CHANGES IN REARFOOT STRIKE PATTERNS OVER CHILDHOOD: A 3-YEAR PROSPECTIVE LONGITUDINAL COHORT STUDY

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Abstract:

Rearfoot strike (RFS) in children running produces impact forces that give rise to a transient stress wave traveling through the body. It could contribute to the development of injuries. The purpose of this study was to determine RFS prevalence during childhood while running at a self-selected velocity in a prospective longitudinal cohort study. A total of 175 children (68 girls), aged 6 to 14 years, participated in this study. The sample was divided into three age groups (age in 2016): 6-8 years, 9-11 years, and 12-14 years, which were analysed again three years later (2019). A 2D video-based analysis was used to record the RFS. Taking into account all samples, in the jogging trial the prevalence of RFS (an average of both feet) was 86.9% in 2016 and 94.7% three years later; in the running trial the prevalence was 82.6 and 94.4%, respectively. In all samples a significant increase of RFS prevalence was found in both the jogging and running trials for both feet over three years (jogging, left foot, $p=.011$, right foot, $p=.023$; running, left foot, $p=.001$, right foot, $p<.001$). In girls, there were no significant differences in any conditions. In boys, a significant increase of RFS prevalence was found after three years in both feet ($p<.01$) in the running trial. This study shows that RFS prevalence in children increases with age and the results may be used to characterize typical running development in children population.

Key words: *running, children, growth, foot strike patterns*

Introduction

Early years of life are a stage of a very rapid child development marked by a considerable growth and change in a child's motor repertoire (Piek, Hands, & Licari, 2012). Motor competence during infancy and childhood is influenced by the child's individual growth and morphological, physiological, and neuromuscular characteristics (Venetsanou & Kambas, 2009). Locomotor skills such as running are basic in most children's physical activities and promote fitness (Nguyen, Obeid, & Timmons, 2011). Running patterns are influenced by numerous internal factors such as sex, age and physical fitness (Ferber, Davis, & Williams, 2003; Fukuchi, Stefanyshyn, Stirling, Duarte, & Ferber, 2014; Sinclair & Selfe, 2015), and external factors such as running surfaces and footwear (An, Rainbow, & Cheung, 2015; Gruber, Silvernail, Brueggemann, Rohr, & Hamill, 2013; Lieberman, et al., 2010; Muñoz-Jimenez, Latorre-Román, Soto-Hermoso, & García-Pinillos, 2015).

For thousands of years humans have been walking and running without shoes (Lieberman, 2012). However, the use of modern footwear might have caused alterations in the motor control of running (Santuz, Ekizos, Janshen, Baltzopoulos, & Arampatzis, 2017). Many children participate in organized sports activities such as endurance races increasing the likelihood of lower limb injuries (Krabak, Snitily, & Milani, 2016). This might be related to the dynamics of the foot in contact with the ground. The orientation of a runner's foot at the initial ground impact is often used as a criterion to classify running technique (Kelly, Farris, Lichtwark, & Cresswell, 2018). Three categories of ground contact are often described (Daoud, et al., 2012; Latorre-Román, et al., 2015): rearfoot strike (RFS) —landing on the half of the heel or the rear third part of the sole only; midfoot strike (MFS) —landing on the heel and the ball simultaneously, and forefoot strike (FFS) —landing on the ball of the foot.

Although running with FFS seems to be a characteristic of human evolution (Daoud, et al., 2012), adult amateur endurance runners exhibit a high prevalence—between 74.9 and 95.4%—of RFS (Hasegawa, Yamauchi, & Kraemer, 2007; Kasmer, Liu, Roberts, & Valadao , 2013; Larson, et al., 2011; Latorre-Román, et al., 2015). The rearfoot strike is associated with a higher vertical loading, ankle stiffness, and knee stiffness (Almeida, Davis, & Lopes, 2015; Hamill, Russell, Gruber, & Miller, 2011) and some previous studies have suggested its association with injury risks (Daoud, et al., 2012; Lieberman, et al., 2010). In particular, RFS in children running produces impact forces that give rise to a transient stress wave traveling through the body (Alcantara, Perez, Lozano, & Garica, 1996). Given the immaturity of children's musculoskeletal system and that the feet experience several changes during childhood, which changes are exposed to various external influences such as age, sex and footwear (de Villiers, 2017), the RFS could contribute to the development of injuries. A recent cross-sectional study (Latorre Román, et al., 2019) indicated that children were originally FFS or MFS runners and they transitioned progressively towards RFS due to morphological/biomechanical changes associated with growth or due to the use of footwear. Particularly, the heavily cushioned heeled sneakers increase RFS in adolescents. However, we do not know whether the altered biomechanics may be detrimental to the adolescent runner who is still developing his/her running style (Mullen & Toby, 2013).

