EFFECT OF CUSTOM-DESIGNED INSOLE WITH ARCH AND METATARSAL SUPPORT ON ADJUSTMENT OF THE LOWER LIMB KINEMATICS

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ABSTRACT. Insole construction is considered to be related to stability in sports, and custom-made insoles with their scientifically tailored approach and effective construction are considered to be the main means of adjusting posture and reducing risk in sports. We have designed a non-100% full-fit design insole (CDI) with an arch support insole and metatarsal liner to determine whether this insole can be adapted to lower limb kinematics. Eleven healthy volunteers participated in this randomized crossover test in which a motion capture and 3D gait analysis system was used to measure the subjects' lower limb kinematic data while exercising at different slopes and speeds wearing three different insoles: CDI, control Insole (CI) and arch support insoles (ASI). In addition, the experiments introduced the speed and slope factor, analyzed the extent to which speed slope affects joint angle using UNIANOVA, and compared the performance differences between the three insoles in different planes in pairs. The CDI inhibited ankle dorsiflexion and knee flexion in the sagittal plane; in the frontal plane, CDI reduced knee adduction and hip abduction angles. There was a statistically significant difference ($p < 0.05$) between the change in joint angle and the velocity slope. Slope*speed had a greater effect on the ankle and knee joints (%sig>30%). The results show that the CDI has better kinematic adjustability in the ankle and knee joints due to its superior insole design approach. Therefore, wearing the CDI may be an effective way of reducing risks in sports.

KEY WORDS: customization, insole, sports injury, joint angle, gait kinematic features

EFECTUL BRANȚULUI PERSONALIZAT CU SUPORT PLANTAR ȘI METATARSIAN ASUPRA REGLĂRII CINEMATICII MEMBRELOR INFERIOARE

REZUMAT. Construcția branțului este considerată a fi legată de stabilitate în sport, iar branțurile personalizate cu structură adaptată din punct de vedere științific și construcție eficientă sunt considerate a fi principalul mijloc de ajustare a posturii și de reducere a riscului de accidentare în sport. S-a proiectat un branț cu un design aproape complet personalizat (CDI), cu un suport plantar și căptușeală în zona metatarsiană pentru a determina dacă acest branț poate fi adaptat la cinematica membrelor inferioare. Unsprezece voluntari sănătoși au participat la acest test randomizat încrucișat în care s-a folosit un sistem de captare a mișcării și analiză 3D a mersului pentru a măsura datele cinematice ale membrelor inferioare ale subiecților în timp ce aceștia se antrenau la diferite viteze și înclinații ale planului, purtând trei branțuri diferite: branțul CDI, branțul martor (CI) și branțuri cu suport plantar (ASI). În plus, experimentele au introdus factorul înclinație-viteză; s-a analizat măsura în care înclinația și viteza afectează unghiul articulației folosind testul UNIANOVA și s-au comparat diferențele de performanță dintre cele trei branțuri în perechi, în planuri diferite. Branțul CDI a inhibat dorsiflexia gleznei și flexia genunchiului în plan sagital; în plan frontal, branțul CDI a redus unghiurile de aducție a genunchiului și a șoldului. A existat o diferență semnificativă din punct de vedere statistic ($p < 0,05$) între modificarea unghiului articulației și factorul înclinație-viteză. Factorul înclinație-viteză a avut un efect mai mare asupra articulațiilor gleznei și genunchilor (%sig>30%). Rezultatele arată că branțul CDI are o ajustabilitate cinematică mai bună la nivelul articulațiilor gleznei și genunchiului datorită designului său superior. Prin urmare, utilizarea branțului CDI poate fi o modalitate eficientă de reducere a riscului de accidentare în sport.

CUVINTE CHEIE: personalizare, branț, accidentare sportivă, unghiul articulației, caracteristicile cinematice ale mersului

L'EFFET DE LA SEMELLE INTÉRIEURE SUR MESURE AVEC SOUTIEN DE LA VOÛTE PLANTAIRE ET DU MÉTATARSE SUR L'AJUSTEMENT DE LA CINÉMATIQUE DES MEMBRES INFÉRIEURS

