Human Movement Science 40 (2015) 273–283

Contents lists available at ScienceDirect

Human Movement Science

journal homepage: www.elsevier.com/locate/humov

Leg and vertical stiffness (a)symmetry between dominant and non-dominant legs in young male runners

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ARTICLE INFO

Article history:

PsycINFO classification:
3720

Keywords:
Running
Leg stiffness
Vertical stiffness
Dominance
Asymmetry

ABSTRACT

Biomechanical findings show that running is asymmetric in many kinetic properties. Running stiffness is a vital kinetic property of yet unknown pattern of lateralization. The aim of this study was to examine the degree and variability of lower limb dominance specific asymmetry of running in terms of leg stiffness, vertical stiffness, contact time, flight time, maximal ground reaction force during contact, vertical displacement of the center of mass, and change in leg length. Leg and vertical stiffness was estimated by the sine-wave method in 22 young males during treadmill running at 4.44 m/s. Lower limb dominance was determined by the triple-jump test. Asymmetry was expressed as dominant – non-dominant, and indexed by the absolute asymmetry index. Significant asymmetry was found only in flight time (3.98%) and in maximal ground reaction force (1.75%). The absolute asymmetry index ranged from 1.8% to 6.4%, showed high variation between subjects (0–31.6%), and differentiated among the 7 analyzed variables. Leg and vertical stiffness in treadmill running of moderate pace (4.44 m/s) should be considered symmetric.

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http://dx.doi.org/10.1016/j.humov.2015.01.005
0167-9457/

1. Introduction

In traditional running mechanics the lower limb of the runner is modeled as a 'spring-mass' system specialized in storing and returning the elastic energy produced during the support phase (Blickhan, 1989; McMahon & Cheng, 1990). This system is used for the definition and measurement of leg and vertical stiffness (Morin, Dalleau, Kyrolainen, Jeannin, & Belli, 2005). Leg stiffness is assessed in running skills, in long jumping skills, and in linear vertical movements (Butler, Crowell, & Davis, 2003; McMahon & Cheng, 1990), while vertical stiffness is assessed in linear movements that occur in the vertical direction such as hopping and jumping (Farley & Gonzalez, 1996; McMahon & Cheng, 1990).

Stiffness in running is well related to performance (Arampatzis, Brüggemann, & Metzler, 1999; Farley, Glasheen, & McMahon, 1993; Günther & Blickhan, 2002; Kuitunen, Komi, & Kyrolainen, 2002) and to running economy (Dutto & Smith, 2002; Kerdok, Biewener, McMahon, Weyand, & Herr, 2002; McMahon & Cheng, 1990).

Lower limb stiffness is a critical factor of musculoskeletal function determined by the partial contributions of the muscles, tendons, ligaments, cartilage and bones involved (Latash & Zatsiorsky, 1993). A better understanding of leg stiffness would be beneficial for the development of injury prevention strategies (Hobara, Inoue, & Kanosue, 2013) as, according to Flanagan and Harrison (2007), stiffness imbalances between the lower limbs could be detrimental to performance or could increase the risk of injury.

In running, in particular, there is a tendency for preferential lateralization of the lower limbs and a follow-up impact on performance (Carpes, Mota, & Faria, 2010). This tendency may lead to asymmetries and trends of lateralization in joint-specific functional properties during running in male runners (Cavagna, 2006; Vagenas & Hoshizaki, 1991, 1992), but not in female runners (Brown, Zifchock, & Hillstrom, 2014). Yet, the potential connection of running asymmetry to injury was an early theory suggesting an asymmetric injury potential in running due to preexisting anatomical and kinematical asymmetries (Vagenas & Hoshizaki, 1992). This theory appears to be at least partially verified by various later studies investigating the connection between asymmetry and injury. For example, asymmetries in foot-support dynamics differentiate between injured (tibial stress fractures) and uninjured subjects, with asymmetry affecting the side of injury (Zifchock, Davis, & Hamill, 2006). In addition, an elevated hip internal rotation rom and peak tibial acceleration is observed on the injured side, with hip internal rotation rom and arch height index being elevated bilaterally in the injured runners (Zifchock, Davis, Higginson, McCaw, & Royer, 2008). However, when asymmetry is expresssed as a relative index, previously injured and never injured runners do not seem to differ (Zifchock et al., 2006, 2008). In that respect, a recent prospective study (Bredeweg, Buist, & Kluitenberg, 2013) revealed that the level of asymmetry in impact peak cannot predict the development of running related injuries and the observed differences in loading of the injured and noninjured side may be the result instead of the cause of injury.

