Gender specific strategies in demanding hopping conditions

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Research article

Gender specific strategies in demanding hopping conditions

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Abstract
Difference in leg stiffness between females and males is considered to be a cause of higher rates of Anterior Cruciate Ligament injury in female athletes. Females are believed to have lower stiffness and as a consequence different recruitment strategies to adapt functional tasks. The aim of the current study was to evaluate how leg stiffness is tuned to demanding conditions. 22 healthy subjects (11 Male-11 Female; age: 20-43 years) participated in this study. Subjects performed two-legged hopping tasks (at their preferred rate, as fast as possible and with added mass of 10% bodyweight) on a force platform. Leg stiffness was calculated for each condition as the ratio between peak ground reaction force and vertical displacement of center of mass. In the preferred and added mass conditions males showed substantially higher leg stiffness than females (p= 0.006 and p = 0.002, respectively). When hopping as fast as possible the gender bias in leg stiffness disappeared (p = 0.880). Added mass had no significant effect on change in leg stiffness. Results have shown that females increased their leg stiffness more than males indicating they have no gender limiting capacity to reach objectives of higher demanding tasks (i.e.fastest hopping).The relationship between observed gender differences in leg stiffness and increased Anterior Cruciate Ligament injury rate in females requires further study.

Key words: Leg stiffness, frequency, added mass, hopping test.

Introduction

Female athletes are more vulnerable to sport injuries of lower extremity than their male counterparts. Commonly they have a higher risk of knee injuries including meniscal and cartilaginous tears, patellafemoral syndromes and Anterior Cruciate Ligament (ACL) injuries (Dugan, 2005). Four to eight times higher rates of ACL injury in female athletes compared to males have been reported by previous studies (Arent and Dick, 1995; Arent and Dick, 1999; Gwinn et al., 2000; Hutchinson and Ireland, 1995; Malone et al., 1993; Messina et al.,1999). These injuries limit the performance level and can be season or career ending; moreover they result in high health care costs for surgery and rehabilitation (Dugan, 2005).

The gender bias in ACL injury rates are believed to be partially explained by differences in physical and biological properties that result in different biomechanical behavior of this ligament and the knee joint in males and females (Griffin et al., 2000; Hewett et al., 2005). An important biomechanical factor is thought to be the stiffness of the leg during functional activities such as running, jumping and hopping. Leg stiffness is considered to be a regulated property of the neuromuscular system (Butler et al., 2003; Chelly and Dennis, 2001; Salsich and Mueller, 2000). These activities are general components of sports and it has been shown that during all these motions the leg behaves like a spring (Blickhan et al., 1989; Farley et al., 1998). Humans maintain this spring-like leg behavior and adjust their leg stiffness to different conditions of locomotion (i.e. hopping at different frequencies or heights, (Farley et al., 1991; Ferris et al., 1998), and running at different speeds and stride frequencies (Arampatsiz et al., 1999) and at different stride frequencies (Farley and Gonzales, 1996) to control the sinusoidal movement of the center of mass (COM).

Leg stiffness represents the average overall stiffness of the integrated musculoskeletal system including tendons, ligaments, muscles and bones during the ground contact phase of locomotion (Farley et al., 1998). Stiffness of leg is believed to considerably affect performance, functional ability and risk of injury in musculoskeletal structures of lower extremity (Butler et al., 2003; Chelly and Dennis, 2001; Salsich and Mueller, 2000). For example, muscle stiffness is required for efficient utilization of elastic energy during a stretch-shortening cycle (Butler et al., 2003; Latash and Zatsiorsky, 1993). Lower stiffness values allow for excessive joint motion, i.e. decreased stability of the knee, leading to soft tissue injury (Williams et al., 2004). It is known that females tend to have a lower leg stiffness compared to males during both static conditions (i.e. knee flexion/extension, Granata et al., 2002a) and functional tasks (i.e. hopping Padua et al., 2005). It may be one of the possible risk factors associated with the high rates of ACL injury in female athletes (Padua et al., 2005), especially during regulation of leg stiffness for increased demands of higher activity levels.

