THE INFLUENCE OF HEEL HEIGHT ON ANKLE KINEMATICS DURING STANDING, WALKING, JOGGING AND SIDESTEPPING IN CHILDREN

Xianyi Zhang[1], Damien O'Meara[2], Benedicte Vanwanseele[1], Adrienne Hunt[3] and Richard Smith[3]
Katholieke Universiteit Leuven, Leuven, Belgium[1]
New South Wales Institute of Sport, Sydney, Australia[2]
The University of Sydney, Sydney, Australia[3]

The aim of this study was to quantify the effects of heel-forefoot height on ankle kinematics during locomotion in children. Measurements were taken by a motion capture system and a force plate on five children. They were asked to perform standing, walking, jogging and sidestepping in barefoot, low heel, standard heel and high heel shoe conditions. Results showed that rearfoot plantarflexion angle was different from shoe rake during standing. There was more ankle plantarflexion as heel height increased during walking, jogging and sidestepping. Ankle inversion velocity increased with shod condition but not significantly. High heel height will affect ankle kinematics during locomotion, which may increase the risk of foot problems. Children and their parents should choose footwear with caution.

KEYWORDS: rearfoot plantarflexion, ankle plantarflexion, ankle inversion.

INTRODUCTION: Children and their parents can choose from a wide variety of shoe styles for school and recreational use. Since shoes affect the physiological development of children's feet, heel height is a shoe variable that must be considered in conjunction with facilitating healthy development of the lower limbs.

Heel height is an influential shoe variable in adults. For example, the excessive ankle inversion movement that occurs when wearing high heels increases the risk for lateral ankle sprain (Foster, Blanchette, Chou, & Powers, 2012). When muscles are used habitually at a particular length, functional adaptations to that length occur in both the muscles (Herzog , Guimaraes, Anton, & Carter-Erdman, 1991) and their tendons (Wren, Beaupre, Carter, 1998). The habitual wearing of high heels constitutes the type of stimulus that induces such changes, and has been found to result in shortening of the gastrocnemius muscle fascicles and increased stiffness of the Achilles tendon (Csapo, Maganaris, Seynnes, & Narici, 2010). Any limitation to active ankle dorsiflexion will be a risk factor for foot problem such as plantar fasciitis.

Most of the research on heel height was conducted on adults. However, children's feet differ in anatomy and function from adult's feet (Walther, Herold, Sinderhauf, & Morrison, 2008). This pilot study was aimed at quantifying the effect of wearing shoes of varying heel height on ankle kinematics during standing, walking, jogging and sidestepping by children.

METHODS: Five healthy girls aged 11.8 ±0.8 years, 1.52 ±0.12 m tall, 40.0 ±11.5 kg in weight, were recruited in Sydney. All participants and their carers gave informed written consent in accordance with the requirements of the University of Sydney Human Research Ethics Committee.

Four shoe conditions were: Barefoot, Low Heel (Technix), Standard (Clarks Daytona standard Oxford style), High Heel (Clarks Rant) provided by Pacific Dunlop, Pty Ltd, Melbourne, Australia. Motion capture of a standardised thigh, shank and rearfoot marker set was achieved by a 14-camera motion analysis system (EVaRT5.0, Motion Analysis Corporation, USA) at 200Hz. Valid and reliable measurement of the rearfoot segment orientation in 3D space was achieved with a detachable marker triad so that rearfoot orientation could be measured in the shoe and compared across shoe conditions (O'Meara, Smith, Hunt, & Vanwanseele, 2007). A joint coordinate system was used to calculate three-dimensional motion between adjacent segments. Five successful trials were recorded for each condition for each participant. Ground reaction force (GRF) data were used to define stance and its sub phases for each trial. The processed data were then time-normalised by linear interpolation to stance phase and ensemble-averaged across trials and participants. Time series curves with mean and 95% confidence intervals were plotted. Statistical analyses were undertaken in SPSS 22.0 (SPSS, IBM, USA) to a predetermined plan. Discrete variables (mean, minimum, maximum and range) were calculated for statistical analysis. A repeated measures ANOVA was used to determine significance. The alpha threshold value was set at 0.05.

RESULTS: Footwear parameters and the degree of rearfoot plantarflexion (relative to the laboratory) during standing are shown in Table 1. The rearfoot plantarflexion angle, the angle of the rearfoot relative to the laboratory coordinate system, in standing was highly correlated with the shoe rake. The correlation coefficient for all the participants was greater than 0.9 while for the mean value, $r = 0.98$ ($p < 0.05$).