Regarding stiffness the existing data are sparse and uncertain. Bachman, Heise, and Bressel (1999) found no significant directional (left vs. right) asymmetry in leg stiffness in runners, with this suggesting that symmetry in leg stiffness is a feature of forward running mechanics. Similarly, Brughelli, Cronin, Mendiguchia, Kinsella, and Nosaka (2010) found no significant directional asymmetry in leg and vertical stiffness during running in football players. Yet, when asymmetry was assessed as percent difference between the right and left leg in order to describe the relative imbalance between the lower limbs, leg and vertical stiffness asymmetries were estimated at 4.2% and 6.5%, respectively. Rumpf et al. (2014) reported 19.7% difference between the right and left side in leg vertical force, while Karamanidis, Arampatzis, and Bruggemann (2003) used the absolute asymmetry index (ASI) and found running asymmetries to range from 16.74% to 22.79% for flight time and from 4.96% to 8.05% for contact time. These conflicting results are possibly due to differences in defining asymmetry, in the methodology used, and in the parameter itself (Karamanidis et al., 2003). Regardless of these reasons, the above data suggest that revisiting the problem of stiffness in running is important in understanding the potential connection of lower extremity dominance to running injury.

Therefore, the aim of this study was to quantify and test the significance and variability of potential asymmetry in leg stiffness, vertical stiffness, and in related kinematic variables of running, using the dominant vs. non-dominant side imbalance as a functional laterality. It was hypothesized that the leg and vertical stiffness of the dominant leg would be greater than that of the non-dominant leg because of its higher strength and coordination abilities (Niu, Wang, He, Fan, & Zhao, 2011; Sadeghi, Allard, Prince, & Labelle, 2000). It was also hypothesized that there will be a significant variability among the asymmetry indexes of the analyzed variables.

2. Methods

2.1. Participants

The subjects were 22 physical education male students (age 22.48 ± 1.09 years, body mass 72.74 ± 8.96 Kg, height 1.77 ± 0.05 m, % body fat 12.27 ± 3.28). They were free of any lower limb injury for at least 6 months prior to testing. Their leg length was measured on each side as the distance between the great trochanter and the ground in a standing position (Morin et al., 2005); none of them exhibited any leg length asymmetry. According to the triple jump test (Risberg, Holm, & Ekeland, 1995) 12 participants had a right leg dominance (54.55%) and 10 a left leg dominance (45.45%). Prior to participation each subject signed an informed consent based on appropriate academic approval of the ethical acceptability of the study.

2.2. Experimental procedures

Prior to data collection participants attended a session of familiarization with the testing procedures. Their height, body mass, and percent body fat were measured. A Technogym Runrace 1200 (Gambettola, Italy) treadmill was used for all running tests, following a 5-min warm-up and familiarization with treadmill running at a speed of 2.22 m/s.

Each participant ran on a treadmill for 30 s at the sub-maximal constant speed of 4.44 m/s using the preferred step length and frequency. This speed was chosen as an average one, considering the range of running speeds (3.33 up to 6.67 m/s) used in previous studies (Morin et al., 2005). To secure the submaximal speed of 4.44 m/s each participant performed a 1 min treadmill run at 5.55 m/s.