Leg stiffness can be modulated during functional loading conditions through different muscle activation and movement strategies. Farley and Morgenroth showed that leg stiffness is primarily adjusted via a combination of changes in ankle stiffness and knee angle excursion (Farley and Morgenroth, 1999). Padua et al. (2005) speculated that females use different stiffness recruitment strategies than males by means of quadriceps dominant and ankle dominant stiffness strategies which could lead ACL injury (Padua et al., 2005). This may be a reflection of the fact that women have a lower capacity to generate muscle stiffness (Granata et al. 2002a). Granata et al. (2002b) also proposed that differences in leg stiffness values of females and males might be related to the gender bias in risk for ACL injury and that women are limited in their capacity to generate sufficient muscle

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stiffness during functional hopping tasks.

Thus far, females' leg stiffness behavior in comparison to males has been studied under conditions close to their preferred hopping rate. To figure out whether women indeed are limited in their capacity to generate sufficient leg stiffness requires testing under more demanding conditions.

Further understanding on how males and females tune their leg stiffness in demanding conditions could help to design exercise prescriptions to protect female athletes from ACL injuries. Female-specific training programs could be improved for rehabilitation programs, particularly in conditions of maximal effort.

The aim of this study was to evaluate how leg stiffness is tuned to demanding conditions like adding mass or hopping as fast as possible. It was hypothesized that females would have lower leg stiffness than males across a broad range of hopping conditions.

Methods

Subjects

Eleven male and eleven female volunteers with no reported knee abnormalities or recent musculoskeletal injuries participated in this study. Also the subjects had neither history of surgery in their lower extremities nor neurological disorders. Subjects signed informed consent. They were recruited from students and staff of Maastricht University, Faculty of Health, Medicine and Life Sciences. Subject's descriptive statistics with respect to gender are included in Table 1.

Protocol for hopping test

To assess the effect of frequency and mass on leg stiffness, subjects were asked to hop in place with training shoes and with their hands on their hips in three different hopping conditions. First, participants hopped at their preferred frequency (PF) and subsequently at the fastest frequency (FF) that they were able to achieve. In addition they were asked to hop with added weight at their preferred hopping frequency (PFM). For this condition participants wore a custom-made weight vest containing 10% of their body mass. The preferred frequency in the loaded condition was not necessarily the same as the preferred frequency in the unloaded condition. Subjects were instructed to hop in a continuous motion and leave the ground between hops. The subjects were allowed as much practice as needed until they felt comfortable at the asked frequency.

Data collection

Measurements of leg stiffness were determined by requiring subjects to perform two-legged hopping on a force platform (Kistler 9281 A, natural frequency 1 KHz) vertical forces were sampled at 1000 Hz via an analogue to digital converter (12 bit, National Instruments). Each subject performed 5 hopping tests for each condition. Subjects put their feet on the middle area of the force platform. Then subjects hopped as the described above. When the subjects felt comfortable at the asked frequency, data was collected for 4 seconds for each hopping trial, which consisted of approximately eight hops. At the end of each hopping test, the subjects were allowed to rest for 1 minute. Thus, the first trial contained five times hopping at preferred frequency and 1 min. rest, and the second trial five times hopping at highest frequency and 1 min. rest and the last trial five times hopping at preferred frequency with added mass.

Table 1. Descriptive statistics of subjects. Data are means (±SD).

	Female	Male	Total
Body Weight (kg)	59.8 (8.0)	77.8 (3.9)	68.8 (11.1)
Height (m)	1.67 (.08)	1.83 (.06)	1.75 (.11)
Greater Trochanter Height (m)	.84 (.06)	.93 (.06)	.88 (.07)
Age (years)	23.7 (3.7)	27.6 (6.8)	25.7 (5.7)

