EFFECTS OF CUSTOM-MADE ORTHOTIC INSOLES ON LOWER LIMB BIOMECHANICS IN CHILDREN WITH FLEXIBLE FLAT FEET

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Received: 20.02.2023 Accepted: 24.04.2023 https://doi.org/10.24264/lfj.23.2.2

EFFECT OF CUSTOM-MADE ORTHOTIC INSOLES ON LOWER LIMB BIOMECHANICS IN CHILDREN WITH FLEXIBLE FLAT FEET

ABSTRACT. This study aimed to investigate the effect of custom-made orthotic insoles on the lower limb biomechanics in children with flexible flat feet. A sample of 27 children (19 boys and eight girls) aged 7 to 13 years old with flexible flat feet participated in the study. Each custom-made orthotic insole was individually designed based on the foot of each subject, using ethylene-vinyl acetate (EVA) material with medium density. The study was conducted using a gait analysis laboratory, and participants were required to walk randomly at a self-selected speed with one of three insole conditions (custom-made orthotic insole, flat insole, and barefoot). The data was processed using Visual 3D software and analyzed by SPSS software. The results showed that using custom-made orthotic insoles resulted in a significant reduction in the maximum ankle inversion angle and ankle inversion moment while increasing the knee adduction moment during the stance phase when compared to wearing either flat insoles or being barefoot ($p<0.05$). This study found that custom-made orthotic insoles significantly altered the biomechanical characteristics of the lower limbs of children with flexible flat feet, reducing the movement of the ankle joint in the frontal plane, thereby enhancing ankle joint stability, but may increase knee joint load.

KEY WORDS: flexible flat foot; orthotic insole; ankle joint; knee joint

INFLUENȚA BRANȚURILOR ORTETICE PERSONALIZATE ASUPRA BIOMECANICII MEMBRELOR INFERIOARE LA COPIII CU PICIOARE PLATE FLEXIBILE

REZUMAT. Scopul acestui studiu a fost de a investiga influența branțurilor ortetice personalizate asupra biomecanicii membrelor inferioare la copiii cu picioare plate flexibile. S-a luat în studiu un eșantion de 27 de copii (19 băieți și opt fete) cu vârsta cuprinsă între 7 și 13 ani, cu picioare plate flexibile. Fiecare branț ortetic personalizat a fost proiectat individual pe baza formei piciorului fiecărui subiect, folosind material pe bază de etilen-acetat de vinil (EVA) cu densitate medie. Studiul a fost realizat într-un laborator de analiză a mersului, iar participanților li s-a cerut să meargă aleatoriu cu o viteză la alegere, în trei situații (cu branț ortetic personalizat, branț plat și desculț). Datele au fost prelucrate folosind software-ul Visual 3D și analizate cu software-ul SPSS. Rezultatele au arătat că utilizarea branțurilor ortetice personalizate a dus la o reducere semnificativă a unghiului maxim de inversiune a gleznei și a momentului de inversiune a gleznei, în același timp crescând momentul de aducție a genunchiului în timpul fazei de sprijin, în comparație cu purtarea branțurilor plate sau mersul cu piciorul desculț ($p<0,05$). Acest studiu a constatat că branțurile ortetice personalizate au modificat semnificativ caracteristicile biomecanice ale membrelor inferioare ale copiilor cu picioare plate flexibile, reducând mișcarea articulației gleznei în plan frontal, sporind astfel stabilitatea articulației gleznei, însă pot crește încărcarea articulației genunchiului.

CUVINTE CHEIE: picior plat flexibil; branț ortetic; articulația gleznei; articulația genunchiului

L'INFLUENCE DES SEMELLES ORTHÉTIQUES PERSONNALISÉES SUR LA BIOMÉCANIQUE DES MEMBRES INFÉRIEURS CHEZ LES ENFANTS AUX PIEDS PLATS FLEXIBLES