A total of 20 consecutive steps were recorded for each participant. Flight and contact times were measured by a Casio EX-F1 (Tokyo, Japan) high speed video camera placed behind the treadmill (1 m) perpendicular to the frontal plane of the runner at a height of 40 cm. The frame rate was set at 300 Hz, the shutter speed at 1/1250 s and the zoom was adjusted to obtain a limited area of shoe-treadmill contact (field of view 40 × 30 cm). An almost perfect intra-analyzer reliability (ICC = 0.999) was obtained by repeating the analysis of 10 consecutive steps (contact time and flight time) of the same participant three times by the same analyzer with weekly intervals.

To test the effects of fluctuating asymmetry (dominant vs. non-dominant), calculations were made by averaging 10 consecutive steps for each tested leg separately (Morin et al., 2005). Recording several consecutive foot strikes is optimal in assessing running asymmetry for variables of high within-limb variability (Zifchock & Davis, 2008), as opposed to non-consecutive foot strikes, which has been considered insufficient in quantifying asymmetry (Vagenas & Hoshizaki, 1989; Zifchock et al., 2006).

Mean values were computed by averaging the corresponding values of the 10 consecutive steps for each of the following variables: vertical stiffness, leg stiffness, contact time, flight time, maximal ground reaction force (F_{max}), vertical displacement of the center of mass (Δy), change in leg length (ΔL).

2.3. Data processing and calculation of stiffness

The spring-mass model (Blickhan, 1989; McMahon & Cheng, 1990) was used to examine the main mechanical parameters that characterized the behavior of the lower limbs during running. Two important assumptions of this model are that (i) the leg length at the moment of ground contact is equal to the initial (standing) length and (ii) the horizontal motion and displacement of the COM are equivalent before and after mid-stance. Based on this model, Morin et al. (2005) proposed the "sine-wave" method in order to calculate leg and vertical stiffness. According to this method, the force curve during contact can be fitted with a simple sine function (Alexander, 1989). These assumptions added together may affect the accuracy of the estimations and the values of leg and vertical stiffness may differ from the absolute values. Morin et al. (2005) validated the sine wave method and reported low bias (0.12–6%) compared with reference values from a force plate. Additionally, Coleman, Cannavan, Horne, and Blazevich (2012) compared several mathematical models with a 'gold standard' that was based on direct kinematic and kinetic measurements and found that the sine-wave method provided values closest to the gold standard model (5% mean difference; intra-class correlation coefficient (ICC) = 0.901), suggesting the sine-wave method as the most appropriate method despite its simplicity. Moreover the authors proposed a correction factor (1.0496 K) that could improve the accuracy of the method. Finally, it has been indicated that the measurements of leg and vertical stiffness obtained during treadmill running by using the sine-wave method are highly reliable for both intra-day (ICCs: 0.982 and 0.972 for leg and vertical stiffness respectively) and inter-day (ICCs: 0.873 and 0.922 for leg and vertical stiffness respectively) designs (Pappas, Paradisis, Tsolakis, Smirniotou, & Morin, 2014).

The Quintic Biomechanics v21 (Sutton, UK) software was used for the analysis of all video recorded steps. Contact and flight times were obtained according to regular procedures (Ogueta-Alday, Morante, Rodríguez-Marroyo, & García-López, 2013). A total of 10 consecutive steps of each leg were video-analyzed. The 10-steps average values for contact and flight times were then used for the estimation of vertical and leg stiffness, according to the sine-wave method equations:

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

$$F_{\max} = mg\frac{\pi}{2}\left(\frac{t_{\mathrm{f}}}{t_{\mathrm{c}}} + 1\right) \quad (2)$$

$$\Delta y = -\frac{F_{\max} t_{\mathrm{c}}^2}{m\pi^2} + g\frac{t_{\mathrm{c}}^2}{8} \quad (3)$$

$$K_{leg} = \frac{F_{\max}}{\Delta L} \quad (4)$$

$$\Delta L = L - \sqrt{L^2 - \left(\frac{vt_{\mathrm{c}}}{2}\right)^2} + \Delta y \quad (5)$$

where $F_{\max}$ is the maximal ground reaction force during contact, Δy is the vertical displacement of the COM, m is the body mass, t_{f} is the flight time, t_{c} is the contact time, ΔL is the leg length variation, and L is the resting leg length (great trochanter to ground distance in a standing position).

