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The influence of shoe aging on children running biomechanics

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ABSTRACT

Athletic children are prone to overuse injuries, especially at the heel and knee. Since footwear is an extrinsic factor of lower limb injury risk, the aim of this study was to assess the influence of shoe aging on children running biomechanics. Fourteen children active in sports participated in a laboratory biomechanical evaluation. A new pair of shoes was provided to each participant at an inclusion visit. Four months later, the participants performed a running task and their kinematics and kinetics were assessed both with their used shoes and with a new pair of shoes identical to the first. Furthermore, mechanical cushioning properties of shoes were evaluated before and after in-vivo aging. After 4 months of use, the sole stiffness increased by 16% and the energy loss capacity decreased by 18% ($p < 0.001$). No ankle or knee kinematic adjustment was found at foot strike in used shoes but changes were observed later during stance. Running with used shoes produced a higher loading rate of the vertical ground reaction force (+23%, $p = 0.016$), suggesting higher compressive forces under the heel and placing children at risk to experience impact-related injuries. Nevertheless, the decreased peak ankle and knee power absorption in used shoes (−11%, $p = 0.010$ and −12%, $p = 0.029$, respectively) suggests a lower ankle and knee joints loading during the absorption phase that may be beneficial regarding stretch-related injuries.

Keywords: Footwear cushioning; Loading rate; Ground reaction force; Kinematics; Ankle; Knee

1. Introduction

Worldwide, millions of children and adolescents are involved in organized sports. The physiological repetitive loadings during sports practice may be beneficial, especially to stimulate bone growth [1]. However, high training volumes, particularly for elite athletes, place children at risk of overuse injuries [2]. The growing bones of the young athlete cannot handle as much stress as the mature bones of adults [3]. The enthesis, where tendon meets bone, is a notably vulnerable zone for children because of the immature skeleton and the constant remodeling process of bones during growth [4]. The most common sites for overuse injuries are the insertion of the Achilles tendon onto the calcaneus (Sever's disease) and the insertion of the patellar tendon onto the tibial tubercle (Osgood-Schlatter disease). These pathologies are caused by the combination of repetitive impact that creates compressive forces and the excessive traction of the tendons that produces tensile forces on the apophysis [5].

Several extrinsic factors were suggested to affect overuse injury rates [6]. Among them, footwear was reported to have a major impact on children's running biomechanics [7,8]. Wearing suitable shoes

seems particularly important since footwear is the first interface between the body structures and the ground, damping the reaction force and thereby attenuating the shock wave when the foot hits the ground. However, although the cushioning in new shoes may be sufficient to protect the wearer, the repeated impact in the course of regular use causes fatigue damage to the midsole and eventually reduces the mechanical capacity to dissipate energy [9–11]. A 15% decrease in the energy loss capacity of the midsole due to shoe aging is enough to affect lower limb muscular activities and to induce increased tibial acceleration peak and rate in a step-down laboratory task from a staircase [12]. Furthermore, finite-element analyses showed that fatigued ethylene vinyl acetate (EVA) in used shoes increased peak plantar pressure and heel pad stress when running [9,13]. These studies suggest that as shoes age, their capacity to protect body structures decreases, with the heel particularly becoming vulnerable to ground impact, which then potentially increases the risk of overuse injury.

Adults running with worn shoes were shown to be able to adapt their running patterns to maintain constant external loads, notably by increasing the running stance time [14]. However, children's proprioception is less developed than that of adults, which might explain why

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they barely – or do not at all – perceive the signs of injury [3]. The consequence may be a lack of kinematic adjustment at foot strike to compensate shoe degradation. Therefore, the purpose of this study was to examine the consequences of shoe aging on the running biomechanics of children. It was hypothesized that running with used shoes, which midsole would become stiffer with aging, results in an increased loading rate of the vertical ground reaction force. This increase in the early phase of support could be explained by the fact that shoe cushioning degradation may not be compensated by lower limb kinematic adjustments at foot strike (ankle and knee flexions) in children. It was also expected that running with used shoes would induce ankle and knee joints kinematic and kinetic changes later during stance. Specifically, increased peak ankle and knee power absorptions due to decreased ability of used shoes to dissipate energy were hypothesized.

