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Bilateral asymmetries and sex differences in the kinematics of running gait cycle of a group of Andalusian recreational runners
Asimetrías y diferencias por sexo en la cinemática del ciclo de carrera en un grupo de corredores recreativos andaluces

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Abstract. Running gait cycle begins when one foot comes in contact with the ground and ends when the same foot contacts the ground again. In a running gait cycle each lower limb has a stance phase and a swing phase. During the stance phase eversion of the subtalar joint is one of the mechanisms used to absorb impact forces. However, excessive rearfoot eversion may contribute to overuse running injuries of the lower limb. It is necessary to provide additional insight on sex differences or differences between dominant and non-dominant limbs in the different phases of the running gait cycle, as well as in the movements of the subtalar joint in the coronal plane. Therefore, the aim of the current study was to determine bilateral asymmetries, sex differences and peak eversion angle in the running gait cycle of recreational runners. 20 recreational runners aged 20 – 28 years (10 males and 10 females) were recorded on a treadmill at a running speed between 11 km/h and 12 km/h with high speed camera at 300 Hz. Males and females showed no significant differences between limbs in any of the variables of interest, indicating no bilateral asymmetries in running gait cycle. Female runners demonstrated a greater time to peak eversion than male runners (36.92 ± 5.79% vs 26.37 ± 5.12%, $p < .01$) and this may be related to some overuse running injuries that are more prevalent in females. The data obtained in this study may serve as a useful reference for future research.
Key words: Running gait cycle, stance phase, swing phase, subtalar joint, eversion.

Resumen. Un ciclo de carrera comienza cuando un pie contacta con el suelo y termina cuando el mismo pie contacta con el suelo de forma consecutiva. En un ciclo de carrera cada extremidad inferior tiene una fase de apoyo y una fase de vuelo. Durante la fase de apoyo la pronación de la articulación subastragalina es uno de los mecanismos para absorber las fuerzas de impacto. Sin embargo, una excesiva pronación puede predisponer a lesiones por sobreuso de la extremidad inferior. Son necesarias investigaciones adicionales sobre las diferencias por sexos y las asimetrías en las diferentes fases del ciclo de carrera, así como en los movimientos de la articulación subastragalina. Por tanto, el propósito del presente estudio fue determinar las asimetrías, las diferencias por sexos y la máxima pronación en un ciclo de carrera de corredores recreativos. 20 corredores recreativos de entre 20 y 28 años (10 hombres y 10 mujeres) fueron grabados corriendo en tapiz rodante entre 11 km/h y 12 km/h con una cámara de alta velocidad a 300 Hz. No existieron asimetrías en el ciclo de carrera pues no se encontraron diferencias significativas entre la pierna dominante y la no dominante en ninguna variable. La máxima pronación fue más tardía en mujeres que en hombres (36.92 ± 5.79% vs 26.37 ± 5.12%, $p < .01$), lo que puede estar relacionado con la mayor prevalencia de ciertas lesiones de la extremidad inferior en mujeres. Los resultados obtenidos en este estudio pueden servir de referencia para futuras investigaciones.
Palabras clave: ciclo de carrera, fase de apoyo, fase de vuelo, articulación subastragalina, pronación.

Introduction

In the last decades running has increased in popularity becoming one of the most important recreational activities (Aminaka, Arthur, Porcari, Foster, Cress, & Hahn, 2018; De Wit, De Clercq, & Aerts, 2000; Fernández & Rojano, 2020; Taunton, Ryan, Clement, McKenzie, Lloyd-Smith, & Zumbo, 2002). The rapid increase in the number of runners has led to an explosion of research and assessment (Novacheck, 1998). The health benefits attributed to running include stress and obesity reduction and an improvement in cardiovascular and mental health (Fernández & Rojano, 2020; Lohman, Balan Sackiriyas, & Swen, 2011; Taunton, et al., 2002).

A gait cycle can be defined as the time interval between two successive occurrences of one of the repetitive events of walking or running, usually the impact of one foot with the ground (Cámara, 2011; Kharb, Saini, Jain, & Dhiman; 2011). In a running gait cycle each lower limb has a stance phase (contact with the ground) and a swing phase and there are two float

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phases where both lower extremities are not in contact with the ground (Nicola & Jewison, 2012; Novacheck, 1998). The two float phases are called «early swing or float» and «late swing or float» by Lohman et al. (2011).