RÉSUMÉ. Le but de cette étude a été d'étudier l'influence des semelles orthopédiques personnalisées sur la biomécanique des membres inférieurs chez les enfants aux pieds plats flexibles. On a étudié un échantillon de 27 enfants (19 garçons et huit filles) âgés de 7 à 13 ans avec des pieds plats flexibles. Chaque semelle orthopédique personnalisée a été conçue individuellement en fonction de la forme du pied de chaque sujet en utilisant un matériau à base d'éthylène-acétate de vinyle (EVA) de densité moyenne. L'étude a été menée dans un laboratoire d'analyse de la marche et les participants ont été invités à marcher au hasard à la vitesse de leur choix dans trois situations (avec semelle orthopédique personnalisée, semelle plate et pieds nus). Les données ont été traitées à l'aide du logiciel Visual 3D et analysées avec le logiciel SPSS. Les résultats ont montré que l'utilisation de semelles orthopédiques personnalisées a entraîné une réduction significative de l'angle maximal d'inversion de la cheville et du moment d'inversion de la cheville, tout en augmentant le moment d'adduction du genou pendant la phase d'appui, par rapport au port de semelles plates ou à la marche pieds nus ($p< 0,05$). Cette étude a révélé que les semelles orthopédiques personnalisées ont modifié considérablement les caractéristiques biomécaniques des membres inférieurs des enfants aux pieds plats flexibles, réduisant le mouvement de l'articulation de la cheville dans le plan frontal, augmentant ainsi la stabilité de l'articulation de la cheville, mais pouvant augmenter la charge de l'articulation du genou.

MOTS CLÉS : pied plat flexible ; semelle orthopédique ; articulation de la cheville ; articulation du genou

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INTRODUCTION

Flexible flatfoot is a common condition in children characterized by the absence or collapse of the medial longitudinal arch of the foot [1]. This condition affects approximately 20% to 30% of the pediatric population [2]. Although it usually does not cause pain, long-term abnormal kinematics and kinetics of the lower extremity joints can lead to muscle fatigue, foot pain, asymmetry of the arches, and knee valgus [3]. If left untreated, flatfoot may result in abnormal movements of the foot and lower extremity joints, leading to continuous flattening of the arch, accelerating soft tissue damage of the foot, joint pain, and even impairing balance, stability, posture, and motor skills development in walking [4].

Non-surgical methods such as foot support, arch training, and foot massage, as well as surgical correction, are used for its treatment. Among them, orthotic insoles are one of the non-surgical methods that provide support and stability to the foot, improving the arch structure and foot function [5]. However, the curative effects of universal orthotic insoles may be limited as they cannot fully adapt to individual differences. In contrast, custom-made orthotic insoles are tailored to the patient's foot shape and condition, which may have better adaptability and treatment effects [5].

Studies have shown that custom-made orthotic insoles with arch support can relieve foot pain, improve foot comfort [6], reduce energy expenditure during movement [7], and enhance gait stability in patients with flatfoot [8]. Karimi *et al*.'s study [9] demonstrated that custom-made orthotic insoles could significantly reduce the energy expenditure of patients during movement and increase stride length and stance time. However, the majority of previous studies on the effect of orthotic insoles on flat feet have focused on gait parameters, stability, and plantar pressure distribution, and little is known about the effect of orthotic insoles on lower limb biomechanics in patients with flexible flat feet. Therefore, the objective of this study was to investigate the effect of custom-made orthotic insoles on lower limb biomechanics in children with flexible flatfoot and provide a theoretical reference for orthotic insole design.

MATERIALS AND METHODS

Participants

Sample size was determined using G*Power Analysis program (G*Power 3.1, The G*Power Team, Belgium [10]). One-way ANOVA with repeated measures was used for statistical analysis. Effect size f was 0.26, which was derived from the pre-experiment. A priori power analysis revealed that 26 subjects would be required to achieve 80% statistical power with an alpha level of 0.05. In order to account for potential drop-out and technical errors during the experiment, 27 children (19 boys and eight girls) with flexible flat feet were recruited to participate in this study. Basic information about the subjects in this study is listed in Table 1. Participation in this study was voluntary, and all participants signed an informed consent form.

Table 1: Basic information of enrolled subjects

Variables	Male	Female
Number	19	8
Age (year)	9.1±1.8	9.1±2.3
Height (cm)	136.8±13.7	134.3±25.9
Weight (kg)	35.4±13.1	34.7±11.7
BMI (kg/m^2)	18.3±3.7	17.4±3.7