RÉSUMÉ. La construction de la semelle intérieure est considérée comme étant liée à la stabilité dans le sport, et les semelles intérieures personnalisées avec une structure scientifiquement adaptée et une construction efficace sont considérées comme le principal moyen d'ajuster la posture et de réduire le risque de blessure dans le sport. Une semelle au design presque entièrement personnalisé (CDI) a été conçue avec soutien de la voûte plantaire et une doublure métatarsienne pour déterminer si cette semelle pouvait être adaptée à la cinématique des membres inférieurs. Onze volontaires en bonne santé ont participé à cet essai croisé randomisé dans lequel un système de capture de mouvement et une analyse de la marche 3D ont été utilisés pour mesurer les données cinématiques des membres inférieurs des sujets pendant qu'ils s'exerçaient à différentes vitesses et inclinaisons du plan, portant trois semelles différentes : la semelle CDI, la semelle de contrôle (CI) et les semelles avec soutien plantaire (ASI). De plus, les expériences ont introduit le facteur inclinaison-vitesse ; on a analysé la mesure dans laquelle l'inclinaison et la vitesse affectent l'angle de l'articulation à l'aide du test UNIANOVA et on a comparé les différences de performances entre les trois semelles par paires dans des plans différents. La semelle CDI a inhibé la dorsiflexion de la cheville et la flexion du genou dans le plan sagittal ; dans le plan frontal, la semelle CDI a réduit les angles d'adduction du genou et de la hanche. Il y avait une différence statistiquement significative ($p < 0,05$) entre le changement d'angle articulaire et le facteur inclinaison-vitesse. Le facteur inclinaison-vitesse a eu un effet plus important sur les articulations de la cheville et du genou (%sig>30%). Les résultats montrent que la semelle intérieure CDI a une meilleure ajustabilité cinématique au niveau des articulations de la cheville et du genou en raison de sa conception supérieure. Par conséquent, l'utilisation de la semelle intérieure CDI peut être un moyen efficace de réduire le risque de blessure dans le sport.

MOTS CLÉS : personnalisation, semelle intérieure, blessure sportive, angle articulaire, cinématique de marche

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INTRODUCTION

Walking is a common activity in daily life, it refers to two main phases: weight-bearing and ground reaction forces transition; in order to walk in a healthy way, our body and joints in the lower limbs require reasonable posture, to accommodate this loading. As the only part of body contact with the ground, abnormal foot posture will directly and negatively affect the ankle, knee and hip joints, as well as the related muscles and ligaments and other tissues [1]. Thereby, effective insole design is a straightforward method to rectify and guarantee the joints of the foot and lower limb.

The varied insole structure plays a specific role in adjusting foot posture. For instance, the metatarsal pad (MP) functions as supporting the transverse arch of the forefoot, balancing the load under each metatarsal area, and then relieving the pain of the forefoot. Meanwhile, the arch support structure (ASS) has the most direct effect on the adjustment of foot posture, a suitable ASS both ensures its space for movement and allows the arch to release its full cushioning potential, while also helping the arch return to a neutral position after changing plantar flexion [2]. Shaw *et al*. [3] share the same view that the addition of an ASS to a lateral wedge minimises ankle eversion change, and also minimises adduction moment reductions. In this way the stability of standing and walking is improved and the body posture is successfully adjusted. In addition, the calcaneal pad and the heel cup height can successfully minimize the resting calcaneal stance position angle in flat-footed patients [4]. Most of the above insoles use prefabricated insoles, which have the advantages of low price and high applicability.

Although prefabricated insoles have a positive effect on foot posture adjustment, custom insoles are more plausible in literature. Rodrigues *et al*. [5] examined the impact of medially supported custom insoles on lower extremity kinematics and they found that insoles systematically decreased the eversion, where a higher rate of eversion would increase the risk of injury. In another study, they showed a less internal rotation of the tibia when using medially, laterally and posteriorly supported insole [6]. Bonifacio (2018) *et al*. [7] indicated that medially wedged insoles were commonly used to reduce post-patellar stress, limit foot reverse and tibial internal rotation, aimed to stabilize the foot and ankle joint in patients with patellofemoral discomfort. Currently, the custom design was 100% matching foot plantar surface and manufactured by 3D printing or CNC technology. Jin *et al*. [8] applied this method to design insoles for patients with arch deformities and they showed that the distribution of pressure on the bottom of the foot had been improved. In comparison to conventional techniques, the way of CAD increases the design flexibility and variability. But drawbacks, such as high cost and long time waiting, precluded large-scale applications [9].

The effect of custom insoles to modify the foot posture could be quantified by kinematics assessment. According to an analysis of joint angles, angular velocities, and moments, we could quantify this process of modification. Although there is a great deal of research to support the benefits of custom insole construction, most of these custom insoles are designed 100% full-fit to sole, which can limit the arch ability to adjust its balance to a certain extent. As the position of the foot arch changes during exercise, a full-fit insole can inhibit the foot's ability to cushion itself, increasing ankle inversion and leading to postural instability and sports injuries. Knowledge of how a non-100% full-fit design insole with arch and metatarsal support affects the lower limb kinematics was lacking.