The duration of the stance phase and the float phase varies with speed. As speed increases the stance phase becomes shorter and the swing phase longer (Deflandre, Schwartz, Weerts, Croisier, & Bury, 2016; De Wit, et al., 2000; Kharb, et al., 2011; Muñoz, García, Soto, & Latorre, 2018; Nicola & Jewison, 2012; Novacheck, 1998; Rubinstein, et al., 2017; Smith & Hanley, 2013). Thus, in running, typical swing times contribute between 64 and 78% of the running gait cycle's duration, dependent on speed (Lohman, et al., 2011; Novacheck, 1998; Smith & Hanley, 2013).

Despite its benefits, running is also associated with a higher risk of overuse injuries than other aerobic activities (Ferber, Sheerin, & Kendall, 2009; Francis, Whatman, Sheerin, Hume, & Johnson, 2018). One of the most analyzed kinematic variables in previous literature due to its association with running related injuries is peak rearfoot eversion angle (Fernández & Rojano, 2020). During the stance phase of a running gait cycle the subtalar joint moves in a triaxial plane, contributing to the motions of pronation and supination. In the coronal plane, internal rotation of the calcaneus is called eversion (Fucci, Benigni, & Formasari, 2003; Kapandji, 2004) and is one of the mechanisms used to absorb impact ground reaction forces (Jiménez, 2004; Nilsson & Thortensson, 1989; Novacheck, 1998; Perry & Lafortune, 1995). However, excessive rearfoot eversion may be a contributing biomechanical factor to overuse running injuries of the lower limb (Ferber, Sheerin, & Kendall, 2009; Hreljac, 2004; Milner, Hamill, & Davis, 2010; Munteanu & Barton, 2011; Novacheck, 1998; Rodal, García, & Arufe, 2013).

Hreljac (2004) affirms that pronation is detrimental to a runner only if it falls outside normal physiological limits and if it continues beyond midstance. After midstance, it is necessary for the foot to become more rigid in preparation of toe-off (Hreljac, 2004). In the same line of thought, Fernández and Rojano (2020) suggest that maybe it is not peak eversion angle but eversion later in stance the biomechanical factor related to running injuries.

To date, kinetic asymmetries in runners have been extensively studied and there are a wide number of investigations trying to establish a relationship between asymmetries in ground reaction forces and risk of injuries of the lower extremities (Carpes, Mota, & Faria, 2010). In the review carried out by Carpes et al. (2010) only a few studies analyzed asymmetries in kinematic variables during running with contradictory results (Carpes, et al., 2010). A more recent study (Gilgen-Ammann, Taube, & Wyss, 2017) analyzed gait asymmetries in ground contact time in well-trained runners and found differences in gait asymmetry index between injured and non-injured groups. However, those differences were only found in short-distance running. To our knowledge, the only study that really analyzed the possible relationships between kinematic asymmetries in the stride cycle and the prevalence of injury (Haugen, Danielsen, McGhie, Sandbakk, & Ettema, 2018) was, similarly, carried out during maximal sprints.

Sex differences in running injuries and running mechanics have also been wide studied. According to the review conducted by Francis et al. (2018), the first four anatomical sites with more injury proportions do not change when analyzed by sex: knee, ankle, shank and hip. However, proportions of injury in the knee and the hip are greater in women and proportions of injury in the ankle and the shank are greater in men (Francis et al., 2018). Most studies analyzing sex differences in lower extremity mechanics during running showed that female runners demonstrated a significant greater peak hip adduction angle than men (Chumanov, Wall-Scheffler, & Heiderscheit, 2008; Ferber, McKlay-Davis, Williams, 2003; Fernández & Rojano, 2020). Nevertheless, results are not so conclusive regarding peak rearfoot eversion angle (Fukano, Fukubayashi, & Banks, 2018; Sinclair & Taylor, 2014; Takabayashi, Edama, Nakamura, Nakamura, Inai, & Kubo, 2017).

With the results obtained to date, we consider that it is necessary to provide additional insight on sex differences or differences between dominant and non-dominant limbs in the different phases of the running gait cycle, as well as in the movements of the subtalar joint in the coronal plane. Therefore, the aim of the current study was to determine bilateral asymmetries, sex differences and peak eversion angle in the running gait cycle of recreational runners. It was hypothesized that there would be no bilateral asymmetries in the running gait cycle or peak eversion angle of recreational runners but sex differences would exist.