Table 1
Footwear parameters and rearfoot plantarflexion angle during standing

	Barefoot	Low heel	Standard heel	High heel
Heel-forefoot height (mm)	0	5	13	34
Rake (º)	0	2.4	6.2	16.5
Rearfoot plantarflexion angle (Mean ± SD) (º)	1.0 ± 0.8	4.0 ± 1.6	8.3 ± 2.7	13.5 ± 3.2

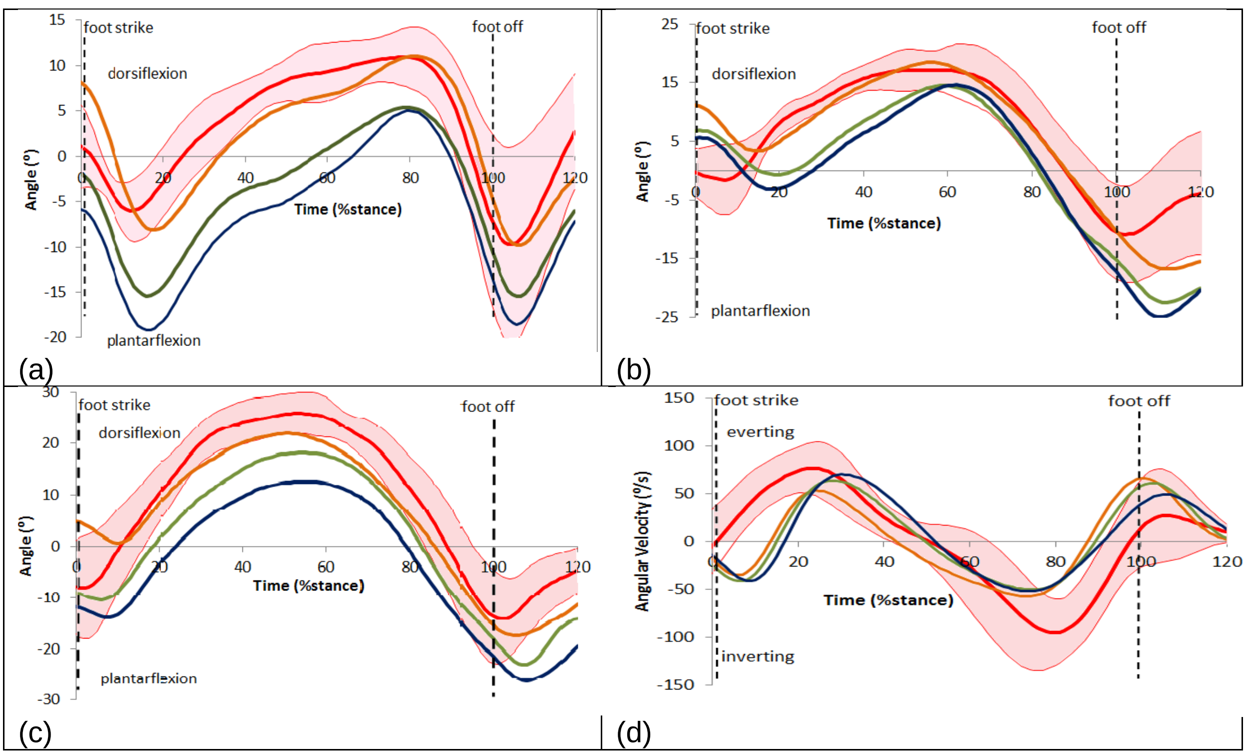

Figure 1: Ankle dorsi/plantar flexion motion time series plots for barefoot (red), low heel (orange), standard (green) and high heel (blue) during (a) walking, (b) jogging and (c) sidestepping. Eversion/inversion angular velocity for the sidestep is shown in (d). The light red shading indicates the 95% confidence interval for the barefoot condition.

Maximum ankle plantarflexion angle increased as heel-forefoot height increased during walking, jogging and sidestepping (Figure 1). However, during walking and running, maximum ankle dorsiflexion was similar for the barefoot and low heel condition and similar for the standard and high heel conditions with the value for the barefoot/low heel pair being greater than the standard/high heel pair. The mean value of ankle dorsiflexion between 15 and 60% of stance decreased in a linear fashion with increasing heel height during walking ($p = 0.002$, $\eta^2 = 0.93$) and jogging ($p = 0.039$, $\eta^2 = 0.49$) where η^2 is the effect size. The means for sidestepping followed the same trend but the result was not significant ($p = 0.11$,

$\eta^2 = 0.522$) due to the high variability of this movement. Considering gait as a main effect, the ankle range of motion (RoM) increased going from walking to jogging then to sidesteppping. Walking ankle RoM (25º) was less than jogging ankle RoM (32º) ($p = 0.008$) and jogging RoM less than sidestepping RoM (40º) $p = 0.06$). As the heel height increased the ankle RoM decreased during sidestepping ($p = 0.013$, $\eta^2 = 0.82$).
Maximum ankle inversion velocity Between 0 and 20% of the stance phase during sidestepping is shown in Figure 1d and Table 2. The ankle inversion velocity was negative for the barefoot condition due to all subjects landing on their toes. The other three conditions exhibited very similar inversion velocities in the first 20% of stance. None were significantly different to the barefoot condition.