Finally, we calculated the progression of error induced by Morin et al. (2005) model of leg and vertical stiffness.

2.4. Determining leg dominance and quantifying asymmetry

There is a lack of consensus in the relevant literature on how to define skill-specific lateral dominance. Leg dominant can be determined according to a variety of criteria, such as strength, functional use, personal preference, or performance in specific skills (Hoffman, Schrader, Applegate, & Koceja, 1998). Early studies defined leg dominance by the kicking leg, the pushing-off leg in jumping skills (Damholt & Termansen, 1978), the preferred push-off leg in long or vertical jumping, and by the one-leg vertical jump test on a platform (Vagenas & Hoshizaki, 1986). Alternatively, the single-legged hop for distance (Noyes, Barber, & Mangine, 1991) and the triple jump (Risberg et al., 1995) tests are often used for the examination of functional laterality in the lower limbs (Logerstedt et al., 2012; Risberg et al., 1995). In the present study the major mechanical property under investigation was stiffness estimated on the basis of the spring mass model. The triple-jump test was chosen for the determination of leg dominance relevant to functional laterality, as single leg hoping and running use similar mechanics that mimic the spring mass model (Ferris & Farley, 1997). This test required each subject starting from a standing position on both legs to firstly jump as far as possible onto the right leg, then to jump again from and onto the right leg, and thirdly jump from the right leg to both legs. The same procedure was applied to the left leg. Each subject performed 2 trials on each leg. The leg (left, right) that resulted in the larger distance jumped (cm) in both trials was assessed as the running-specific dominant in terms of functionality. All subjects were consistent in terms of performing asymmetrically in this test. According to Risberg et al. (1995) the triple-jump test has high test–retest reliability (0.81–0.97) and a very low variation (Coefficient of Variation: 2.1–3.8%).

Asymmetry was calculated as fluctuating (dominant vs. non-dominant), and as percent absolute using the absolute (%) asymmetry index ($ASI = 2|L - R|/[L + R]$) (Karamanidis et al., 2003). This index is a modification of the symmetry index $SI = 2(L - R)/(L + R)$ initially proposed by Robinson, Herzog, and Nigg (1987). It protects the data from directional bias, thus providing an estimate of "laterality free" (absolute) asymmetry as percentage of total (both-sides) value. Even though this index tends to calculate higher in general values of % asymmetry (Sadeghi et al., 2000), as it uses the average of both sides ($0.5[L + R]$), we choose it against the Index of Asymmetry $Ia = |L - R|/\max(L, R)$ initially proposed by Vagenas and Hoshizaki (1992) and later used in other studies (Carpes et al., 2010; Sadeghi et al., 2000), as this index produces rather conservative estimates of asymmetries.

2.5. Statistical analysis

The 7 dependent variables were statistically described as means, standard deviations, and percent asymmetries (%). Paired sample *t*-tests were used to test the significance of asymmetry in each dependent variable (difference between dominant and non-dominant side). The raw data were checked for normality using the Shapiro–Wilk test as sample size was <50. With the exception of the Δy of the dominant leg all the other dependent variables were normally distributed. All statistical analyses were performed in SPSS21 and significances were tested at the $\alpha = 0.05$ probability of type I error.