The most current findings of the analyses of foot strike patterns (FSP) come from cross-sectional studies performed in a laboratory setting (Hollander, Riebe, Campe, Braumann, & Zech, 2014; Mullen & Toby, 2013). Therefore, an ecological approach is necessary in the analysis of the FSP evolution over childhood. In this regard, the purpose of this prospective longitudinal cohort study was to determine RFS prevalence during childhood, regarding sex and age, while running at a self-selected velocity.

Material and methods

Participants

This prospective longitudinal cohort study involved a total of 175 (68 girls) aged 6 to 14 years. *A priori* sample size was performed using the G-Power software (Faul, Erdfelder, Lang, & Buchner, 2007). The following parameters were selected: moderate effect size (w=0.252), significance level of 0.05, a power level of 0.95, one group, two measurements, noncentrality parameter $\lambda=13.05$, critical $\chi^2=3.841$. The sample size was determined to be at least one hundred seventy-five participants.

The sample was a convenient one, selected from a school in southern Spain. Inclusion criteria for the participation were: the absence of any neurodevelopmental or neuromotor disability, such as autism, Down's syndrome, and/or the presence of any pathological disorder associated with the visual or vestibular systems, and finally, not having suffered from any injuries in the last six months. Inclusion and exclusion criteria were evaluated upon the answers given in a parental questionnaire. Parents voluntarily signed an informed consent form permitting their children to participate in this study. In 2016, a total of three hundred eighty-nine children were analyzed and one hundred seventy-five were recruited in 2019. The sample was divided into three age groups (age in 2016): 6-8 years (n=71, age =7.66 ±0.68 years), 9-11 years (n=65, age=10.47 ±0.86 years), and 12-14 years (n=39, age=13.41 ±0.87), which were analyzed three years later (2019). More information about the participants is shown in Table 1. This study was completed under the norms of the Declaration of Helsinki (2013 version) and was approved by the Ethics Committee at the University of Jaén.

Materials and testing

Sagittal and frontal plane videos (240 Hz) were recorded using a high-speed camcorder (Casio Exilim EXF1, Shibuyaku, Tokyo 151–8543, Japan). Videos were taken from a lateral view, with the camera perpendicularly placed five meters from the participant so that they could be filmed in the sagittal plane. The filming location was set along a five-meter corridor. Video data were analyzed using a 2D video editor (VideoSpeed vs1.38, ErgoSport, Granada, Spain). The 2D video-based determination of the FSP has been used in other studies (Latorre-Román, Párraga-Montilla, Guardia-Monteagudo, & García-Pinillos, 2018; Latorre-Román, Balboa, & Pinillos, 2017), and despite it is not being as exact as the biomechanical determination, it is practical for the assessment of a large cohort (Hollander, et al., 2016) and is valid and highly reliable regardless of the experience of the assessor (de Oliveira, Fredette, Echeverría, Batcho, & Roy, 2019). According to the procedure used in previous studies (Hollander, et al., 2018; Latorre Román, et al., 2019), the FSP was rated as RFS or non-RFS since this dichotomous variable showed very high accuracy in determining the RFS (inter-rater accordance: 0.981) and lower accuracy between the FFS and MFS (0.893) (Hollander, et al., 2018). Figure 1 shows pictures that illustrate different FSP. Moreover, asymmetries between the right and the left foot were also analyzed. Running speed was measured using two double-light barriers (WITTY; MicrogateSrl, Bolzano, Italy; the accuracy of 0.001 seconds).

