Leg stiffness: Comparison between unilateral and bilateral hopping tasks

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Abstract

Leg stiffness is a predictor of athletic performance and injury and typically evaluated during bilateral hopping. The contribution of each limb to bilateral leg stiffness, however, is not well understood. This study investigated leg stiffness during unilateral and bilateral hopping to address the following research questions: (1) does the magnitude and variability of leg stiffness differ between dominant and non-dominant legs? (2) Does unilateral leg stiffness differ from bilateral leg stiffness? and (3) Is bilateral leg stiffness determined by unilateral leg stiffness? Thirty-two physically active males performed repeated hopping tests on a force platform for each of the three conditions: bilateral hopping, unilateral hopping on the dominant leg, and unilateral hopping on the non-dominant leg. Leg stiffness was estimated as the ratio of the peak vertical force and the maximum displacement using a simple 1-D mass-spring model. Neither the magnitude nor variability of leg stiffness differed between dominant and non-dominant limbs. Unilateral leg stiffness was 24% lower than bilateral stiffness and showed less variability between consecutive hops and subjects. Unilateral leg stiffness explained 76% of the variance in bilateral leg stiffness. We conclude that leg stiffness estimates during unilateral hopping are preferable for intervention studies because of their low variability.

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1. Introduction

Leg stiffness is an important parameter in human biomechanics research because of its proposed influence on performance and injury (see review by Butler, Crowell, & Davis, 2003). For instance, leg stiffness has been shown to correlate positively with performance in high intensity sports, such as sprinting and countermovement jumping (Bret, Rahmani, Dufour, Messonnier, & Lacour, 2002; Chelly & Denis, 2001; Durand, Ripamonti, Beaune, & Rahmani, 2010) and has also been shown to be higher in power-trained athletes compared to endurance-trained athletes (Hobara et al., 2008). However, high leg stiffness is also thought to increase the risk of bony injury in high intensity sport, while low leg stiffness is thought to raise the risk of soft tissue damage (Butler et al., 2003; Granata, Padua, & Wilson, 2002; Williams, Davis, Scholz, Hamill, & Buchanan, 2004; Williams, McClay, & Hamill, 2001).

Such findings, however, are largely based on a one-dimensional spring-mass model of a bilateral hopping task, in which a lumped mass representing the body is attached to a single, in-plane weightless spring representing combined leg stiffness (Fig. 1). Although these studies focused mainly on bilateral hopping, presumably because of its simplicity and high reliability (McLachlan, Murphy, Watsford, & Rees, 2006), they do not allow for an evaluation of the stiffness of each limb. Recent research in which unilateral hopping was evaluated have indicated that soft tissue injuries may be related to both high and low leg stiffness (Maquirriain, 2012; Watsford et al., 2010). In a prospective study of professional footballers, Watsford et al. (2010) reported that footballers who sustained a hamstring injury over the course of the season had higher preseason leg stiffness in the affected limb (5%) than footballers who did not sustain an injury (Watsford et al., 2010). In contrast, Maquirriain (2012) observed that athletes with unilateral Achilles tendinopathy had lower leg stiffness in the affected leg when compared to the contralateral limb.

While estimation of combined limb stiffness during a bilateral hopping task is widely used, it is based on two unverified assumptions (Nikooyan & Zadpoor, 2011). The first assumption is that leg stiffness determined during bilateral hopping provides insight into leg stiffness during unilateral hopping. It is possible that individuals may adopt a different movement strategy during unilateral hopping compared to bilateral hopping, due to the higher loading of the limb in the unilateral task. The second inherent assumption is that both legs have similar leg stiffness and hence contribute equally to overall leg stiffness values (Fig. 1b). Such an assumption, however, fails to consider the potential effects of limb dominance, laterality and asymmetric limb loading reported in able-bodied walking (Sadeghi, Allard, Prince, & Labelle, 2000) and drop landing tasks (Niu, Wang, He, Fan, & Zhao, 2011).

The aim of this study, therefore, was to evaluate leg stiffness during unilateral and bilateral hopping tasks in a cohort of healthy young males. The following three research questions were specifically...
addressed: (1) Does the magnitude and variability of leg stiffness during unilateral hopping differ between dominant and the non-dominant limbs? (2) Does the magnitude and variability of leg stiffness determined during unilateral hopping differ from bilateral hopping? and (3) Is leg stiffness during bilateral hopping determined by unilateral leg stiffness?