3. Results

Means, standard deviations and percent asymmetries are presented in Table 1. The statistical analysis revealed only two significant dominant – non-dominant asymmetries: flight time ($t_{(21)} = 3.952$, $p = .001$) and F_{max} ($t_{(21)} = 5.626$, $p = .000$). Asymmetry was not significant in any of the other five variables: contact time ($t_{(21)} = -1.119$, $p = .276$), Δy ($t_{(21)} = 1.247$, $p = .226$), ΔL ($t_{(21)} = -0.358$, $p = .724$), vertical stiffness ($t_{(21)} = -0.285$, $p = .778$), leg stiffness ($t_{(21)} = 1.614$, $p = .121$), step rate ($t_{(21)} = -1.236$, $p = .230$).

Table 1
Descriptive statistics (Mean ± SD) for the fluctuating (dominant vs. non-dominant) asymmetries of the lower limbs.

Variable	Dominant	Non-dominant	Δ%
K_{vert} (kNm^{-1} kg^{-1})	32.861 ± 4.342	32.999 ± 4.605	0.417
K_{vertC} (kNm^{-1} kg^{-1})	34.491 ± 4.557	34.635 ± 4.833	0.417
K_{leg} (kNm^{-1} kg^{-1})	9.952 ± 2.058	9.721 ± 2.117	−2.318
K_{legC} (kNm^{-1} kg^{-1})	10.445 ± 2.160	10.203 ± 2.222	−2.318
t_c (s)	0.208 ± 0.020	0.210 ± 0.019	0.851
t_f (s)	0.127 ± 0.029	0.122 ± 0.031*	−3.984
F_{max} (kN)	1.807 ± 0.233	1.775 ± 0.234*	−1.753
Δy (m)	0.055 ± 0.007	0.054 ± 0.006	−2.140
ΔL (m)	0.186 ± 0.028	0.187 ± 0.024	0.590

K_{vert} = vertical stiffness, K_{vertC} = vertical stiffness corrected values according to Coleman et al. (2012), K_{leg} = leg stiffness, K_{vertC} = leg stiffness corrected values according to Coleman et al. (2012), t_c = contact time, t_f = flight time, F_{max} = maximal ground reaction force during contact, Δy = vertical displacement of the center of mass, ΔL = change in leg length, Δ% = percent difference between dominant and non-dominant leg.

* Significant different from dominant ($p < .05$).

Table 2
Descriptive statistics (mean ± SD) of the % absolute asymmetry index (ASI) for the 7 parameters.

Variable	ASI%
t_c	2.83 ± 2.02
t_f	5.64 ± 6.58
F_{max}	1.81 ± 1.59
Δy	5.90 ± 4.73
ΔL	5.80 ± 4.11
K_{vert}	5.59 ± 3.93
K_{leg}	6.38 ± 4.43

K_{vert} = vertical stiffness, K_{leg} = leg stiffness, t_c = contact time, t_f = flight time, F_{max} = maximal ground reaction force during contact, Δy = vertical displacement of the center of mass, ΔL = change in leg length.

Percent asymmetry (ASI) values for all depended variables are given in Table 2. Lowest mean ASI values were observed for F_{max} (1.81%) and contact time (2.83%), and greatest for leg stiffness (6.38%), Δy (5.90%), ΔL (5.80%), and vertical stiffness (5.59%). Additionally, inter-subject variability in ASI varied among the 7 variables. Two of the variables showed a rather high range of variability in ASI: flight time (0.00–31.58%) and Δy (0.21–17.45%). Lower variability in ASI was found for the rest of the variables: 0.42–6.48% for contact time, 0.25–7.14% for F_{max}, from 0.41% to 12.15% for vertical stiffness, from 0.18% to 13.33% for ΔL, and 0.72–14.09% for leg stiffness.