Data analysis

Data was analyzed by custom-made software developed with MATLAB (version 6.5.1). First the vertical ground reaction force was filtered with a recursive Butterworth filter (4^{th} order, 50 Hz lowpass), to eliminate the influence of potential high frequency peaks in the data. The filtered vertical ground reaction forces traces were used to determine the peak forces, ground contact times and COM movements for each individual hop. Vertical displacement of COM was calculated using the following procedure. First the instantaneous acceleration of COM was calculated according to:

$$a = \frac{Fz - G}{m} \qquad \text{Equation 1}$$

In this equation a represents acceleration, Fz is the measured vertical component of that ground reaction force, G equals the weight of the subject and m the mass. Subsequently the vertical displacement of the COM (ΔL) was calculated from numerical integration of the acceleration data during the contact phase. Integration constants for velocity were based upon steady-state performance criteria wherein the mean vertical COM velocity is zero. Since the goal was to determine COM displacement, the integration constant for position was set arbitrarily to zero at touchdown. Leg stiffness (kleg) was defined as:

$$Kleg = \frac{Fpeak}{\Delta L} \qquad \text{Equation 2}$$

Contact time was defined as the time spent on the force platform from initial contact to take off. Hopping frequency was determined from the average number of hops per second during the trial. For each trial the average data for the first five hops were calculated and this data was used in the statistical analysis.

Statistical analyses

Statistical analyses were performed using the SPSS.11 for windows package. In this study a repeated measurements ANOVA was used to determine if there is a significant difference between adjusting leg stiffness for preferred hopping frequency, fastest hopping frequency and preferred hopping frequency with added weight. The three condition serve as a within subjects factor and gender as a between subjects factor. A LSD post-hoc test was performed to see if there was a significant difference between variables among conditions. An Unpaired T-Test was performed to evaluate possible differences in body weight, height, greater trochanter height from ground and age between male and female subjects. Statistical significance was set at $\alpha < 0.05$ for all analyses.

Results

Two subjects were excluded from analysis, as their dataset was incomplete. The data was analyzed for 10 female and 10 male subjects ranging in age from 20 to 43 years. Subjects exhibited significant gender differences in weight, height, greater trochanter height, but demonstrated no significant differences in age (Table 1).

Effect of different hopping conditions on leg stiffness

There was a significant effect of hopping condition on evaluated parameters (frequency, leg stiffness, force, vertical displacement). Especially, the high frequency hopping condition differed significantly from the preferred hopping and hopping with an added mass condition. There was no significant difference between the preferred hopping and the added mass condition.

At the high frequency hopping condition, the maximum frequency that subjects performed was twice as high compared to both other conditions (2.20 ± 0.26 Hz, 4.16 ± 0.56 Hz and 2.26 ± 0.40 Hz for PF, FF and PFM respectively). Leg stiffness was increased by a factor three in the high-frequency hopping compared to the both other hopping conditions (24.1 ± 9.94 kN·m^{-1}, 70.12 ± 22.0 kN·m^{-1} and 24.2± 10.7 kN·m^{-1}, for PF, FF and PFM respectively). The significant increase in frequency resulted in a significant reduction of the ground contact times (286 ± 42ms, 183 ± 23 ms and 300 ± 40ms, for PF, FF and PFM respectively) and a reduced peak ground reaction forces (2314 ± 603 N, 1844 ± 382 N and 2320 ± 556 N for PF, FF and PFM respectively). Likewise the vertical displacement of COM was four times smaller (0.107 ± 0.03m, 0.029 ± 0.02m, 0.112 ± 0.04m, for PF, FF and PFM respectively)

Effect of gender on leg stiffness

In preferred frequency and added weight hopping conditions leg stiffness differed significantly between men and women. In both conditions leg stiffness in men was approximately 1.5 times higher than in women. Frequency, ground contact time, vertical displacement of COM did not differ between males and females in any of the hopping conditions (Table 2).

Males had significantly greater peak ground reaction forces than females at all hopping conditions. When peak forces were normalized to body weights of subjects this significant difference disappeared and both sexes had almost similar values of peak forces (Table 2).