We hypothesized that the stiffness of the dominant leg would be greater than that of the non-dominant leg because of its higher strength and coordination abilities (Niu et al., 2011; Sadeghi et al., 2000). Second, given that spring stiffness in a passive system is additive for springs arranged in parallel (Fig. 1), we hypothesized that leg stiffness during bilateral hopping would be higher than that during unilateral hopping. Finally, since we assumed the general movement pattern of unilateral and bilateral hopping to be the same, we expected that the variance in leg stiffness during bilateral hopping would be explained to a greater extent by unilateral limb stiffness, particularly of the dominant leg.

2. Methods

2.1. Subjects

Thirty-two male subjects (mean ± SD; age: 26.7 ± 8.0 years; height: 181 ± 5 cm; mass: 74.9 ± 7.4 kg) participated in the study after signing informed consent. All study procedures complied with the principals of the Declaration of Helsinki for ethical research in human subjects. All subjects were physically active (3.6 ± 1.8 exercise exposures/week) and injury free for at least two years prior to testing. To determine leg dominance, subjects were asked to perform a unilateral maximum jump, and the take-off leg was recorded as the dominant leg (Miyaguchi & Demura, 2010). For 26 subjects the left leg was the dominant leg, and for 6 subjects the right leg was the dominant leg.

2.2. Data collection

After a five minute individual warm-up, subjects familiarized themselves with the hopping test routine for each of three conditions: bilateral, unilateral dominant leg, and unilateral non-dominant leg. Tests for the three conditions were carried out twice to determine the reliability of each test. Within each set, the order of test condition (bilateral, unilateral dominant leg, and unilateral non-dominant leg) was randomized with a 1-min rest session provided between conditions and sets, respectively. Thus, each subject performed six hopping tests, each lasting 17 s. Initially, subjects stood erect for approximately three seconds and then commenced hopping in place until instructed to stop. A digital metronome (MA-30, KORG Inc., Japan) was used to set a hopping frequency of 2.2 Hz. This frequency was specifically used as the human leg is known to behave as an elastic spring during hopping at this rate (Farley, Blickhan, Saito, & Taylor, 1991). To avoid the potential influence of arm movement, subjects performed the hopping task with their hands laterally positioned on their waist. Potential between-subject influences of footwear on estimated leg stiffness were avoided by using the same pair of shoes for all subjects (Broadway, size US 9, Li Ning Co., China).

Vertical ground reaction forces were measured using a force platform (Kistler 9655, Kistler Instrument Corp., Amherst, NY, USA) sampling at 1000 Hz. Force data were subsequently band pass filtered (band pass frequencies 0.5–40 Hz, 4th order Butterworth, zero-lag) using custom code (Matlab 2011b, Mathworks, Natick, MA, USA). Vertical displacement of the center of mass was estimated by double integration of the vertical force signal (Cavagna, 1985). For data reduction, the final two hops of each condition were disregarded and the 15 preceding hops were used in further post-processing.

To allow direct comparison to previous studies, leg stiffness ($K_{leg}$) was estimated according to the method originally described by Cavagna (1985), in which leg stiffness was defined as the ratio between the peak vertical ground reaction force ($F_{peak}$) and the maximum vertical displacement of the center of mass ($\Delta L$: difference of center of mass vertical position at initial ground contact and at the lowest point):

$$K_{leg} = \frac{F_{peak}}{\Delta L} \text{ [kN/m]}$$

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This method has been widely used to evaluate leg stiffness during hopping tasks (Hobara et al., 2008, 2009, 2010; Watsford et al., 2010). Ground contact time was also determined for each hop. The threshold of the ground reaction force for detecting ground contact was set to 50 N.

2.3. Statistical analysis

All statistical tests were performed using SPSS 19 (IBM Inc., Armonk, NY, USA). For each test, the mean and standard deviation (SD) of the 15 selected hops were calculated for each parameter. Coefficients of variability (CoV, SD/mean) were calculated for each test as a measure of intra-test variability. To compare data between tests, ensemble averages and standard deviations were computed. The ensemble standard deviations were used as a measure of between-subject variability. Kolmogorov–Smirnow-Tests were used to confirm the data were normally distributed. Differences between conditions were analyzed using one-way repeated measures analysis of variance (ANOVA). The significance level was set a priori at 5% (\(\alpha = 0.05\)), and Bonferroni corrections were applied to all post hoc tests. Eta-squared (\(\eta^2\)) was calculated to evaluate effect sizes (Levine & Hullett, 2002). On the basis of the two recorded sets for each condition (unilateral dominant, unilateral non-dominant and bilateral), a within-day test–retest reliability analysis was conducted using Bland–Altman plots (Bland & Altman, 1986) and Pearson’s correlation coefficients (r). Multiple linear regression analysis was used to determine the association between unilateral and bilateral leg stiffness where unilateral leg stiffness of the dominant leg and the non-dominant leg were entered as independent variables and bilateral leg stiffness was entered as dependent variable.