Additionally, we calculated the progression of error in Morin et al. (2005) formulas of stiffness on each subject and side (leg). We estimated the total absolute error (maximum possible) and the total statistical (limits) error (most probable): For F_{max} the error was possibly as large as 0.0157 + 0.0028 = 0.0185 kN (0.9%), but probably not larger than 0.0107 + 0.0017 = 0.0124 kN (0.6%). For Δy the error was possibly as large as 0.007 + 0.001 = 0.008 m (4.5%), but probably not larger than 0.006 + 0.001 = 0.007 m (3.9%). For ΔL the error was possibly as large as 0.01 + 0.001 = 0.011 m (3.6%), but probably not larger than 0.008 + 0.001 = 0.0091 m (2.7%). For vertical stiffness the error was possibly as large as 0.6066 + 0.1549 = 0.7605 $kNm^{-1}\,kg^{-1}$ (5.4%), but probably not larger than 0.5174 + 0.1314 = 0.6488 $kNm^{-1}\,kg^{-1}$ (4.6%). Finally, for leg stiffness the error was possibly as large as 0.2883 + 0.0833 = 0.3716 $kNm^{-1}\,kg^{-1}$ (4.4%), but probably not larger than 0.2385 + 0.0688 = 0.3073 $kNm^{-1}\,kg^{-1}$ (3.7%). In light of these error estimates, it cannot be excluded that some of the stiffness asymmetry estimates are within the range of probable error. This means that for some of the 22 subjects tested in the present study a partial overlap between probable error and asymmetry estimates occurs as a result of using Morin et al. (2005) sine-wave method to estimate stiffness. Obviously, this holds for the mean (%) asymmetry estimates, thus introducing some degree of uncertainty regarding the lack of statistical significance for stiffness asymmetries.

4. Discussion

4.1. Lower limb dominance and stiffness symmetry

One of this study's major objectives was to quantify and test the significance of potential asymmetry in leg and vertical stiffness in running. The results clearly showed that no significant influence of lower limb dominance on leg and vertical stiffness in treadmill running at moderate pace (4.44 m/s).

These results agree with previous studies which examined the difference between unilateral calculations and showed no significant influence of leg sidedness on vertical and leg stiffness in running at 3.5 m/s and 5.3 m/s (Bachman et al., 1999) and at 80% of the maximum running speed (Brughelli et al., 2010).

The results also agree with previous ones showing no significant difference between dominant and no-dominant legs in vertical stiffness in cyclical rebound jumping tasks (Flanagan & Harrison, 2007), in unilateral hoping tasks at 2.2 Hz (Brauner, Sterzing, Wulf, & Horstmann, 2014), and in unilateral hoping tasks at 1.5, 2.2 and 3.0 Hz (Hobara et al., 2013). In addition, in the study of Dalleau, Belli, Bourdin, and Lacour (1998) stiffness did not differ significantly between legs in a 4-min treadmill run at a velocity corresponding to 90% of VO_{2max}.

The absence of any significant asymmetry in vertical and leg stiffness in treadmill running is explained by the high capability of runners to adapt vertical and leg stiffness to changes in the speed of running (Farley et al., 1993; McMahon & Cheng, 1990), step rate (Farley & Gonzalez, 1996), in contact time (Morin, Samozino, Zameziati, & Belli, 2007), and in the type of running surface (Kerdok et al., 2002). This adaptability may result to the conservation of an optimal stiffness level during running, which, in turn, minimizes any contralateral differences possibly due to changes in the level of muscle activation (Arampatzis, Schade, Walsh, & Brüggemann, 2001) and/or to adjustments in the geometry of the lower limbs (Farley, Houdijk, Van Strien, & Louie, 1998).

Previous studies assumed gait symmetry for simplicity in data collection and analysis (Apkarian, Naumann, & Cairns, 1989; Hobara et al., 2010; Yang & Winter, 1985). On the other hand Karamanidis et al. (2003) and Brauner et al. (2014) have test asymmetry in lower limbs and concluded that recording a single unilateral trial would provide reproducible and symmetric values for most kinematic parameters. Thus, considering all the above, it appears that stiffness estimates in running are symmetric.

4.2. Kinetic, kinematic asymmetries, and stiffness

The second objective of this study was to revisit the traditional problem of lower limb kinematic and kinetic asymmetry in running. According to the results, the dominant leg produced significantly higher F_{max} and flight time than the contralateral leg.