2. Methods

2.1. Study design

Fourteen young males (age = 10.7 ± 0.4 years old, height = 1.46 ± 0.05 m, body mass = 35.0 ± 4.2 kg) were recruited from local sport associations to participate in this study. Inclusion criteria were weekly sports practice (≥ 3 h/week), age from 9 to 12 years, and shoe size \leq EU39. Parents were informed of the experimental procedures that complied with the Declaration of Helsinki, and gave written consent for their child's participation in this study, which was approved by the local ethics committee.

The participants first came to the laboratory for an inclusion visit, where the inclusion criteria were checked. A new pair of sport shoes was provided to each participant with the instruction to use them every time they practiced sports at school, in organized structure or outside. Sport shoes were prototypes based on a benchmark of those available on the market for the practice of indoor sports activities (similar construction, same midsole and outsole compounds than those used for commercially-available racket sports, basketball or handball shoes). They were composed of 5-mm rubber outsole, 4-mm EVA insole and EVA midsole of 17 mm under the heel and 5 mm under the metatarsals. Four months after the inclusion visit, each participant came back to the laboratory for a biomechanical evaluation. First, they performed a running task (described later) with the used shoes provided in the inclusion visit. Then, a new pair of shoes, identical to the first one, was given to perform the same task.

2.2. Mechanical shoes testing

Mechanical tests of used and new shoes were run after the biomechanical evaluation in order to assess the effect of shoe wear on several cushioning parameters of the sole. The shoes were conditioned 24 h before the test measurement in the laboratory (23 ± 2 °C and $50 \pm 5\%$ of humidity). All the tests were performed with a force-driven compression tester ([®]Instron E3000, Norwood, USA). To be the most representative of the reality of the field, a force of 785 N, corresponding to a heel impact of 2.0 body weight (BW) of a mean child body mass of 40 kg, was applied 30 times at 1.5 Hz (each 0.67s). The load-deformation curves from the last 5 impacts were recorded and averaged [15]. Three parameters were extracted: stiffness, energy loss and energy returned. The stiffness was computed as the slope of the load-deformation curve between the maximal and minimal values. The energy returned corresponded to the area under the lower unloading curve. The energy loss was the area within the upper loading curve and the lower unloading curve [16] (Fig. 1).

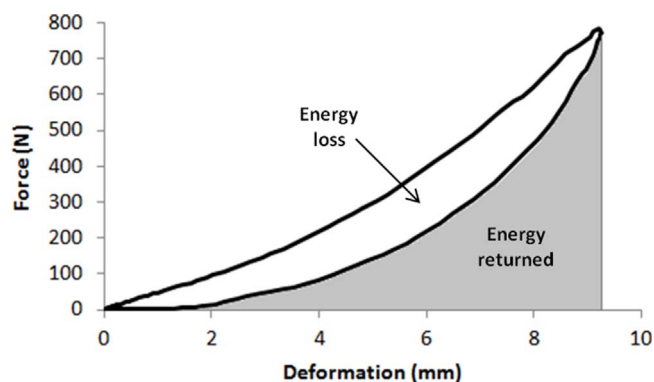


Fig. 1. Load-displacement curve of a mechanical test on a representative shoe. The superior line represents the force-deformation curve as force was applied to the shoe and the inferior line is the response of the shoe as the force was removed. The energy returned corresponds to the shaded area under the lower unloading curve. The energy loss is the white area within the upper loading curve and the lower unloading curve.

2.3. Biomechanical tests

2.3.1. Instrumentation

Twelve retro-reflective markers were placed on each lower limb at the following locations: 2nd and 5th metatarsal heads, calcaneus, internal and external malleoli, tibial tubercle, internal and external femoral epicondyles, mid femoral, greater trochanter, anterior and posterior superior iliac spines (Fig. 2). A 10-IR optoelectronic camera system ([®]Vicon T20, Oxford, UK) and two forceplates ([®]Kistler 9286BA, Switzerland) placed side by side recorded marker positions and ground reaction force data synchronized at 500 and 1000 Hz, respectively.