Material and Methods

Participants

Twenty recreational runners aged 20 – 28 years volunteered to participate in this study. Ten of them were males (age: 22.00 ± 1.89 years, mass: 73.60 ± 8.15 kg, height: 176.90 ± 9.27) and the other ten females (age: 22.60 ± 2.59 years, mass: 62.05 ± 7.30 kg, height: 171.00 ± 3.65). Body height was measured with a stadiometer to the nearest 0.1 cm (SECA, Germany) and body mass was measured with a digital scale (Holtain, England) to the nearest 0.1 kg. Participants ran a minimum distance of 10 km per week and none of them had experienced lower extremity injuries at least three months before the testing sessions. All the participants gave written informed consent according to the Declaration of Helsinki.

Procedures

Some days prior to data collection participants ran for 30 minutes on a treadmill at self-selected speed to become familiar with it. The day of data collection participants carried out a warm-up period and then they ran 10 minutes on the treadmill (Technogym, Italy) at a speed at which they felt comfortable between 11 and 12 km/h. During the last minute they were recorded for about ten seconds. They ran with their usual (not worn-out) training shoes.

All kinematic data were collected with a two-dimensional video recording from a posterior view with a high speed digital camera (Casio EX-F1 at 300 Hz). The camera was placed two meters away from the treadmill at ground level. To evaluate eversion of the subtalar joint two markers were placed along the vertical axis of the shoe heel and two markers were placed along the long axis of the shank. The angle between the long axis of the rearfoot and the long axis of the shank indicated inversion/eversion of the subtalar joint (Figure 1).

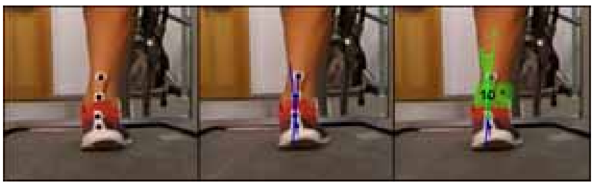

Figure 1. Markers placed on the right lower limb of a participant, lines representing the long axis of the rearfoot and the shank, and peak eversion angle measured with Kinovea software.

In order to minimize errors concerning the use of 2D recordings, the longitudinal axis of the camera has to be aligned with the longitudinal axis of the foot (Aguado, 1997; Novacheck, 1998; De Wit, et al., 2000). Since we wanted to analyse both limbs with the same video recording the longitudinal axes of the two feet had to be parallel to the longitudinal axis of the camera and for this reason some of the participants were excluded. Three running gait cycles were analysed using the stable version of Kinovea 2D video editing program (Kinovea-0.8.15, Bordeaux, France) and mean values of the variables measured were used for subsequent analysis.

Study variables

We considered that the gait cycle begun with the initial contact of the dominant foot with the treadmill surface and ended when the dominant foot contacted with the treadmill surface again. The step duration of each limb begun with the initial contact of the corresponding foot with the treadmill surface and ended with the initial contact of the opposite foot with the treadmill surface. Therefore, two consecutive steps (one of each limb) together made a complete running gait cycle. The following temporal variables were measured for each limb:

- Step duration (SD): duration of each step measured as a percentage of the total gait cycle.
- Stance phase (SP): duration of the stance phase of each limb measured as a percentage of the total gait cycle.
- Float phase (FP): duration of the float phase of each limb measured as a percentage of the total gait cycle.
- Time to peak eversion (TPE): time elapsed from the beginning of each half-cycle to the instant the subtalar joint reaches its maximal eversion angle. It is measured as a percentage of the stance phase.
- Time to neutral position (TNP): time elapsed from the beginning of each half-cycle to the moment the subtalar joint reaches a neutral position after the peak eversion. It is measured as a percentage of the stance phase.

Apart from those temporal variables, peak eversion angle of each foot was also measured.