3. Results

There were no statistically significant differences in leg stiffness, peak ground reaction force, center of mass displacement, and contact time between dominant and non-dominant legs. However, unilateral hopping differed significantly from bilateral hopping in most variables (Table 1). Unilateral stiffness for both the dominant and non-dominant leg was significantly lower (−24%) than bilateral leg stiffness (\(p < 0.001; \eta^2 = 0.328;\) Fig. 2). While maximum displacement remained unchanged between hopping tasks, peak forces during unilateral hopping were significantly lower than during the bilateral hopping task (Table 1; Fig. 3). The ground contact time for unilateral hopping was longer than that for bilateral hopping corresponding to shorter flight intervals and lower hopping height. The standard deviations of the leg stiffness ensemble means, as measure of between-subject variability, were 1.7 times smaller for unilateral hopping than for bilateral hopping (Table 1).

The intra-individual coefficient of variation differed significantly between conditions (\(p = 0.007\)). Post hoc comparisons revealed that the within-test variability (CoV) in leg stiffness was significantly larger during bilateral hopping compared to hopping on the non-dominant leg (8.1 ± 0.3 % vs. 6.7 ± 0.2 %;\(p = 0.002\)) but was not significantly different from hopping on the dominant leg (\(p = 0.172\)) (Fig. 4).

<table>
<thead>
<tr>
<th>Condition</th>
<th>(K_{leg} \text{ [kN/m]})</th>
<th>(F_{peak} \text{ [kN]})</th>
<th>(D_L \text{ [m]})</th>
<th>GCT [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bilateral</td>
<td>26.5 (6.5)</td>
<td>2.85 (0.54)</td>
<td>0.11 (0.01)</td>
<td>0.239 (0.032)</td>
</tr>
<tr>
<td>Unilateral dominant leg</td>
<td>19.4 (3.9)(^a)</td>
<td>2.01 (0.37)(^a)</td>
<td>0.11 (0.01)</td>
<td>0.288 (0.031)(^a)</td>
</tr>
<tr>
<td>Unilateral non-dominant leg</td>
<td>19.3 (3.7)(^a)</td>
<td>2.10 (0.39)(^a)</td>
<td>0.11 (0.01)</td>
<td>0.293 (0.030)(^a)</td>
</tr>
<tr>
<td>p-Value</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>0.341</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Effect size (\eta^2)</td>
<td>0.328</td>
<td>0.345</td>
<td>0.014</td>
<td>0.390</td>
</tr>
</tbody>
</table>

\(^a\) Significantly different from bilateral in post hoc comparisons (\(p < 0.05\), Bonferroni adjusted).

Table 1

Mean (SD) leg stiffness (\(K_{leg}\)), peak force (\(F_{peak}\)), maximum displacement of the center of gravity (\(D_L\)) and ground contact time (GCT) for the bilateral hopping test and the unilateral hopping tests for the dominant leg and the non-dominant leg, and corresponding results of the repeated measures ANOVA and post hoc tests.

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Eigenvalues close to zero in the collinearity diagnostic for both parameters (dominant: 0.017; non-dominant: 0.001).

Between-test reliability of leg stiffness was very high for unilateral hopping (dominant: $r = 0.942$; non-dominant: $r = 0.990$) and high for bilateral hopping ($r = 0.914$). Correspondingly, Bland–Altman
analyses revealed very tight limits of agreement (95% confidence interval) in leg stiffness for unilateral hopping (dominant: ±2.7 kN/m; non-dominant: ±1.7 kN/m) and tight limits of agreement for bilateral hopping (±5.0 kN/m; Table 2, Fig. 5). The inter-test differences were small (0.06–0.38 kN/m) which confirms that there was no systematic offset between the first and the second test for each condition (Table 2). Inter-test differences were not related to the magnitudes of the means.

4. Discussion

This study used a simple one-dimensional spring-mass model to compare estimates of leg stiffness during unilateral and bilateral hopping tasks. It is important to note that leg stiffness during hopping represents a complex interaction of muscles, tendons, ligaments, cartilage and bones to resist the applied force (Butler et al., 2003). While more complex models have been described (Nikoooyan & Zadpoor, 2011), this simple one-dimensional spring-mass model has been widely used because it requires minimal time, is easy to calculate, and has been shown to predict injury and performance outcomes in high intensity sports involving running and jumping (Chelly & Denis, 2001; Durand et al., 2010; Hobara et al., 2008). Leg stiffness values estimated during bilateral hopping in our investigation are in close agreement with those of previous studies, in which stiffness values ranging between 14.9 and 33.9 kN/m have been reported (Dalleau, Belli, Viale, Lacour, & Bourdin, 2004; Farley & Morgenroth, 1999; Granata et al., 2002; McLachlan et al., 2006; Watsford et al., 2010). Results of most previously published studies on leg stiffness, however, cannot be readily generalized because of their low

Table 2

Intra-day test–retest reliability of bilateral and unilateral leg stiffness. Pearson’s correlation coefficient, mean differences and 95% confidence interval (CI_{95%}) for the test–retest comparison are reported according to Bland and Altman (1986).