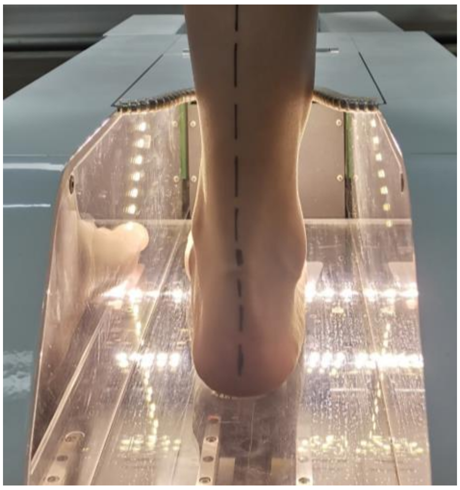
Note: BMI, Body mass index

The inclusion criteria of this study included: (i) children aged 7 to 13 years with flexible flatfoot diagnosed by an orthotic surgeon; (ii) have no history of lower limb injuries or surgeries within the previous six months; and (iii) have no history of wearing custom-made orthotic insole. Exclusion criteria were: (i) rigid flatfoot; (ii) being overweight, (iii) being unable to complete the experimental procedures as required.

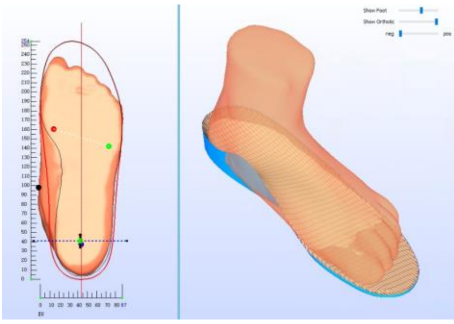
Materials

The custom-made orthotic insole is made of medium-density ethylene-vinyl acetate (EVA). It was designed with two parts to provide both comfort in the forefoot area and support in the rearfoot region. This combination of features helps to promote proper foot alignment and alleviate discomfort for the patient with flexible flat feet. The hardness of the fore and rear parts are Shore C 50° and Shore C 60°, respectively. Each custom-made orthotic insole is custom-made for an individual participant. The process involves taking 3D scans (Upod-s, Carotec Ltd., Guangzhou, China, Figure 1-a) of the subject's feet while they were in a non-weight bearing neutral position [11] and then using these scans to design (IsoleCAD5.4.0, Vismach Technology Ltd., Wuhan, China) and produce a personalized insole for each participant. The design process of custom-made orthotic insoles is shown in Figure 1. This study used the flat insole as a control condition with a thickness of 4mm and a hardness rating of 50° on the Shore C scale. In addition, the same type of children's sports shoes (361° CO. Ltd., Xiamen, China) and cotton socks were used to control for any potential influence they may have on the results. The shoes, orthotic insoles, and flat insoles used in this study are shown in Figure 2. In this study, the orthotic insole's heel cup has a height of 12mm, while the actual thickness of the rear part of the insole remains at 4mm (Figure 2-b). The primary function of the heel cup is to improve the heel's containment and stability within the shoe, without significantly altering the internal dimensions of the shoe cavity or causing discomfort for the subject during wearing.