Statistics

Statistical analysis was carried out with the program SPSS for Windows, v. 22.0 (SPSS Inc., USA). The means and standard deviations of all variables were calculated. Shapiro-Wilk test was applied for testing normality of data and, as this condition was always fulfilled, a two-way analysis of variance (ANOVA) was carried out to examine the effect of limb (dominant/non-dominant) and sex on the dependent variables. Since no significant differences in any of the dependent variables between both limbs and no interaction between limb and sex were found, we pooled the data obtained from both limbs and t-Student tests were carried out to determine significant differences between males and females. Results were considered statistically significant at $p < .01$. In order to determine the magnitude of the difference between groups, measures of effect size were assessed using Cohen's d: minimal effect (< .20), small effect (.20 – .50), moderate effect (.50 – .80) or large effect (> .80) (Cohen, 1988).

Results

Table 1 provides the means and standard deviations of all the measured variables for dominant and non-dominant limbs in male and female groups. Significant differences between limbs and groups are also provided in Table 1. Significant differences were only found in time to peak eversion between males and females ($p < .01$).

Table 2 provides the means and standard deviations of all the measured variables for both limbs together in male and female groups. Significant differences between groups and effect sizes are also provided in Table 2. Significant differences between males and females were only found in time to peak eversion ($p < .01$), with a large effect size. Effect sizes for the rest of the variables were minimal or small.

Table 1.
Descriptive statistic of the study variables for dominant and non-dominant limbs.

Variables	Males		Females	
	Dominant limb (mean ± sd)	Non-dominant limb (mean ± sd)	Dominant limb (mean ± sd)	Non-dominant limb (mean ± sd)
SD (% of TGC)	49.70 ± .50	50.30 ± .50	49.91 ± 1.01	50.09 ± 1.01
SP (% of TGC)	38.95 ± 3.20	38.94 ± 3.39	38.36 ± 4.93	39.13 ± 4.53
FP (% of TGC)	61.05 ± 3.20	61.06 ± 3.39	61.64 ± 4.93	60.87 ± 4.53
TPE (% of SP)	26.28 ± 4.06	26.45 ± 6.24	37.43 ± 6.47	36.40 ± 5.32
PE angle (º)	11.37 ± 2.27	11.43 ± 2.93	11.40 ± 6.75	12.13 ± 8.38
TNP (% of SP)	72.83 ± 10.28	76.52 ± 12.45	68.85 ± 13.19	68.09 ± 18.29

Notes: SD: step duration; TGC: total gait cycle; SP: stance phase; FP: float phase; TPE: time to peak eversion; PE: peak eversion; TNP: time to neutral position.

Table 2.
Descriptive statistic and effect sizes of the study variables for both limbs together.

Variables	Both limbs		Effect Size
	Males (mean ± sd)	Females (mean ± sd)	Cohen's d
SD (% of TGC)	50.00 ± 1.26	50.00 ± .99	.00
SP (% of TGC)	38.94 ± 3.21	38.74 ± 4.63	.05
FP (% of TGC)	61.06 ± 3.21	61.26 ± 4.63	- .05
TPE (% of SP)	26.37 ± 5.12**	36.92 ± 5.79**	-1.93
PE angle (º)	10.90 ± 2.61	11.77 ± 7.42	- .16
TNP (% of SP)	74.68 ± 11.28	68.47 ± 15.53	.46

Notes: SD: step duration; TGC: total gait cycle; SP: stance phase; FP: float phase; TPE: time to peak eversion; PE: peak eversion; TNP: time to neutral position; **: significant differences males – females ($p < .01$).

Discussion

The fact that we did not find significant differences in any of the variables measured between dominant and non-dominant legs revealed that there are no bilateral asymmetries in running with regard to temporal variables and peak eversion angle. Similar results were found by Nakayama, Kudo and Ohtsuki (2010) in running gait cycle of trained runners and non-runners.