2.3.2. Procedures

Before recording the trials, participants were instructed to run in the laboratory for 5 min to warm up and become accustomed to the shoes. They were then asked to run at preferential speed on a 9-m runway and to impact the forceplates with the dominant foot after 5 m of run-up. The movement was repeated to obtain 10 valid trials for each shoe condition. The participants' speed was recorded for the tests in used shoes and the experimenter may ask to each participant to accelerate or decelerate for the tests in new shoes to keep consistency for this parameter.

2.3.3. Data processing

A generic model composed of three rigid segments for each lower limb was scaled to each participant's anthropometric data (thigh: great trochanter to centre of femoral epicondyles, shank: centre of femoral epicondyles to centre of malleoli, foot: centre of malleoli to centre of metatarsal heads). The knee angle was the angle between the shank and the thigh. The ankle angle was the angle between the foot and the shank. Kinematic and kinetic variables were calculated using Visual 3D ([®]C-Motion, Rockville, MD). Knee and ankle joint motions were normalized regarding a reference position taken at the beginning of each test session in each shoe with the participant standing upright. The three-dimensional joints kinematics was calculated using an XYZ cardan sequence of rotations (X: flexion-extension, Y: ab-adduction, Z: in-external rotation) [17]. Marker trajectories and ground reaction force (GRF) data were low-pass filtered using a fourth-order zero-lag Butterworth filter with cutoff frequencies of 15 and 50 Hz, respectively.

All kinetic variables were calculated from the vertical component of the GRF (vGRF) and normalized to the body weight (BW) of each participant. The impact peak of the vGRF and the time to peak were extracted. The loading rate was calculated as the slope of the vGRF curve from 20% to 80% of the impact peak magnitude [18]. Joint moment was calculated using Newton-Euler inverse dynamics approach. Joint power was determined as the product of the internal

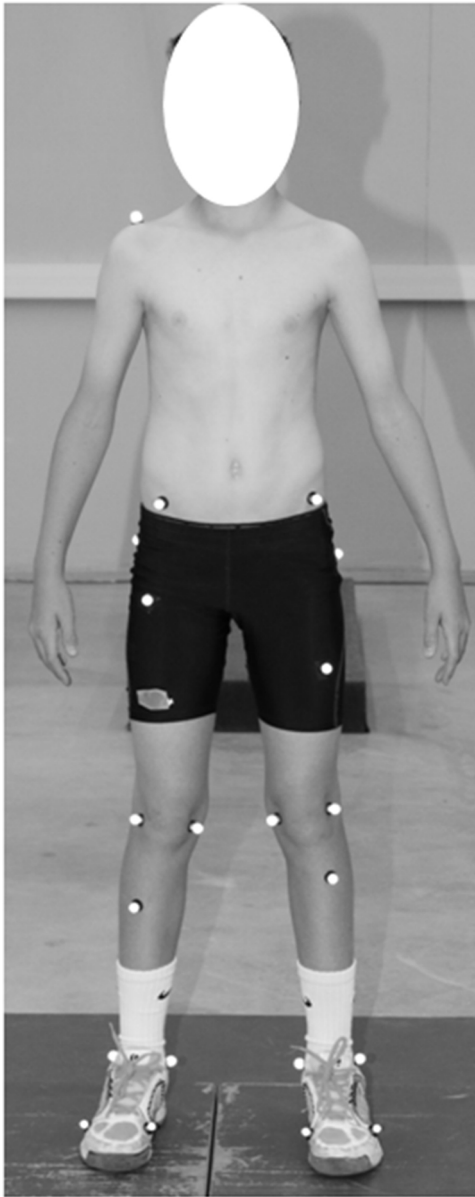


Fig. 2. Front view of markers placement on a representative participant.

joint moment and the joint angular velocity. Joint work was evaluated by integrating the joint power-time profile. Negative values of the joint power and work corresponded to the absorption phase (first half of stance) and positive values indicated the generation phase (second half of stance).

2.4. Statistical analysis

All statistical procedures were conducted using Matlab (Mathworks, R2015a, USA). The significance threshold was set at 0.05. Shapiro-Wilk test confirmed that all mechanical and biomechanical variables were normally distributed and allowed the use of parametric tests. Each variable was expressed as the mean \pm standard deviation of 10 successful trials.