Discussion

The aim of the current study was to test if males and females react similarly to demanding conditions like hopping with additional mass attached to the body or hopping as fast as possible. Contrary to our initial hypothesis, that a difference in leg stiffness between males and females is maintained across all hopping conditions, it was found that the gender bias on leg stiffness disappears at the fastest hopping rate. Thus females appear to have no limitations to generate sufficient musculoskeletal stiffness when they are asked to perform at their maximum hopping rate. These results are in contrast with recent theories, which suggested that the lower capacity of women to generate muscle stiffness limits their leg stiffness during functional hopping tasks (Granata et al. 2002b). Interestingly, males and females chose similar hopping frequencies for each particular experimental condition (i.e. preferred, added mass and fast hopping), but it seems that there are distinct differences in how males and females regulate their leg stiffness in these tasks. In the preferred and added mass conditions males need substantially higher leg stiffness to attain the same hopping frequency, on the contrary, when hopping as fast as possible, the gender bias in leg stiffness disappeared.

The fact that males and females select similar frequencies when asked to hop at a comfortable self selected pace, irrespective of substantial differences in anthropometrics and leg stiffness has been found in several studies (Granata et al., 2002b). In this study both females and males attained hopping frequencies of approximately 2.20 Hz, similar to values reported by earlier others (Granata et al., 2002b; Heise et al., 2001). Granata et al. (2002b) proposed three possible explanations for the constancy of preferred hopping frequency. One possible explanation is that reflex delays, which are body mass independent, constrain the preferred hopping frequency. Heise et al. (2001) found that males activated their muscle earlier than females at preferred hopping frequency and had greater-stiffness values (Heise et al., 2001). On the other hand, previous studies of reflexive neuromuscular activation in response to landing and perturbation have found females to tend to activate quadriceps muscle earlier than males

Table 2. Gender effects on leg stiffness parameters for different hopping conditions. Values are means (± SD).

	Preferred Hopping		Fastest Hopping		Added Mass Hopping	
	Female	Male	Female	Male	Female	Male
Frequency (Hz)	2.07 (.18)	2.21 (.31)	4.19 (.65)	4.13 (.49)	2.04 (.23)	2.36 (.48)
Ground contact time (ms)	299 (46)	273 (33)	191 (27)	187 (18)	313 (41)	286 (35)
COM displacement (m)	11.5 (2.0)	9.80 (3.0)	2.70 (1.0)	2.90 (2.0)	12.7 (4.0)	9.6 (4.0)
Peak Force (N)	1986 (543)	2642 (483)*	1656 (263)	2033 (399)*	2038 (490)	2602 (485)**
Corrected Peak Force (N·kg^{-1})	34.0 (14.6)	33.9 (13.7)	27.7 (10.6)	25.5 (9.3)	34.1 (14..9)	33.4 (12..2)
Leg stiffness (kN·m^{-1})	18.3 (6.1)	29.9 (9.9)**	66.3 (21.2)	73.9 (22.5)	17.2 (6.2)	31.3 (9.9)**

* and ** denote significant ($p < 0.05$ and 0.01, respectively) gender effect by repeated measurements ANOVA with post-hoc test.
COM= Center of Mass.

(Huston and Wojtys 1996, Malinzak et al., 2001). Conversely, Medina et al. (2008) have shown that female and male athletes had the same recruitment patterns during drop landing (Medina et al., 2008). The data of the current study do not enable us to draw conclusions about the role of gender differences in reflex factors.

Alternative explanations include the inherent active muscle stiffness differences between genders and energy conservation mechanisms. With respect to the latter Granata et al. (2002b) argued that the preferred frequency of hopping is related to energy cost and that it should be independent of body mass. Assuming that the human musculoskeletal system behaves like a true spring-mass system, it would be expected that the preferred frequency coincides with the natural frequency of the system, according to equation $\omega^2 = k/2m$, where ω is the frequency of spring system, k is the stiffness of spring and m is the mass of system Conceptually, as the preferred frequency for females and males is similar, the lower leg stiffness in females could be explained by their lower body mass. Indeed, if leg stiffness is normalized for body mass the differences in leg stiffness between males and females disappear.