a. Foot scanner used in this study

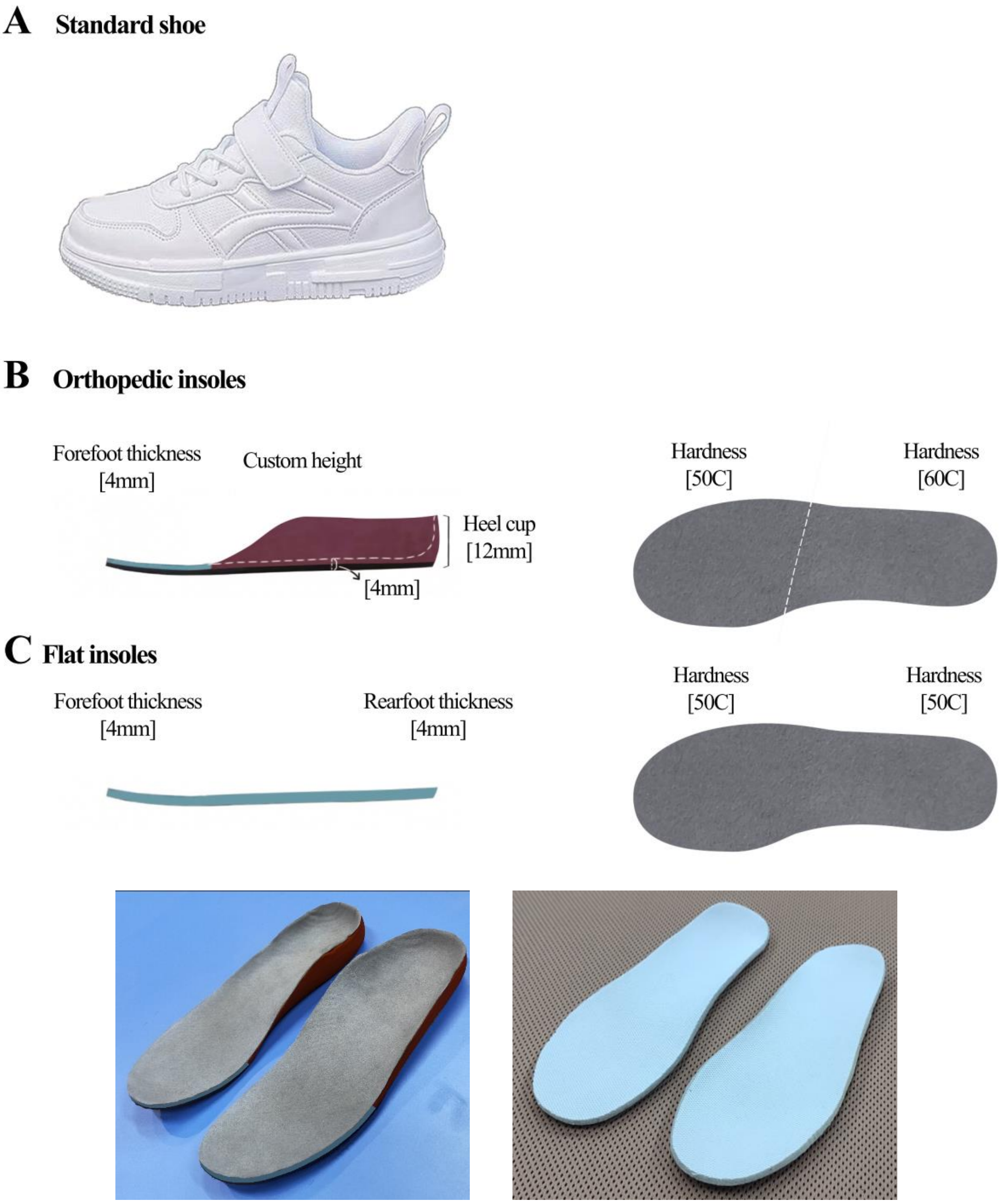


b. Foot scan process



c. Custom-made orthotic insole design process

Figure 1. Foot scan and orthotic insole design process used in this study



Custom-made orthotic insoles Flat insoles

Figure 2. Shoe and insoles used in this study

Experimental Set-Up and Procedures

Overground gait analysis in the present study was performed in a gait analysis lab. Two force plates (Kistler9260AA6, Winterthur, Switzerland, Figure 3-a) were placed in the middle of a 10 m walkway to acquire ground reaction forces of the left and right lower extremities during the stance phase of a walking cycle. Thirty-seven reflective markers placed bilaterally on the pelvis, thighs, shanks, and feet [12] were tracked using a 12-camera motion capture system (ProReflex MCU 1000, Qualisys AB, Sweden, Figure 3-b). Participants were required to walk randomly at a self-selected speed with one of the three insole conditions (custom-made orthotic insole, flat insole, and barefoot). Kinematics and kinetics data were recorded at 100 Hz and 1000 Hz sampling rates, respectively. For gait analysis, three successful self-selected speed gait trials were collected where the foot naturally landed on the force plate, and the gait cycle was detected.

a. Force plate

b. Motion capture system

Figure 3. The force plate and motion capture system used in this study

Data Reduction and Processing

The kinematic and kinetic data were processed using Visual 3D software (C-motion, Rockville, MD, USA) and a fourth-order Butterworth filter was applied with cut-off frequencies of 10 and 50 Hz to filter marker trajectories and ground reaction forces [13]. The 3D joint angles and moments were calculated at the distal segment relative to the adjacent proximal segment using a right-handed orthogonal Cardan x-y-z sequence of rotations. This sequence was chosen to align with the joint coordinate system and included rotations for plantarflexion/dorsiflexion, eversion/inversion, and abduction/adduction [14]. Hip, knee, and ankle joint angles and moments were calculated using inverse kinematics and inverse dynamics for the stance phase. Positive values of the joint angles and moments indicate extension, adduction, internal rotation, dorsiflexion, and inversion, depending on the joint and axis. The time series of each stance phase were normalized to a range of 0% at heel strike on the force plate to 100% at toe-off. Joint moments were normalized by dividing them by body mass and expressed in N·m/kg [15].