These results are in agreement with those of Dalleau et al. (1998) suggesting significant force production asymmetry leading to a distinct mechanical role for each leg: one leg is propulsive (exerts higher forces in order to propel the runner faster and higher) and the other is supportive (presents a smaller flexion–extension action during stance, stick leg). Early theory by Sadeghi, Allard, and Duhaime (1997) suggested that the propulsive leg is more power generating, whereas the supportive is more power absorbing. In the present study the dominant leg was determined by the triple jump test as the powerful and propulsive one and this was expressed in the asymmetrical behavior of the legs in maximal force and in flight time. On the other hand, the disagreement of these results with those of Brown et al. (2014), who found no kinematic nor kinetic asymmetry between the kicking and non-kicking leg in female runners, are due to differences in the methodology (sex, speed of running, and method of defining the dominant leg).

It appears that the runner's body comprises a rather complex locomotor system. The dynamics of this system are simplified and described in terms of vertical and leg stiffness on the basis of the spring-mass model. This model represents the elasticity of the entire musculoskeletal system and includes muscles, tendons, and ligaments acting across joints (Alexander & Vernon, 1975). Thus, vertical and leg stiffness is produced by the activation of both elastic and contractile components. The number of attached cross-bridges grossly determines the stiffness properties of the contracting fibers (Julian & Sollins, 1975). The attached cross-bridges of the active muscles and the parallel and series elastic components can be stretched and recoil; during stretching elastic energy is stored and during recoil the stored energy is reused. The stiffness of the series elastic component of muscles is mainly determined by the cross-bridge and tendon stiffness (Alexander & Vernon, 1975; Shorten, 1987), but its modulation is controlled by neuromuscular activation factors (Shorten, 1987). This appears to be true in running, where proper spinal reflexes maintain stiffness nearly constant regardless of force changes (McMahon, 1984; Taylor, 1985), which is in agreement with findings from animal studies (Hoffer & Andreassen, 1981). This is probably the intra limb compensation strategy, which regulates lower limb stiffness (Hobara, Inoue, Kato, & Kanosue, 2011). Thus, asymmetry in F_{max} and flight time found in the 22 male runners examined in the present study was not expressed in their vertical and leg stiffness, due to these intra-limb compensatory mechanisms that selectively regulated these variables at the inter-joint coordination phase. These intra-limb compensations secure running to be as symmetrical as possible in spite of the asymmetrical stimuli of the running environment and the anatomical and functional asymmetries observed in the lower limbs of runners in general (Vagenas & Hoshizaki, 1988, 1992). Thus the symmetry of lower limb stiffness found in male runners may be due to neuromuscular mechanisms responsible for the integrity of the musculoskeletal system.

4.3. Variability in kinetic and kinematic asymmetries

Another objective of this study was to quantify and examine the variability in kinematic and kinetic asymmetry of treadmill running by using the ASI index. Percent asymmetry was found to be very low (ASI $\leqslant$ 2.83%) for F_{max} and contact time and rather low (ASI $\leqslant$ 6.38%) for flight time, Δy, ΔL, leg stiffness and vertical stiffness. Karamanidis et al. (2003) found similar low asymmetries for the linear and angular displacement parameters and the contact times (ASI for most data <8%), higher asymmetries for angular and linear velocity and flight times (ASI > 15%); they also found high percent variability of asymmetry between kinematic parameters (ASI from 3.0% in knee angle at touchdown to 53.8% in hip velocity). High ASI values were also found by Korhonen et al. (2010) in maximum speed running in kinetic and spatio-temporal parameters ranging from 2.7% to 14.3% in a group of young runners, and from 2.2% to 18.8% in a group of older runners. The higher relative asymmetry values found in these studies compared to our results might be attributable to the different running conditions, since an increase in running speed improves kinetic symmetry at take-off, but does not improve kinematic symmetry (Carpes et al., 2010; Zifchock et al., 2006).