The argument for energy conservation may also explain why in the added mass condition subjects chose almost the same hopping frequencies as in the preferred hopping condition. In this case one would expect that leg stiffness is augmented to accommodate the increased mass. In contrast, it was found that both males and females maintained leg stiffness at the same level as in the preferred condition. It could be argued that amount added weight was not sufficient to produce any noticeable effects. However, in a similar type of experiment Austin et al. (2003) have used added weights of 10% and 20% of body weight and they still could not find any significant effect of added weights on vertical stiffness during hopping test. This suggests that the subjects alter their hopping strategy to deal with the extra mass. In accordance to Austin et al (2003), we have found an increase in ground contact time in the added weight condition although this effect was not significant. It appears that humans are capable of compensating added mass effects to maintain their leg stiffness and hopping frequency via modulation of the ground contact time. This adaptation strategy is used by both males and females to accommodate mass perturbations. Although differences in leg stiffness between males and females seem to be explained largely by differences in mass it should be noted that the underlying recruitment strategies are very different between males and females. It has been shown that during hopping at preferred rates females increase their quadriceps and soleus activation, while keeping the kinematics similar to males (Padua et al., 2005).

Males and females chose similar hopping frequencies when asked to hop as fast as possible. In this study we found that on average subjects could attain hopping frequencies of 4.16 Hz, which is about twice their preferred hopping frequency. Although the cycle time was reduced by half, the contact time reduced only by approximately one third (286 vs. 183 ms). This means that fast hopping is mostly achieved by reducing the aerial time and thus the hopping height. For fast hopping it is unlikely that energy conservation is the main objective. Instead the ability to generate force fast enough might be a more constraining factor, which might explain why contact time does not change linearly with hopping frequency. Hobara et al. (2007) have found that subjects enhance their muscle activity when instructed to hop with shorter contact times at the same frequency (Hobara et al., 2007). It could be argued that fast hopping rates requires higher muscle activity than preferred hopping rates. Granata et al. (2002a) has shown that women demonstrate considerably less muscle stiffness in open-chain measurements. It has been argued that the lower capacity of women to generate muscle stiffness can explain why they have lower leg stiffness during hopping tasks (Granata et al., 2002b). In contrast in this study it was found that the difference in leg stiffness between males and females disappears when hopping as fast as possible. Females clearly increased their leg stiffness more in comparison with males to attain similar fast hopping rates. This suggests that under functional tasks like hopping females have sufficient capacity to generate the required levels of muscle stiffness. Furthermore, based on these results it can be concluded that males and females have to deal with similar constraints during fast hopping.

In addition, Blickhan (1989) stated that the changes in stiffness with increasing frequencies are largely induced by leg kinematics and not by material properties. They observed that leg kinematics demonstrated maximum leg stiffness is acquired at maximum hopping frequency by letting the knee move 180 degree out of phase with the ankle (Blickhan, 1989). This can be a limiting property for fast hopping by means of changing leg kinematics for both females and males.

The question 'How females reacted different than males to adapt their leg stiffness to the fastest hopping frequency' is still unable to be answered by the results of this study information. Future studies, including EMG and 3D motion analyses and muscle strength assessments, are necessary to elucidate the contribution of individual joints and muscles to overall leg stiffness. Data from present study agreed with the previous studies by revealing females and males reacted differently to adapt their leg stiffness to different functional tasks. Distinctly, results have shown that females could increase their leg stiffness more than males indicating they are not limited in their capacity to reach objectives of higher demanding tasks (as fastest hopping). Higher incidence of ACL rupture in female athletes and its relation with leg stiffness behavior at highly demanding tasks is still unclear and requires further studies.

Conclusion

The results of this study showed that females reacted different than males to adapt their leg stiffness in condition of fastest hopping. There appears to be no limiting factor in the musculoskeletal system of females to recruit their leg stiffness as high as males under condition of maximum effort.

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Key points

- Leg stiffness is an adaptable property of neuro musculoskeletal system to different functional loading conditions.
- Females can increase their leg stiffness more than males indicating they have no gender limiting capacity to reach objectives of higher demanding tasks as fastest hopping.

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