Therefore, the purpose of this study was to develop a non-100% full-fit design insole with ASS and MP and then assess its influence on the lower limb kinematics. The hypothesis was made: since CDI has an optimal plantar fit and accurate structure, it would contribute a positive effect on reducing the ankle dorsiflexion and plantar flexion angles and knee inversion compared to the prefabricated insole.

EXPERIMENTAL

Methods

Participants

The study recruited 11 volunteers including 4 males and 7 females, the inclusion and exclusion criteria for all participants are as follows.

The inclusion criteria were:

(1) healthy people aged 18-40 years old; (2) regular exercise habits in daily life.

Exclusion criteria were:

(1) unstable joints of the lower limbs such as hip, knee and ankle; (2) patients with lower limb deformities; (3) surgery on the lower limbs within six months; (4) previous neurological disorders; (5) inability to complete all test movements as required.

The participant's morphological details were: Mean age: 29.36±3.38 years; mean height: 165.54±10.34 cm; mean weight: 59±13.68 kg; male mean shoes size: 42 (eur); female mean shoes size: 37 (eur). Participants were informed of all test content and signed a written informed consent before the measure. The whole process followed the ethical principles of the Helsinki Declaration and was approved by the Institutional Review Committee of Sichuan University.

LuxScan Software Scanning and Modeling of the Foot

LuxScan (v1.1.25, LuxCreo, China) is an application based on the depth-of-field camera of iPhone phones (iPhone X and above) for easy scanning of foot models. The structure-based optical depth camera consists of a point projector, an IR camera and an RGB camera. During the scanning process, the point projector projects special structural patterns onto the object surface; the neural network algorithm in the phone's bionic chip calculates the 3D shape and depth information of the object based on the distortion of the structural light observed by the IR camera on the 3D physical surface, as shown in Figure 1. After obtaining the 3D structure of each subject's foot, the custom design of the insole is performed according to the corresponding algorithm.

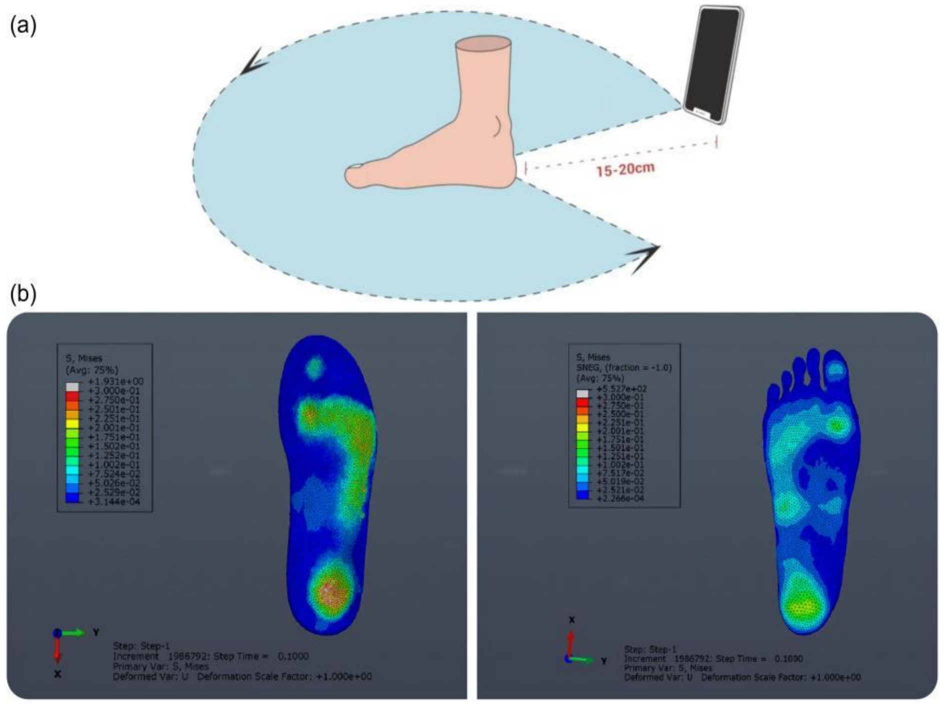

Figure 1. Diagram of LuxScan software operation
(a) Schematic of 3D scan of the foot; (b) 3D plantar structure acquired by LuxScan

Insole Customization Process

The design of the key points for the CDI in this study followed the following steps and the process is shown in Figure 2.

(I) Plane and size design of insole: (Figure 2(a))

The plane of the insole was determined by the first metatarsophalangeal (MTH) joint (72.5% of foot length), the fifth MTH joint (63.5% of foot length) and the key points of the heel (18% of foot length) center.