High variability of asymmetry between kinetic variables in running has also been found to range from 3.9% (peak vertical force) to 28.3% (mediolateral force) in the study of Williams, Cavanagh, and Ziff (1987). To the contrary, Divert, Baur, Mornieux, Mayer, and Belli (2005) found very low asymmetry (SI < 2%) in leg and vertical stiffness and in related mechanical parameters during shoe and barefoot running. However, variables with relatively low values tend to have a much greater asymmetry index since small absolute variations could produce large relative variations.

Overall, a trend is evident for the variability in relative running asymmetry to be specific to the kinetic or kinematic parameter under assessment. Considerable differences were found in the present study between some of the variables in terms of % asymmetry values. These differences are in agreement with those of Rumpf et al. (2014) who showed that asymmetries in vertical force (19.7%) and mechanical work (19.5%) are significantly greater than those of the horizontal force (15%) in a 30 meters sprint on non-motorized force treadmill.

Considering the increased risk of injury when asymmetries exceed the empirical 10% level (McElveen, Riemann, & Davies, 2010; Noyes et al., 1991), the percent asymmetries (ASI) found in the present study may not constitute a risk provoking condition as they were smaller than 10%. Exceptions such as the 32% asymmetry found in flight time may suggest preventive analysis and assessment of the lower limb kinematic and/or kinetic asymmetry at the individual runner level (Rumpf et al., 2014).

4.4. Limitations and recommendations

Studies have shown significant asymmetry in various biomechanical parameters (Karamanidis et al., 2003; Vagenas & Hoshizaki, 1992) and the symmetry vs. asymmetry problem in running depends on several environmental and technical factors. According to Vagenas and Hoshizaki (1992) the running shoes may significantly decrease the degree of rear foot asymmetry compared to barefoot running, as the shoes appear to alter each foot's approach pattern and contact time. In addition other limiting factors that must be considered when interpreting running asymmetries are related to the running environment as well as to gender, age, anthropometric and musculoskeletal asymmetries (Vagenas & Hoshizaki, 1992).

Another factor that could affect lower limb asymmetry is training experience. According to Cavanagh, Pollock, and Landa (1977) there is a relationship between running asymmetry and time of practice, showing that the experienced athletes adopt more "symmetric" running pattern than the simply good runners. Running speed is also a potential limiting factor, as it appears to influence kinetic symmetry at take-off (Carpes et al., 2010). Considering the above limitations, future studies may be based on a more appropriate sample for the investigation of lower limb stiffness in running, for example by including a group of males purposely selected for their high degree of asymmetries, preferably from both sexes. This will clarify the possibility that runners possessing higher lower limb asymmetries may also possess some degree of asymmetry in stiffness too.

Finally, it is possible that, for some of the subjects of the present sample, percent asymmetries in both estimates of stiffness are within the estimated probable error as presented in the results section. Overall, the mechanical simplifications are necessary because the complexity of the mechanics of running makes any totally accurate macroscopic approach impossible, and these limitations are surpassed by the data and analyses that are made available by the use of the spring mass model. However, the addition of the assumptions of the spring mass model to the postulates of the sine wave method might have led to an oversimplified model for stiffness calculations during running, and this possibility must be considered. Such oversimplification would most likely result in a lack of sensitivity of the method.

5. Conclusions

On the basis of the present results the following conclusions can be drawn and interpreted within the limitations described above. First, there is strong indication that leg and vertical stiffness are symmetrical biomechanical traits of physically active males running on the treadmill at moderate speeds. Secondly, for the particular set of seven biomechanical parameters of running only maximum vertical force and flight time presented significant asymmetry between the dominant and non-dominant leg. Thirdly, percent asymmetry (ASI) and its variability among the seven biomechanical parameters of running were rather small. And, lastly, the possibility that different samples and experimental conditions may produce different levels of asymmetries must not be excluded, and this must be taken into consideration in future studies of this content and scope.

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