Firstly, a traditional approach was conducted. Paired Student *t*-tests were performed on biomechanical variables at 2 discrete events of the running pattern: foot strike and peak during stance. Similar analysis was made for shoe mechanical parameters. Effect size was assessed with Cohen's *d* to determine the meaningfulness of the statistical differences between used and new shoes. It was evaluated as trivial (0–0.19), small (0.20–0.49), medium (0.50–0.79) and large (0.80 and greater) [19].

Secondly, a statistical parametric mapping (SPM) was conducted to identify potential differences during the stance phase caused by shoe aging. Thus, paired Student *t*-tests were applied on the whole curves (normalized from 0 to 100% of stance) of ankle and knee joint angles, moments and powers. All SPM analyses were implemented using the open-source *spm1d* code (v.M0.3.2, www.spm1d.org). More details can be found elsewhere [20].

3. Results

3.1. Shoes characteristics

After 4 months of use, the mean thickness under the heel decreased by 19% (-4.9 mm), the stiffness increased by 16%, and the energy loss and energy returned capacity of shoes were reduced by 18% and 10%, respectively ($p < 0.001$) (Fig. 3).

3.2. Biomechanics

No effect of shoe aging was detected for either the participants' speed or the stance time, allowing to compare the biomechanical variables of interest and to use SPM.

The vGRF time to peak was shorter (-10% , $p = 0.047$, $d = 0.49$) and the loading rate was steeper ($+23\%$, $p = 0.016$, $d = 0.85$) in used shoes compared with new shoes (Table 1). The peak ankle dorsiflexion and the peak knee flexion decreased in used shoes (-2.2° , $p = 0.019$, $d = 0.63$ and -2.6° , $p = 0.049$, $d = 0.40$, respectively) (Table 1). SPM revealed that the ankle was significantly less dorsiflexed within 41–62% and 88–100% of stance, and that the knee was significantly less flexed within 90–100% of stance in used shoes (Fig. 4a). A significant reduction in used shoes was observed for the peak ankle power absorption (-11% , $p = 0.010$, $d = 0.70$), the peak knee power absorption (-12% , $p = 0.029$, $d = 0.59$) and the ankle negative work (-13% , $p = 0.002$, $d = 1.01$) (Table 1, Fig. 4c).

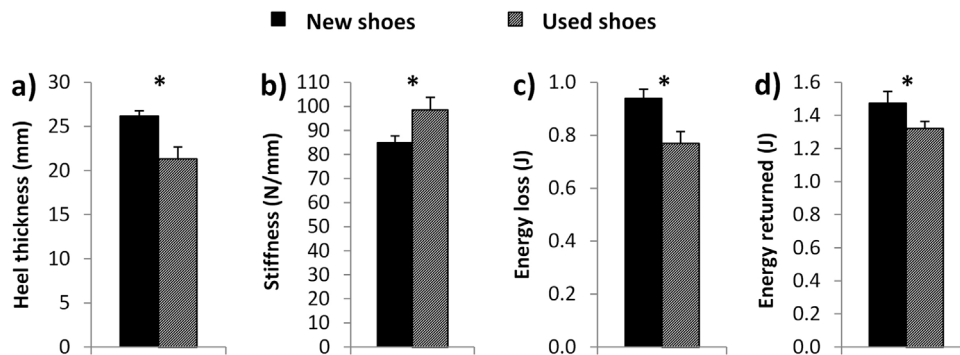


Fig. 3. Main parameters of the new shoes (dark bar) and used shoes (grey bar). a) heel thickness (mm), b) stiffness (N/mm), c) energy loss (J) and d) energy returned (J). * $p < 0.05$.

Table 1
Main kinetic and kinematic variables for running stance phase in used and new shoes.