Statistical Analysis

In this study, all analyses were performed by SPSS software (version 21.0, SPSS Inc., USA). All data were represented as the mean ± S.D. One-way repeated measures analysis of variance (ANOVA) was performed to examine if there were significant differences in lower limb kinematic and kinetic variables across three insole conditions. Post hoc Bonferroni tests were performed to examine the differences in each dependent variable between insole conditions when a significant difference was observed. The significance level was set at 0.05 ($p < 0.05$).

RESULTS

Kinematics

Table 2 presents the lower limb joint kinematics results for the three insole conditions. The result of this study indicated that different insole conditions significantly impacted ankle joint kinematics ($p<0.05$). The peak hip flexion angle was significantly decreased in custom-made orthotic insoles ($p=0.0003$) and flat insoles ($p=0.0184$)

compared to barefoot. Custom-made orthotic insoles resulted in a significantly greater peak hip adduction angle than flat insoles (p=0.0399).

Results showed a significant increase in peak knee flexion angle (p<0.0001) but a significant decrease in peak knee extension angle (p<0.05) when subjects wore custom-made orthotic insoles compared to being barefoot. No significant differences were observed in knee joint kinematics between custom-made orthotic insoles and flat insoles (P>0.05).

Results showed that different insole conditions significantly impacted ankle joint kinematics (p<0.05). Specifically, the peak ankle dorsiflexion angle significantly increased in both custom-made orthotic insoles (p=0.0001) and flat insoles (p=0.0003) compared to barefoot. Custom-made orthotic insoles resulted in a significantly greater peak ankle dorsiflexion angle than flat insoles (p=0.0247). Additionally, custom-made orthotic insoles and flat insoles resulted in less ankle inversion angle (p=0.0154) and ankle internal rotation angle (p=0.0375) compared to the barefoot condition.

Table 2: Lower limb joint kinematics in three insole conditions during walking (°)

Variables	Barefoot	Flat insoles	Custom-made orthotic insoles	p-value
Peak hip extension angle	36.19±6.41	36.23±6.72	36.16±7.23	0.9909
Peak hip flexion angle	-4.19±6.47	-2.81±6.02*	-2.09±6.62*	0.0002
Peak hip adduction angle	5.69±3.05	5.61±3.35	5.09±3.35#	0.0907
Peak hip abduction angle	-7.90±4.28	-7.64±3.84	-7.81±3.77	0.7270
Peak hip internal rotation angle	-5.92±7.36	-4.61±6.69	-6.08±6.75	0.1922
Peak hip external rotation angle	-15.07±7.28	-13.85±6.08	-14.71±6.48	0.2439
Peak knee extension angle	-12.24±4.64	-9.08±4.31*	-8.64±4.45*	<0.0001
Peak knee flexion angle	-46.72±5.68	-55.13±3.85*	-54.63±4.69*	<0.0001
Peak knee varus angle	3.61±3.81	3.45±3.62	3.58±3.94	0.8855
Peak knee valgus angle	-3.64±3.44	-3.03±2.79	-3.42±3.30	0.3514
Peak knee internal rotation angle	3.39±6.78	3.05±6.40	3.07±6.68	0.8891
Peak knee external rotation angle	-13.80±5.00	-11.88±5.04	-11.86±5.76	0.0521
Peak ankle dorsiflexion angle	14.53±4.39	17.29±4.30*	18.42±4.30*#	<0.0001
Peak ankle plantar Flexion angle	-14.09±6.24	-12.01±5.81	-11.92±5.41	0.0245
Peak ankle inversion angle	6.09±7.54	3.45±4.49*	2.21±4.21*	0.0134
Peak ankle eversion angle	-9.69±7.11	-9.05±3.70	-9.72±3.07	0.6817
Peak ankle internal rotation angle	12.40±5.02	10.82±5.85	9.51±6.30*	0.0274
Peak ankle external rotation angle	-6.69±4.27	-8.66±4.87	-8.71±4.50	0.0377

Note: *indicates a statistically significant difference from the barefoot condition, and #indicates a statistically significant difference from the flat insoles condition.