Figure 1. Examples of FSP, from the left to the right: rearfoot strike, midfoot strike, and forefoot strike.

Procedure

In this experiment the participants were asked to run steadily in their usual sneakers at a self-determined comfortable speed (jogging) and a self-determined high speed (running). Some indications were given to the participants: in jogging *run comfortably*, *don't run too fast,* and in running *don't sprint*. The research team demonstrated slow and fast running and the children performed some familiarization trials for the two different modes of running (slow and fast). The participants ran 40 meters to the recording area formed by a corridor of five meters long and two meters wide. The running tests were performed on a flat, hard, non-slip surface. Approximately 12 steps were observed for each child. The evaluations from lateral point of view were compared for both the right and the left foot between the observers. In case of disagreement on FSP, the observers re-watched the video and agreement was reached on the categorization of FSP.

Statistical analysis

Data were analysed using SPSS, v.22.0 for Windows (SPSS Inc, Chicago, USA) and the significance level was set at $p<.05$. Descriptive statistics are represented as M (mean), SD (standard deviation), and % (percentage). To analyze the differences between the quantitative and nominal variables, the paired *t*-test and McNemar's test were used, respectively. Also, in a sample of 50 participants and with the participation of three experienced observers, intra-observer and inter-observer reliability were calculated using Cohen's kappa and proportion of agreement for FSP.

Results

The intra-observer reliability was obtained for FSP kappa =0.926, proportion of agreement =98% and inter-observer reliability was kappa =0.801±0.09, proportion of agreement =90%.

In all samples a significant increase of RFS prevalence was found in both the jogging and running trials for both feet over three years (jogging: left foot, p=.011, right foot, p=.023; running: left foot, p=.001, right foot, p<.001). In girls, there were no significant differences in any conditions. In boys, a significant increase of RFS prevalence was found after three years in both feet (p<.01) in the running trial. According to age group, a significant increase of RFS prevalence in both feet (p<.05) was found in the jogging trial in the group of 6-8 years three years later. In the group aged 12-14 years the significant increases of RFS prevalence were found in both feet (p<.001) in the running trial.

Taking into account all samples, in the jogging trial the prevalence of RFS (an average of both feet) was 86,9% in 2016 and 94.7% three years later; in the running trial the prevalence was 82.6 and 94.4%, respectively. In girls the prevalence of RFS in jogging was 81.8 and 91.7% in 2016 and 2019, respectively, whereas in the running trial it was 81.3% in 2016 and 92.2% in 2019. Also, in boys, the prevalence of RFS in jogging was 90.4 and 96.8% in 2016 and 2019, respectively, whereas in running it was 83.5% in 2016 and 95.8% in 2019. Moreover, the girls showed an increase in the prevalence of RFS from 2016 to 2019 of 9.9% in jogging and 10.9% in running; in turn the boys displayed an increase of 6.4% in jogging and an increase of 12.3% in running. Taking into account age groups in the jogging trial, an increase of 12.7%, an increase of 1.6% and an increase of 10.0% were found in the age groups of 6-8, 9-11 and 12-14 years, respectively, and in the running trial they were 3.85, 5.95 and 35.1%, respectively.

Concerning FSP asymmetry, a significant increase of this parameter was found from 2016 to 2019 in the whole sample (3.8% vs.10.6%, p=.027) and in boys (2.1% vs.13.8%, p=.003) in the jogging trial. No significant changes (p≥.05) were found in girls and in the age groups.