With running speeds between 11 km/h and 12 km/h, the average duration of the stance phase and the swing phase were, respectively, 38.94 ± 3.21% and 61.06 ± 3.21% of the running gait cycle in males and 38.74 ± 4.63% and 61.26 ± 4.63% of the running gait cycle in females, with no significant differences between male and female groups. Our values for the swing phase are somewhat lower than those found by Smith and Hanley (2013) and those suggested by Lohman et al. (2011) and Novacheck (1998) in their systematic reviews because they affirm that typical swing times contribute between 64 and 78% of a running gait cycle's duration, dependent on speed. These differences may be attributed to our testing running speeds. Our participants were not professional runners and at the moment the study was carried out they ran two/three times per week and not much more than 10 km per week, so our testing speeds were lower than those used in most investigations with runners and, as it is well known, the swing phase becomes proportionately longer and the stance phase shorter as the speed increases (Deflandre, et al., 2016; Kharb, et al., 2011; Muñoz, et al., 2018; Nicola & Jewison, 2012; Novacheck, 1998; Rubinstein, et al., 2017; Smith & Hanley, 2013). However, our results are similar to those calculated with the data provided by López-Gómez et al. (2020) even if their soccer players run at a higher speed but it may be explained by the different running pattern due to the different running surfaces (Ariza-Viviescas, et al., 2021; López-Gómez, et al., 2020) or by the fact that they were children with a lower height which undoubtedly reduces the stance phase.

We have found an average time to neutral position of the subtalar joint of 74.68 ± 11.28% of the running gait cycle in males and 68.47 ± 15.53% in females, with no significant differences between them. These values are in good agreement with the data published by Novacheck (1998), who states that after peak eversion the foot begins to supinate and reaches a neutral position at about 70% of the stance phase.

Average peak eversion angle was 10.90 ± 2.61º for males and 11.77 ± 7.42º for females, with no significant differences between groups. According to Aguado (1997), these values can be considered as «normal» for a typical subtalar joint. However, our values are lower than those provided by Sinclair et al. (2013) who found an average peak eversion angle of 15.5 ± 8.9º but their participants ran at 14.4 km/h and since eversion is one of the mechanisms used to absorb impact ground reaction forces it is expected greater rearfoot eversion with higher running speeds. In addition, they found significant differences in peak rearfoot eversion between treadmill and overground running, differences not found by other authors like Fellin, Manal and Davis (2010) and Riley, Dicharry, Franz, Della Croce, Wilder and Kerrigan (2008) and may be related to the excessive deformation characteristics of the treadmill surface utilized in their investigation (Sinclair, et al., 2013).

Peak rearfoot eversion occurred at 26.37 ± 5.12% of the stance phase for males and at 36.92 ± 5.79% for females. These values are very different, particularly in males, from those published by Ferber et al. (2009) and Sakaguchi, Ogawa, Shimizu, Kanehisa, Yanai, and Kawakami (2014) who found that maximal eversion occurred at approximately 45% of the stance phase. Our lower values may be due the different running speeds and the different shoes used. Our participants ran with their usual (not worn-out) training shoes while the others ran in the same brand and style of neutral running shoe (Ferber, et al., 2009) or in and identical-model running shoes with a moderate cushioning property (Sakaguchi, et al., 2014). In addition, Ferber et al. (2009) had only runners with heel-strike pattern which could also delay peak rearfoot eversion.

Irrespective of those differences, the most relevant result is that female runners demonstrated a greater time to peak eversion than male runners. This may be the cause of some overuse running injuries that are more prevalent in females because time to maximum rearfoot eversion has often been linked to overuse running injuries (Ferber, et al., 2009). Women are more prone to tibial stress syndrome and tibial stress fractures (Fernández & Rojano, 2020; Kozinc & Šarabon, 2017; Taunton, et al., 2002) and Becker et al. (2017) and Fernández and Rojano (2020) suggest that eversion later in stance may be one of the biomechanical factors related to this type of injury risk. Sakaguchi et al. (2014) also found a later occurrence of peak eversion in female runners but the differences between males and females were not significant and effect sizes were small. Further research in this area is needed to clarify the contradictory results.

This study has important limitations: 1) In order to have a more homogenous group regarding the level of the runners, it would have been better to use as an inclusion criteria the time they took to run a given distance; 2) Although all the participants confirmed they felt comfortable running at a speed between 11 and 12 km/h, it would have been more appropriate a really self-selected speed; 3) An 1% treadmill grade would also have been more appropriate to compensate for the difference between treadmill and outdoor running.

Conclusions

There were no bilateral asymmetries in kinematic variables of running gait cycle of recreational runners and there were no significant differences between males and females, except for time to peak eversion angle. Peak rearfoot eversion occurred later in females than in males and this may be responsible for a greater risk of some overuse lower extremity injuries more prevalent in females. The data obtained in this study may serve as a useful reference for future research with different running speeds and future studies assessing sex differences, especially with professional runners.

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