Variables	Used shoes		New shoes		Student <i>t</i> -test	Cohen's <i>d</i>
Spatiotemporal parameters						
Stance time (s)	0.23	(0.02)	0.23	(0.02)	0.626	0.18
Participants' speed (m/s)	3.40	(0.52)	3.42	(0.35)	0.947	0.03
GRF parameters						
Impact peak (BW)	2.1	(0.2)	2.1	(0.3)	0.822	0.07
Time to peak (ms)*	27.9	(6.1)	30.9	(6.2)	0.047	0.49
Loading rate (BW/s)*	125.5	(28.8)	102.3	(25.9)	0.016	0.85
Joint angle (°)						
Foot vs ground at foot strike	23.4	(7.7)	24.1	(8.9)	0.643	0.08
Ankle dorsiflexion at foot strike	10.4	(3.7)	11.6	(4.5)	0.315	0.29
Peak ankle dorsiflexion*	21.9	(3.3)	24.1	(3.8)	0.019	0.63
Ankle inversion at foot strike	4.0	(4.0)	4.5	(4.1)	0.438	0.13
Peak ankle eversion	7.5	(2.3)	7.5	(2.1)	0.957	0.02
Knee flexion at foot strike	16.2	(5.1)	16.5	(5.2)	0.867	0.04
Peak knee flexion*	45.0	(7.3)	47.6	(5.6)	0.049	0.40
Joint moment (Nm/kg)						
Ankle plantarflexor moment peak	2.4	(1.0)	2.4	(0.9)	0.988	0.00
Ankle evertor moment peak	0.2	(0.1)	0.2	(0.2)	0.863	0.02
Knee extensor moment peak	2.3	(0.9)	2.4	(0.9)	0.138	0.12
Joint power (W/kg)						
Peak ankle power absorption*	-7.6	(1.5)	-8.5	(1.1)	0.010	0.70
Peak ankle power generation	11.3	(2.2)	11.5	(2.2)	0.592	0.10
Peak knee power absorption*	-15.5	(2.9)	-17.6	(4.0)	0.029	0.59
Peak knee power generation	5.6	(1.3)	5.9	(1.3)	0.445	0.18
Joint work (J/kg)						
Ankle negative work*	-0.46	(0.09)	-0.53	(0.05)	0.002	1.01
Ankle positive work	0.66	(0.10)	0.66	(0.10)	0.728	0.06
Knee negative work	-0.63	(0.14)	-0.70	(0.18)	0.173	0.46
Knee positive work	0.32	(0.08)	0.34	(0.07)	0.352	0.19

* Indicates a significant difference between used and new shoes ($p < 0.05$).

4. Discussion

This study was the first to examine the influence of shoe aging on children's running kinetics and kinematics. The main findings were that running with used shoes increased the vGRF loading rate and induced no ankle and knee joints kinematic adjustments at foot strike but some changes later during stance.

4.1. Aging of shoe cushioning

After 4 months of use, the midsole thickness under the heel was on average reduced by 19%. Some authors highlighted that the repeated heel impacts in many sports causes fatigue damage to the EVA foam by partial cell wrinkling and the loss of pressure containment [9,13]. In our study, this resulted in increased midsole stiffness (+16%) and reduced capacity to dissipate energy (-18%) (Fig. 3). The degree of degradation was in accordance with the results from Verdejo & Mills [9] and Schwanitz & Odenwald [10], who showed that the energy absorbing capacity of running shoes was reduced by 15% and 20% after a machine-simulated shoe aging protocol of 270 and 600 km, respectively. However, it was in contrast with those from Wang et al. (2010) [21], who showed a decrease of only 5% in the attenuation capacity of the midsole after a 500-km *in vivo* aging of running shoes by adult runners. These discrepancies may be explained by the midsole density and materials since it was shown that after a 660-km machine-fatigue protocol for running shoes, the decrease in the midsole capacity to dissipate energy was different between viscous material (-8.5%) and elastic material (-15.6%) [12].

4.2. Effect of shoe aging on running biomechanics

The impact peak of the vGRF was similar in used and new shoes but the time to peak was shorter in used shoes, consequently resulting in an

increased loading rate (+23%) (Table 1). The lower midsole stiffness in new shoes (-16%) likely delayed the time to peak through a more pronounced crushing of the foot into the midsole and thus decreased the loading rate [22,23]. This result was in contrast with Kong et al. study that found a constant loading rate of vGRF in adult runners between used and new shoes [14].