Table 1. Anthropometric characteristics, jogging and running speeds in 2016 and 2019 in relation to sex

	Boys M (SD)		p-value	Girls M (SD)		p-value
	2016	2019		2016	2019	
Body weight (kg)	38.87 (13.86)	51.94 (16.46)	<.001	35.46 (12.59)	46.75 (15.21)	<.001
Body height (cm)	141.97 (15.56)	158.01 (13.87)	<.001	136 .57 (14.47)	151.37 (11.94)	<.001
Jogging speed (m/s)	3.07 (0.47)	3.31 (0.42)	<.001	2.91 (0.42)	3.34 (0.35)	<.001
Running speed (m/s)	4.13 (0.49)	4.14 (0.47)	.847	3.90 (0.49)	3.99 (0.42)	.243

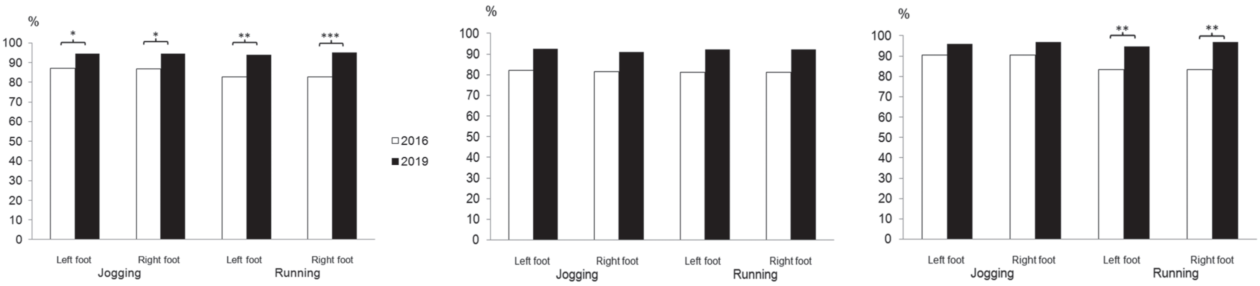

*Figure 2. Prevalence of RFS in relation to all sample, girls and boys (from the left to the right) in the jogging and the running trials from 2016 to 2019.*p<.05 **p<.01,***p<.001.*

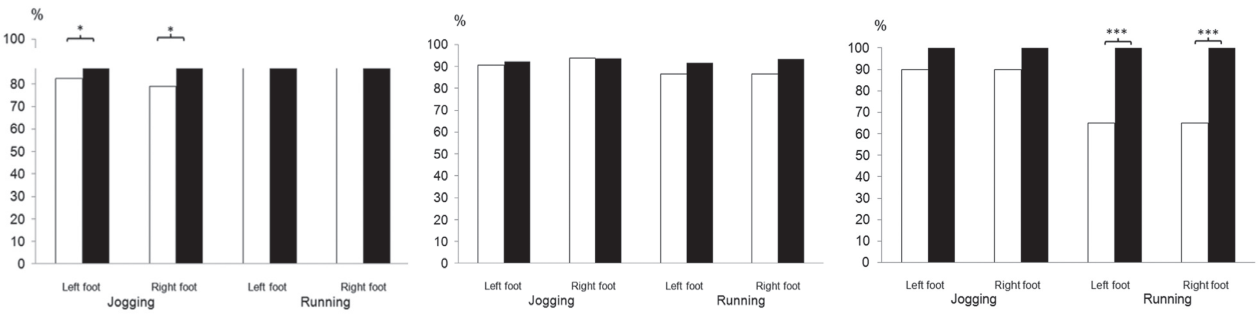

*Figure 3. Prevalence of RFS in relation to age group; 6-8 years old, 9-11 years old and 12-14 years old (from the left to the right) in the jogging and running trials from 2016 to 2019. *p<.05 **p<.01,***p<.001.*

Discussion and conclusions

The main purpose of this prospective longitudinal cohort study was to determine the RFS prevalence during childhood while running at a self-selected velocity. The main finding was an increase of RFS prevalence both in jogging and running from 2016 to 2019. A previous cross-sectional study noted that there was a significant increase (p<.001) of RFS prevalence during childhood, e.g., preschool children (3-6 years old) displayed an RFS prevalence of 46.65% and the adolescent's population (15-16 years) an RFS prevalence of 92.20% (Latorre Román, et al., 2019). However, a similar longitudinal study showed no significant differences over three years (2014-2017) in children's FSP (Yoshida, 2018).