Kinetics

Table 3 shows the joint moments in the sagittal, frontal, and transverse planes for the hip, knee and ankle joints. Results showed a significant decrease in peak hip flexion moment (p=0.0341) and peak hip extension moment (p=0.0002) when subjects wore custom-made orthotic insoles compared to barefoot. Additionally, the peak hip flexion moment (p<0.0001) and peak hip internal rotation moment (p=0.0441) were significantly lower when subjects wore the flat insole compared to being barefoot.

Results showed a significant increase in peak knee abduction moment (p=0.0399) but a significant decrease in peak knee external rotation moment (p=0.0095) when subjects wore custom-made orthotic insoles compared to barefoot.

Specifically, the peak ankle dorsiflexion moment was significantly increased in both custom-made orthotic insoles (p<0.0001) and flat insoles (p<0.0001) compared to being barefoot. Additionally, custom-made orthotic insoles (p=0.0011) and flat insoles (p=0.0049) resulted in a lesser peak ankle inversion moment than barefoot. Custom-made orthotic insoles resulted in a significantly lesser peak ankle inversion moment than flat insoles (p=0.0047).

Table 3: Lower limb joint kinetics in three insole conditions during walking (Nm/Kg)

Variables	Barefoot	Flat insoles	Custom-made orthotic insoles	p-value
Peak hip extension moment	0.41±0.10	0.39±0.10	0.39±0.10*	0.0237
Peak hip flexion moment	-0.46±0.20	-0.32±0.13*	-0.33±0.15*	<0.0001
Peak hip adduction moment	0.12±0.05	0.11±0.04	0.11±0.04	0.2520
Peak hip abduction moment	-0.3±0.14	-0.31±0.15	-0.31±0.17	0.3792
Peak hip internal rotation moment	0.06±0.03	0.05±0.02*	0.06±0.02	0.0209
Peak hip external rotation moment	-0.10±0.04	-0.10±0.04	-0.10±0.04	0.7415
Peak knee extension moment	0.73±0.39	0.68±0.36	0.73±0.36	0.2138
Peak knee flexion moment	-0.43±0.28	-0.39±0.19	-0.37±0.22	0.2059
Peak knee adduction moment	0.20±0.13	0.17±0.10	0.17±0.10	0.0639
Peak knee abduction moment	-0.37±0.19	-0.39±0.21	-0.41±0.24*	0.0170
Peak knee internal rotation moment	0.17±0.09	0.17±0.09	0.18±0.09	0.2249
Peak knee external rotation moment	-0.10±0.05	-0.09±0.05	-0.08±0.04*	0.0057
Peak ankle dorsiflexion moment	0.35±0.15	0.48±0.20*	0.49±0.21*	<0.0001
Peak ankle plantar flexion moment	-1.44±0.64	-1.43±0.58	-1.40±0.53	0.3427
Peak ankle inversion moment	0.28±0.16	0.22±0.11*	0.19±0.10*#	0.0003
Peak ankle eversion moment	-0.05±0.05	-0.07±0.05	-0.08±0.07	0.0759
Peak ankle internal rotation moment	0.05±0.03	0.05±0.02	0.05±0.02	0.2678
Peak ankle external rotation moment	-0.11±0.04	-0.12±0.06	-0.12±0.05	0.1586

Note: *indicates a statistically significant difference from the barefoot condition, and #indicates a statistically significant difference from the flat insoles condition.

DISCUSSION

Using custom-made orthotic insoles in children with flexible flat feet has been an area of interest for clinicians and researchers. The present study aimed to investigate the effect of custom-made orthotic insoles on the lower limb joint kinematics and moments in children with flexible flat feet during the stance phase of gait. The results showed that custom-made orthotic insoles had a significant impact on hip, knee, and ankle joint biomechanics during gait. The specific effects of custom-made orthotic insoles on each lower limb joint and the study's limitations will be discussed as follows.

Effect of Custom-made Orthotic Insoles on the Hip Joint

The study found that custom-made orthotic insoles could reduce the hip flexion angle, hip extension angle, and hip extension moment, which is consistent with previous research findings [16]. However, the exact mechanism by which custom-made orthotic insoles reduce hip joint flexion and extension is unclear. It could be due to changes in the plantar pressure distribution, alterations in muscle activity, or a combination of both factors. Further research is needed to determine the specific impact of custom-made orthotic insoles on hip joint flexion and extension.