No significant differences between used and new shoes were observed for the ankle and knee angles at foot strike (Fig. 4a). This may indicate that children were not able to adjust the ankle and knee joints kinematics prior to impact in order to minimize the shock magnitude. Similar results were found for adult runners [12,14]. It was suggested that impact forces can be regulated later during the initial stance phase by passive mechanisms, requiring no change in the muscle activities or kinematics before or at touchdown [24]. For example, Pratt (1989) explained that foot pronation attenuates the impact after the heel strike by increasing the time over which the energy can be absorbed [25]. However, in our study, no ankle or knee joints kinematic change was found in the first third of stance, even for the ankle eversion angle.

Kinematic differences in the ankle sagittal plane were observed during the transition between absorption and propulsion phases (41-62%) and at the end of the propulsion phase (88-100%) (Fig. 4a). The used shoes reduced the peak ankle dorsiflexion and increased the ankle plantarflexion at toe-off, which was consistent with the results of Kong et al. study of adults running with worn shoes [14]. The firmer midsole in the used shoes would have required less crushing of the foot during the propulsion phase to improve the forward push.

A significant decrease of the peak ankle and knee power absorption was observed in used shoes compared with new shoes (-11% and -12%, respectively). As no differences were observed for ankle and knee joints moments, it should be due to decreased ankle dorsiflexion and knee flexion velocities in used shoes. It contradicts our initial hypothesis and Hardin et al. results on adult runners showing that ankle