Although in the jogging trial there was an increase of speed between years 2016 and 2019, in both the boys and girls, some previous studies in runners showed that running speed did not influence RFS prevalence (Muñoz-Jimenez, et al., 2015; Wang, et al., 2018). Even when running speed increases, some runners tend more towards of an FFS, so that with an increase of 1 m/s some runners could change their FSP (Cheung, et al., 2017). In the current study the increase of speed was less than 1 m/s, therefore the jogging speed was not a relevant factor.

Regarding the RFS prevalence, previous studies have shown high values of RFS between 69.8-92.2% in children and adolescent population in both the shod and unshod conditions (Latorre Román, et al., 2017; Mullen & Toby, 2013). In the current study the RFS prevalence was also between this interval in both 2016 and 2019.

On the other hand, a previous study (Latorre Román et al., 2017) indicates that barefoot running reduces the prevalence of RFS in children aged 6-16 years; in the unshod condition there was a significant reduction (p<.001) in RFS prevalence in both boys (shod condition =83.95% vs. unshod condition =62.65%) and girls (shod condition =87.85%

vs. unshod condition =62.70%). Even at higher speeds wearing sneakers resulted in far more RFS compared with track flats or barefoot so that the adolescent athlete who run predominantly in sneakers may not develop adequate musculature and ligament strength in the foot to perform at the highest level and prevent injury (Mullen & Toby, 2013). In this sense runners who displayed habitual RFS with modern running shoes exhibited a decreasing trend in the muscle strength of the medial longitudinal arch (Zhang, Fu, & Liu, 2019). A recent study (Aibast, et al., 2017), investigated foot structure, foot function, injury and physical activity levels in Kenyan children and adolescents who were habitually barefoot compared with those who were habitually shod, and their main findings were that the lower-limb injury prevalence was 8% in the habitually barefoot and 61% in the habitually shod. A previous study (Hollander, et al., 2014) showed that running biomechanics of pre-adolescent children were influenced by the use of footwear, especially by the cushioned running shoes, eliciting significantly increased maximum impact and ground reaction forces, step length, step width and rate of RFS, which might pose an injury risk. Additionally, another finding of this study was that there was a significant increase in FSP asymmetry during childhood. In this regard, kinetic asymmetries between the legs could expose one of the lower limbs to more stress and injury risk (Zifchock, Davis, & Hamill, 2006). Therefore, the heavily cushioned sneakers change the gait pattern; however, we do not know whether the altered biomechanics may be detrimental to the adolescent runner who is still developing a running style (Mullen & Toby, 2013).

A possible explanation of the findings of the current study could be that the increased step rate reduces the amount of RFS (Allen, Heisler, Mooney, & Kring, 2016). In this regard, Kampmiller, Vanderka, Šelinger, Šelingerová, and Čierna (2011) showed that there was high ontogenetic stability of the kinematic parameters during running in the population of 7 to 18 year olds. Only during the prepubescent and beginning of the pubescent period, at ages of 11 to 15 years, were the stride frequencies reduced significantly, which may be related to the rapid growth (a significant increase in body height and weight) and the deterioration of biomechanical and coordination conditions of the organism. Therefore, children that displayed lower stride frequency also could exhibit high RFS prevalence. Also, typical barefoot or minimal-shoe runners showed an FFS gait and a high stride frequency (Allen, et al., 2016). However, in the present study the stride frequency was not recorded.

Some limitations of this study must be mentioned. The main limitation is the sample comprised of schoolchildren in southern Spain, and generalization to a wider population should be taken with caution. Second, the current study used video analysis system to measure FSP that is less accurate than a 3-D motion capture system. And third, footwear was not controlled nor assessed. Notwithstanding these limitations, the current study includes a large population sample of children and to our knowledge it is the first research to determine the FSP in children in a longitudinal cohort study.

In conclusion, the results of the current study show that RFS prevalence in children increases with age regardless of running speed. From a practical point of view, the results of the current study may be used to characterize typical running development in children and the adolescent population, providing useful information for athletes and coaches to gain a better understanding of the impact that RFS may have on athlete performance or injury rates. Future research could investigate the relationship between RFS prevalence and several variables such as: footwear type, physical activity level or the effects of a retraining program on FSP.

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