Effect of Custom-made Orthotic Insoles on the Knee Joint

The study showed that knee joint flexion and extension significantly increased in the custom-made orthotic insoles and flat insoles compared to the barefoot condition, which is consistent with the findings of Chen *et al*. [17]. This could be due to the cushioning effect that shoes and insoles provide during walking, which enhances knee flexion and extension mobility. In addition, the internal and external rotation of the knee joint was significantly reduced in both insole conditions, suggesting that wearing both regular and custom-made orthotic insoles reduced the rotational motion of the tibia relative to the femur in children with flexible flat feet. This suggests that wearing the insoles was beneficial in limiting the movement of the knee in the transverse plane.

However, in terms of the knee motion in the frontal plane, results showed that the peak knee abduction moment was significantly increased when subjects wore the custom-made orthotic insole than the barefoot condition. These findings can be explained by the custom-made orthotic insole with arch support shifting the center of pressure inward, resulting in an increased lever arm of the knee joint center to the ground reaction force vector, leading to increased external knee abduction moments. The knee muscles produce more joint muscle moments to balance the increased external knee abduction moment [18]. These findings suggested that wearing custom-made orthotic insoles may increase the stress on the knee joint in the frontal plane. It highlights the need for further research to understand the potential side effects of custom-made orthotic insoles on the knee joint, especially in patients with knee problems or in conditions where the knee joint is already under stress.

Effect of Custom-made Orthotic Insoles on the Ankle Joint

The results of this study indicated that using custom-made orthotic insoles had a substantial impact on ankle joint biomechanics. The study found that the peak ankle dorsiflexion angle and moments were increased, and the peak ankle inversion angle and moments were decreased when subjects wore custom-made orthotic insoles, which is consistent with the finding of Arvin [19] and Hsu *et al*. [20]. The increased ankle dorsiflexion motion in the sagittal plane could enhance the range of motion in the ankle joint and improve its flexion and extension capabilities. The reduced ankle inversion angle and moments observed in children with flat feet who use custom-made orthotic insoles with arch support may be attributed to a shift in the center of pressure towards the inside of the foot. This shift decreases the lever arm between the ankle joint center and the ground reaction force (GRF) vector [21], decreasing the external moment of ankle eversion and a corresponding reduction in the muscle moment responsible for ankle inversion around the ankle joint. The findings in this study suggested that custom-made orthotic insoles could limit the ankle motion in the frontal plane, help improve the stability of the ankle joint, and reduce the strain on the ankle joint during the stance phase, which is consistent with the findings of Karimi *et al*. [22]. These findings suggest that custom-made orthotic insoles may be an effective intervention for children with flexible flat feet. However, more research is required to understand their long-term effects.

It is important to note that the current study has some limitations. It only analyzed the immediate effects of custom-made orthotic insoles on lower limb biomechanics and did not provide information on their long-term effects. Further research that combines surface electromyography tests with kinematic and kinetic variables on the lower limbs could provide valuable insight into the effects of custom-made orthotic insoles. Additionally, it would be helpful to study the impact of other variables, such as different types of movements, movement speeds, insole materials, and hardness, on lower limb biomechanics in children with flexible flat feet.

CONCLUSIONS

Results in this study indicated that custom-made orthotic insoles could effectively reduce ankle joint moments in patients with flexible flat feet during gait. However, the results also suggested that using custom-made orthotic insoles may have an unintended side effect on the knee joint, as the knee abduction moment was significantly increased in the orthotic condition compared to the barefoot condition. This highlights the importance of considering both the positive and negative effects of custom-made orthotic insoles and carefully evaluating their use in each individual case. Further research is needed to fully understand the effects of custom-made orthotic insoles on the mechanics of the ankle and knee joints in patients with flexible flat feet during gait. It is recommended that children with flexible flat feet be given an adjustment period to get used to wearing custom-made orthotic insoles. It can be done by gradually increasing the time the child wears the insoles daily, allowing them to adapt to the insoles and reduce the potential adverse effects on the knee joint.

Acknowledgments

This study was supported by the Shaanxi Provincial Department of Education Key Scientific Research Program Project (No. 21JT002); Health Scientific Research Talent

Project of Xi'an Municipal Health Commission (No. 2022qn09); Xi'an Municipal Health Commission Traditional Chinese Medicine Research Project (No. SZL202205).

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