed during squat or countermovement jumps. Whilst stiffness can be calculated within any activity involving stretch deformation of the muscle-tendon unit (i.e. stiffness could be determined during an eccentric-only action), it would appear appropriate to recommend that stiffness should be determined during tasks involving an initial impact phase (i.e. repeated hopping or drop jumping) and fast stretch-shortening cycle requirement.

Maloney, et al. (2015) examined inter-session coefficients of variation of vertical stiffness obtained during bilateral hopping, bilateral drop jumping and unilateral drop jumping, figures of 14%, 13% and 8% were reported respectively. Although further investigation is warranted, such values suggest that the reliability of drop jump assessments compare favourable to bilateral hopping. Moreover, unilateral drop jump may prove a more reliable assessment than bilateral hopping.

Currently, to the authors’ knowledge, drop jump investigations have only utilised force plates to measure ground reaction forces directly. In principle, it would be possible to employ the procedures outline by Dalleau, et al. (2004) to determine vertical stiffness during drop jumping with the use of a contact mat. Flight time could be estimated based upon the prescribed drop height or, more accurately, by using video analysis to identify the apex of the athlete’s drop. If an exact dropping distance can be measured, this will allow a more accurate determination of the body’s velocity at the instant of ground contact. Nonetheless, this concept remains speculative at this point and future investigation is required to determine the efficacy of this approach.

Advantages

- Models stiffness in an acyclic and ballistic task performed with maximal intent, a closer representation of typical athletic performance.
- Limited frontal/transverse plane demand; may therefore provide a close representation of a simple spring-mass model.
- Data suggest that the reliability of stiffness measures compares favourably with hopping tasks.
- Relationships with athletic performance measures have been demonstrated.

Limitations

- The assumption of the spring-mass model relies on appropriate performance of the jump (i.e. no heel contact).

Sledge Ergometry

A sledge apparatus has been used to evaluate vertical stiffness during both repeated hopping and maximal drop jumping tasks (Flanagan and Harrison, 2007). The sledge apparatus secures the athlete into a chair that slides along a fixed track, typically at an inclination of 30° (Comyns, Harrison, Hennessy, & Jensen, 2007; Flanagan and Harrison, 2007; Harrison, Keane, & Coglan, 2004), thereby ensuring that only flexion-extension movement can take place within the sagittal plane. This set-up seeks to minimise the potential contribution of factors such as movement from the upper body and any contribution from the contralateral limb during unilateral tasks (Flanagan and Harrison, 2007). Also, the attachment of the chair to a winching system allows for greater consistency of dropping height in comparison to typical drop jumps (Flanagan and Harrison, 2007). The intra-trial reliability of the method has been noted in two of these investigations. Harrison, et al. (2004) reported an average intra-class correlation coefficient of 0.996 for repeated drop jumps. Similarly, Flanagan and Harrison (2007) reported values of 0.98 and 0.97 (dominant and non-dominant limbs) for repeated drop jumps, and values of 0.95 and 0.96 for single drop jumps. Such correlations compare well to other assessment tasks, although absolute measures of reliability (i.e. coefficient of variation) have not been detailed.

During drop jumping tasks performed on the sled, vertical stiffness has been shown to differentiate between sprint and endurance athletes (Harrison, et al., 2004) and to be sensitive to changes induced by post-activation potentiation protocols (Comyns, et al., 2007). It is important to consider the limitations of the sledge apparatus in the evaluation of stiffness if seeking to explore relationships with athletic performance. The angle at which the force is applied to the leg-spring during these tasks is not representative of typical locomotion. As demonstrated in the figures reported by Comyns, et al. (2007) during a single leg drop jump, this is likely to independently reduce the reaction forces (single leg ground reaction force: ~2000 N) experienced by the leg-spring and also increase the ground contact times (> 0.4 seconds). This results in large discrepancies between the vertical stiffness values reported during sledge-based investigations (typically ≤10 kN/m (Comyns, et al., 2007; Flanagan and Harrison, 2007; Harrison, et al., 2004)) and those reported in tasks such as hopping (i.e. 23-35 ≤10 kN/m (Farley, et al., 1998)) and running (i.e. 20 - >100 kN/m (Morin, et al., 2005)).

Advantages

- Can be employed to model stiffness in an acyclic and ballistic task performed with maximal intent, a closer representation of typical athletic performance.
- Carries minimal frontal/transverse plane demand and may therefore provide a close representation of a simple spring-mass model.
- Greater control of dropping height and velocity at ground contact.
- Relationships with athletic performance measures have been demonstrated.