Table 2
Maximum ankle inversion velocity between 0 – 20% stance during sidestepping

	Barefoot	Low heel	Standard heel	High heel
Ankle inversion velocity (mean± SE) (deg/s)	-0.6 ±17	41 ±13	37 ±28	45 ±29

There were no significant differences.

DISCUSSION: The deleterious effects of using muscles of the calf at a habitually shortened length was reported in the introduction. Thus, this study set out to test whether wearing shoes of different heel heights resulted in sustained shortening of these muscles. This would be the case if the ankle plantarflexion angle was increased on average during common physical activities. First we measured the rearfoot plantarflexion angle relative to the laboratory during standing and then observed whether the effect was carried through to the ankle plantarflexion angle (rearfoot relative to the shank) during physical activity.
The difference between the rearfoot plantarflexion angle during standing and shoe rake angle suggests that foot alignment was changed, which further confirmed that the foot is not a rigid structure. The rearfoot plantarflexion in the low and standard heel condition is larger than the corresponding shoe rake, indicating that the arch is flattened, which may be due to the shoe's upper restraining the foot morphology. This may be associated with the high incidence of flat feet in regularly shod children (Rao & Joseph, 1992). However, the rearfoot plantarflexion angle is smaller than the shoe rake in high heel condition, indicating that the midfoot is raised. This may because the windlass effect due to the flexion of the toes in this position outweighed the footwear restraining effect and thus raised the arch. Changes in foot alignment would induce changes in the load on foot muscles, ligaments and tendons, and thus affect the development of foot structure. Further studies are needed to determine the optimized heel-forefoot height. According to our results, a height between 13 mm and 34 mm may not affect arch morphology.
A greater rearfoot plantarflexion angle does not necessarily mean a greater ankle plantarflexion as the shank could compensate by rotating forward in the sagittal plane. However, the results showed that higher heels caused larger ankle plantarflexion during locomotion, which is consistent with the previous study on high heel shoes (Mika, Oleksy, Mika, Marchewka, & Clark, 2012). This may be because that the rearfoot is already in a plantar flexed position when the heel is lifted. Similar to the data presented by Stefanyshyn et al(2000), ankle dorsiflexion decreased as heel height increased, which would increase risk of plantar fasciitis (Riddle, Pulisic, Pidcoe, & Johnson, 2003). During walking, the ankle RoM in the sagittal plane increased as heel-forefoot height increased, indicating higher plantar flexor muscle acitivity, which would have an influence on muscle development in children. Previous study suggested that footwear constrains the midfoot motion and cause an increase in ankle motion as compensation during walking in children (O'Meara, et al., 2007). Our findings further confirmed that footwear can cause a larger range of motion of ankle and that higher heel lift can exacerbate this negative effect.
Compared to the barefoot condition, ankle RoM in the sagittal plane was smaller in shod conditions during jogging and sidestepping. This may be because this shoe type lacks flexibility to adapt to fast movement in the sagittal and frontal plane. Thus it should be used with caution for sports.

The large ankle inversion velocity during the first 20% of sidestepping stance phase when wearing shoes suggest increased risk for lateral ankle sprain. Increased ankle inversion movement may be due to the changed strike pattern during sidestepping caused by shoes. The results of the study by Foster et al. (2012) suggested that wearing high heel shoes places the ankle in a more ''at risk'' position for lateral ankle sprains compared to low heel condition. In our study, interestingly, the inversion velocity of high heel shoe is similar to that of the standard shoe, suggesting that heel height is not the only risk factor and further studies are needed.

CONCLUSION: This study quantified the effects of heel height on ankle kinematics in children's everyday activities. Results suggest that heel-forefoot height may have an impact on children's foot development. High heel shoes cause changes in ankle kinematics during locomotion, which might increase risk for problems such as plantar fasciitis and lateral ankle sprain. When choosing a proper shoe for both school use and sport, heel-forefoot height of shoe should be taken into consideration.

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