<table>
<thead>
<tr>
<th></th>
<th>Bilateral</th>
<th>Unilateral dominant leg</th>
<th>Unilateral non-dominant leg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pearson’s correlation coefficient (r)</td>
<td>0.914</td>
<td>0.942</td>
<td>0.990</td>
</tr>
<tr>
<td>Mean difference [kN/m]</td>
<td>–0.38</td>
<td>–0.18</td>
<td>–0.06</td>
</tr>
<tr>
<td>CI_{95%} of test differences (±1.96 * SD) [kN/m]</td>
<td>±5.00</td>
<td>±2.66</td>
<td>±1.74</td>
</tr>
</tbody>
</table>

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numbers of participants (Hobara et al., 2008, 2009; Kuitunen et al., 2002, 2011; Moritz & Farley, 2003). To the best of our knowledge, leg stiffness determined during unilateral hopping has been reported by only one other study, and our results are comparable (Watsford et al., 2010). While data of our study allows a more general analysis of bilateral and also unilateral leg stiffness, one should consider that the studied population only consisted of young healthy and physically active males. Despite the homogeneity of the analyzed population, inter-subject variability was unexpectedly high, especially in bilateral hopping, which likely reflects that bilateral hopping is a complex leg coordination task.

4.1. Limb dominance during unilateral hopping

The first research question addressed in this study was whether the magnitude and variability of unilateral leg stiffness differed between dominant and non-dominant limbs. The magnitude and variability of leg stiffness were similar for both legs during unilateral hoping indicating that laterality effects are negligible. One possible explanation for this somewhat unexpected finding is that, despite reported differences between dominant and non-dominant legs in other activities including drop landing and walking (Niu et al., 2011; Sadeghi et al., 2000), there is an optimal leg stiffness value for the required task (hopping at 2.2 Hz) for each subject and that the body actively adjusts leg stiffness accordingly. In support of this concept, Ferris, Liang, and Farley (1999) observed an immediate adjustment in leg stiffness in healthy adults in response to changes in the impact properties of the contact surface. This instantaneous adjustment was thought to reflect active muscle-tension control mechanisms. Similarly, Arampatzis, Schade, Walsh, and Brüggemann (2001) demonstrated that leg stiffness can be actively controlled through adjusting muscle tension and was tuned to an optimal value for different tasks. Thus, including muscle activity in future models may prove beneficial in identifying potential differences in mechanisms underlying the control of leg stiffness between dominant and non-dominant legs.

Another possible explanation for observing similar leg stiffness in dominant and non-dominant legs is that the demand of the unilateral hopping was not sufficiently intense to reveal laterality differences, similar to those reported during drop landings (Niu et al., 2011). Although there is evidence that the non-dominant leg has lower strength and is possibly less coordinated than the dominant leg (Jones & Bampouras, 2010), it is possible the relatively low demands of the hopping task used in this study may have allowed athletes to generate sufficient muscle tension to execute similar hopping movements in each leg. In contrast, drop landings from 30 to 50 cm height, as examined by Niu et al. (2011), presumably impose higher demands on each leg, hence revealing discrepancies between the biomechanics of the dominant and the non-dominant leg. Future analyses with more sophisticated models including muscle activity, more degrees of freedom or dampening may help to gain further insights into this phenomenon. Based on the findings of this study, we would expect muscle activity in the non-dominant leg to be greater than the dominant leg, while producing similar leg stiffness values.