Limitations

- Does not replicate how the leg-spring is typically loaded during athletic performance.
- Absolute reliability measures are yet to be determined.

Changes of Direction

Calculations of lower limb stiffness during changes of direction are less common than during the previously mentioned tasks. However, vertical stiffness has been determined during a power-cutting task in an attempt to better replicate loading of the lower limb during change of direction manoeuvres (Serpell, et al., 2014; Serpell et al., 2016). The power-cut procedure requires the athlete to perform a single-leg ballistic hop at an angle of 45°, land on the ipsilateral leg and immediately perform another ballistic hop to land back on the starting leg (Serpell, et al., 2014; Serpell, et al., 2016). The reliability of the method was determined by Serpell, et al. (2014) using the typical error of measurement; values of 4.3%, 4.9% and 5.7% were reported when hopping from distances of 1.0 m, 1.2 m and 1.5 m, respectively.

The determination of stiffness directly during changes of direction carries high ecological validity to athletes engaging in such actions within their sport. However, as noted previously in this review, it must be acknowledged that changes of direction are multi-planar. Uniplanar models of vertical and/or leg stiffness cannot provide a detailed evaluation of leg-spring properties during changes of direction, but may provide an indication of force-deformation profiles under conditions more replicative of sporting performance.

Advantages

- Models stiffness directly during an athletic movement; highly specific for athletes with change of direction requirements in their sport.
- Can be performed at a task-specific cutting angle and velocity.
- Preliminary data suggest that the reliability of stiffness measures compares favourably when considered in relation to other assessment tasks.

Limitations

- High frontal and transverse plane demands question the efficacy of simple spring-mass and torsional spring models.
- Relationships with athletic performance are yet to be established.
- The influence of cutting angle is yet to be determined.

Summary

The most common approximations of lower limb stiffness during athletic performance tasks are vertical, leg and joint stiffness. These measures have been determined in a wide range of athletic tasks using simple spring-mass and/or torsional spring models. Global measurements of vertical and leg stiffness aim to provide a simplistic representation of leg-spring deformation in response to ground reaction forces by using inverse dynamics to estimate centre of mass displacement or leg deformation. These measurements of whole-body stiffness allow the characterisation of force-deformation characteristics with minimal equipment (a measurement of force and/or velocity is required) and without the need for kinematic analyses. In most instances, global stiffness measures have demonstrated strong reliability across all tasks which have been employed. Increases in both vertical and leg stiffness have demonstrated associations with increased task intensity and improved task performance. During running tasks, vertical stiffness may be more sensitive to change than leg stiffness in high-velocity tasks whilst leg stiffness may be more sensitive in exhaustive running. Measurements of joint stiffness, specifically stiffness of the ankle and knee, may facilitate a deeper understanding of the respective contribution of each joint to global stiffness of the lower limb. However, the reliability of ankle stiffness measures has differed substantially between investigations and appropriate reliability of knee stiffness is yet to be shown. Determination of joint angular displacements would necessitate kinematic analyses, although recent advancements in smartphone technology could make this a more practical concept in future if such techniques can be appropriately validated. The simplicity of the spring-mass and torsional spring models may provide an appropriate representation of stiffness during sagittal plane tasks with limited frontal and transverse plane demand. However, given the sagittal nature of these models, it is rational to question their ability to effectively describe stiffness in tasks with a high multi-planar demand. As such, these models may not be appropriate to employ within change of direction tasks.

As highlighted in this review, practitioners have a range of methods by which to determine lower limb stiffness in athletes. Careful consideration should be given to the demands of the athlete’s sport as this is likely to determine the preferred assessment task and type of stiffness measurement. Global stiffness measures are likely to demonstrate stronger reliability than joint stiffness, although practitioners should seek to establish reliability within their own testing methods and cohorts. At this point in time, it would appear prudent to recommend that practitioners test and monitor vertical stiffness during sagittal plane tasks such as reactive hopping and jumping (i.e. drop jumps). Vertical stiffness measurements are the quickest and easiest to obtain in the field, requiring the least amount of equipment and measurements. Vertical stiffness appears to provide a reliable profile of an athlete's stiffness profiles and has shown strong associations with performance on both an inter- and intra-individual level.

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Figure Captions

Figure 1 - An inverted pyramid representing the different physiologic levels at which parameters of stiffness may be determined.

Figure 2 - An example of the simple spring-mass model used to approximate lower limb stiffness. COM = centre of mass, GRF = ground reaction force, Δ_y = centre of mass displacement.

Figure 3 - An example of the torsional spring model used to approximate lower limb stiffness. α = angular displacement.