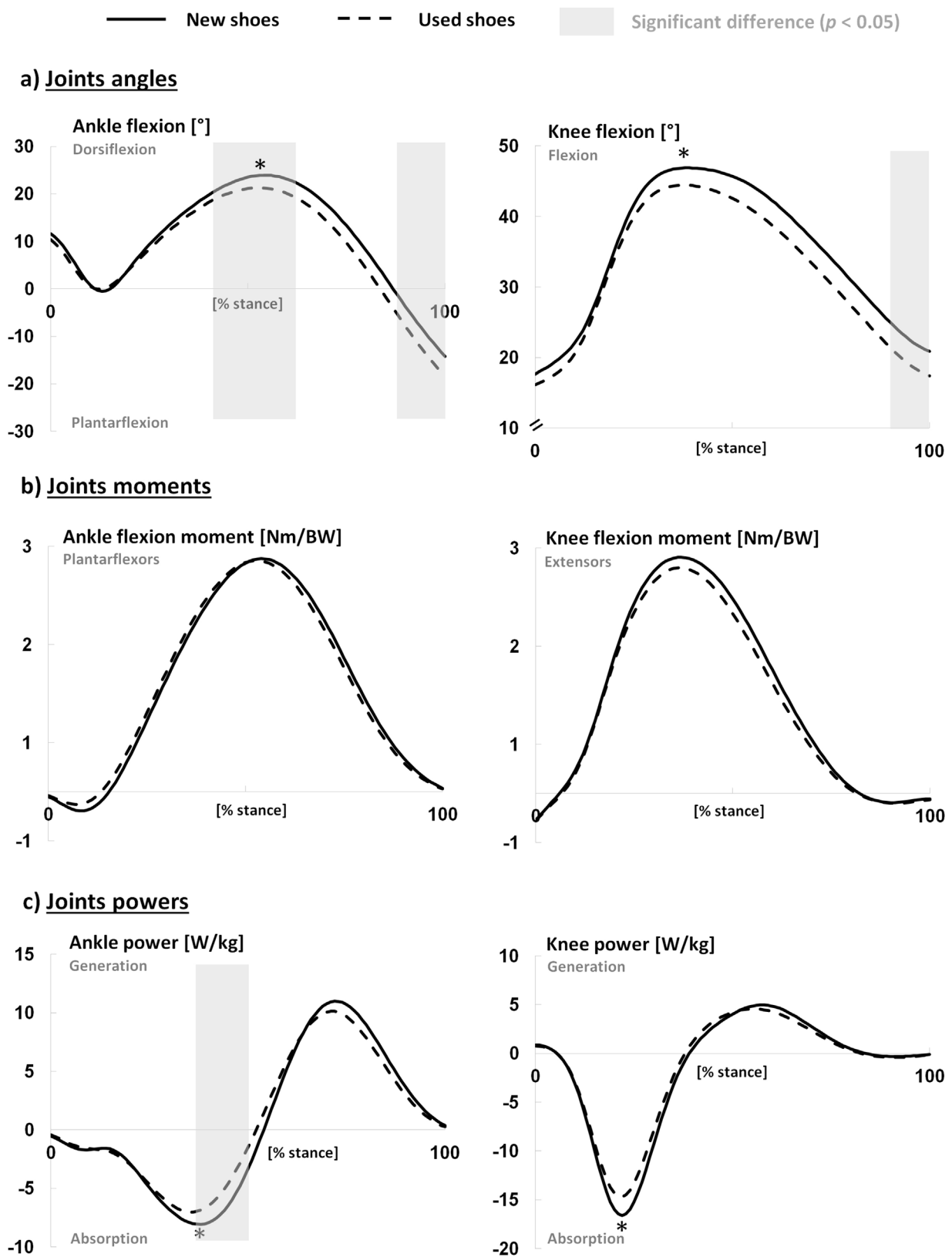


Fig. 4. Mean group ankle and knee a) joints angles, b) joints moments and c) joints power during the running stance phase as a function of shoe aging (solid: new shoes, dashed: used shoes). * indicates significant differences for the peak during stance ($p < 0.05$). Shaded areas indicate significant differences between new and used shoes according to SPM ($p < 0.05$).

and knee joints angular velocities increased in shoes with stiffer midsoles [26]. However, in the present study, other footwear parameters may have been altered. For instance, the longitudinal bending stiffness likely decreased due to repeated foot flexions in sports

activities and it was shown that ankle dorsiflexion velocity was smaller in shoes with lower longitudinal bending stiffness [27].

4.3. Clinical implications & limitations

The increase in the loading rate of the vGRF when running in used shoes may increase the risk for children to experience impact-related injuries. A high loading rate has been suggested to be a cause of overuse injuries in adult runners [18,28] and large heel compressive forces are a predominant factor in the occurrence of heel pain for children [29]. On the other hand, the reduced peak ankle dorsiflexion may have beneficial effects. Indeed, it was suggested that an excessive dorsiflexion might irritate the Achilles tendon insertion site onto the calcaneus, because of an impingement between tendon, bursa and bone [30]. Furthermore, the decreased peak ankle power absorption and ankle negative work in used shoes suggests a lower ankle joint load during the absorption phase that may be beneficial regarding stretch-related injuries. Finally, using new shoes may place children at risk for knee pain during the first weeks of use. The increase in the peak knee flexion might cause increased stress of the quadriceps muscle insertion site on the tibial tuberosity, thus constituting a predisposing factor for knee pain [31].

In contrast with Kong et al. outcomes [14], showing that adults were able to modify their running pattern to maintain constant external load regardless shoe aging, it seems that children were unable to do so. However, one limitation is that the participants performed the running task while they were in a fresh state. It is likely that they were able to withstand the biomechanical load inherent to the higher vGRF loading rate when running in used shoes. Since overuse injuries are due to the repetition of loads on internal structures, it would be relevant to examine whether the differences observed in this study would be exacerbated or attenuated for children in fatigued state.

5. Conclusion

This study showed that children running with used shoes exhibited a higher loading rate of the vertical GRF compared to running with new shoes. That may be explained by the shoe cushioning degradation and the absence of kinematic adjustment at foot strike to compensate for it, whether at the level of the ankle or knee. Given the suggested relationship between high loading rate and running-related injuries, practicing sport activities with used shoes might place children at risk to experience impact-related injuries. Nevertheless, the decreased peak ankle power absorption and knee power absorption in used shoes suggest a lower ankle and knee joints loading during the absorption phase and a greater efficiency that may be beneficial regarding stretch-related injuries. A prospective epidemiological study with a large cohort of children may be relevant to examine how aging and renewal of shoes may affect heel and knee pains in children.

Conflict of interest statement

The authors declare no conflict of interest. The tested shoes were non-commercial, with an original design based on authors' specifications.

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