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4.2. Leg stiffness during unilateral vs. bilateral hopping

The second research question in this study was to evaluate whether the magnitude and variability of leg stiffness differed between unilateral and bilateral hopping. The findings indicate that the magnitude and variability of leg stiffness, both within consecutive hops as well as between subjects, were lower for unilateral hopping when compared to bilateral hopping. We had hypothesized that leg stiffness would be lower during unilateral rather than bilateral hopping because the two legs effectively act as two parallel-arranged springs during bilateral hopping. Thus, in a passive system, the effective stiffness estimated during bilateral hopping would reflect the sum of the individual stiffness values of each limb. However, we also noted that unilateral hopping was characterized by lower peak vertical force compared to bilateral hopping while the maximum displacement remained unchanged. In addition, the ground contact time for unilateral hopping was longer than that for bilateral hopping confirming that ground contact time is strongly related to leg stiffness (Arampatzis et al., 2001; Morin, Samozino, Zameziati, & Belli, 2007). Adjustment of the spring-like behavior of the leg in response to soft or dampened surfaces which increase ground contact times has been previously reported (Ferris et al., 1999; Moritz & Farley, 2003). In such cases, it was hypothesized that leg stiffness was adjusted to maintain the movement of the body’s center of mass constant. Moritz and Farley (2003) concluded that the conservation of the body’s trajectory might be an important strategy in fast-paced locomotion on varying surfaces.

In our study, variability in leg stiffness between consecutive hops was lower for the non-dominant leg than for the bilateral condition. It is possible that unilateral hopping on the non-dominant leg is the most demanding of the three tasks with regards to coordination. Research of various motor tasks has shown that the association of variability and athletes’ skill level seems to be U-shaped, with high variability at low and high skill level (Schorer, Baker, Fath, & Jaitner, 2007; Wagner, Pfusterschmied, Klos, von Duvillard, & Müller, 2012; Wilson, Simpson, van Emmerik, & Hamill, 2008). According to this relationship, athletes in our study may have performed at a very high skill level for unilateral hopping on the dominant leg and for bilateral hopping characterized by higher variability referred to as functional variability (Wilson et al., 2008). In comparison, hopping on the non-dominant leg may still represent a sufficiently familiar task for our athletes that could be executed using an automated coordination pattern characterized by lower variability. However, the observed differences were small, and these possible explanations are speculative and should be addressed in future studies.

4.3. Relationship between leg stiffness during unilateral and bilateral hopping

The final aim of this study was to determine if bilateral leg stiffness is determined by unilateral leg stiffness. We found that leg stiffness during unilateral hopping accounted for 76% of the variance in leg stiffness during bilateral hopping. In addition, we observed that leg stiffness for hopping on the dominant and on the non-dominant leg were highly collinear and therefore not independent of each other in healthy physically active young male adults. Thus, even though leg stiffness during unilateral hopping differed from bilateral hopping, the general hopping coordination appears to be based on the same basic pattern. Hence, the results of this study suggest that findings from investigations on unilateral hopping allow the deduction of general or combined leg stiffness behavior.

The hopping test represents a simple procedure for determining bilateral and unilateral leg stiffness. Difficulties in performing the test were neither reported by the subjects nor observed by the investigator. The test required only a very short familiarization time prior to the actual testing. The high between-test reliability observed in the current study is in agreement with that reported by McLachlan et al. (2006) and suggests that potential learning or fatiguing effects can be minimized through the use of appropriate rest periods. Thus, in future testing, repeated testing does not seem necessary. This makes the hopping test even more attractive for use in different settings (e.g., clinical settings). Considering future applications of bilateral and/or unilateral hopping tests, we suggest that unilateral hopping is preferable over bilateral hopping because of the considerably lower variability between-subjects and higher test–retest reliability. In addition, many daily and athletic movements are executed with unilateral loading phases, and thus, unilateral leg stiffness tests may be more representative of these tasks than bilateral leg stiffness tests. Moreover, in contrast to bilateral hopping,
unilateral leg stiffness tests have the additional benefit of allowing detection of potential between-limb differences, and can be applied in research settings focusing on clinical, sports performance, or athletic equipment aspects. Keeping in mind that unilateral stiffness insights in this study are based on young and healthy populations, the unilateral hopping test may nevertheless be useful for evaluating the rehabilitation progress of athletes following unilateral lower limb injuries such as ACL-ruptures, ankle sprains or Achilles tendon injuries since a restoration of these injured structures is necessary to prevent re-injury. Furthermore, if leg stiffness indeed predicts the risk of injuries as previously reported by Butler et al. (2003) and Watsford et al. (2010), leg stiffness measurements should be included in standard test batteries for athletes to identify individuals at risk of injury. None-the-less, the findings of this study suggest that leg stiffness during bilateral hoping differs to that during unilateral hoping. Therefore, leg stiffness during unilateral hoping should not be directly compared to the literature on bilateral hoping. In the current study, leg stiffness during unilateral hoping was not influenced by limb dominance and was more consistent than that determined during bilateral hoping. It is recommended, therefore, that unilateral, rather than bilateral hopping be adopted as the standard test for leg stiffness in healthy populations.

Conflict of interest

The authors declare that there are no conflicts of interest.

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