(II) ASS design of insole: (Figure 2(b))

Arch length: make the medial plantar tangent, and determine the length of the insole arch on the basis of the intersection of the first MTH joint, and the medial heel point with the medial tangent.

Arch width: Using the vertical distance between the medial tangent line and the arch's midpoint (41% of the foot length), calculate the arch width.

Arch height: Excluding the toes, split the foot's shape into three equally sized segments (forefoot A, mid-foot B, and heel C), the height of the arch is determined according to the relationship between the arch index x [x=B/(A+B+C)] and the standard navicular bone y (y=-0.3x+0.2) [10]. The height of the arch is adjusted according to the foot type, the high arch is increased by 2mm, and the flat foot is decreased by 2mm.

(III) MP design of insole: (Figure 2(c))

Determine the position of the MP according to the intersection point between the connecting line of the first MTH joint, the fifth MTH joint and the mid-axis of the foot, adjust the range and height of the MP based on the plantar condition to lift the transverse arch area of the forefoot.

(IV) Heel cup design: (Figure 2(d))

Research on the data from foot type survey in China, the average height of male and female heel bumps is 20mm [11]. The insole is 3D printed with PLA material.

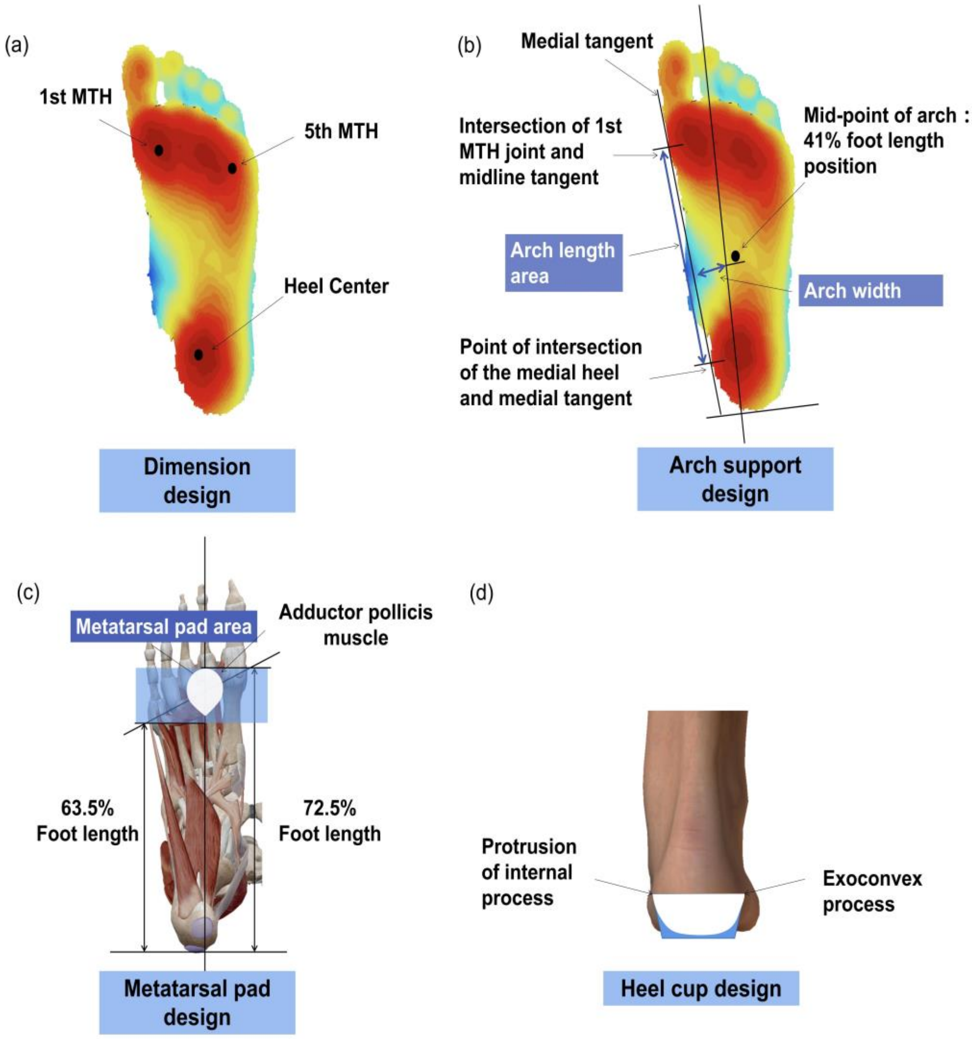

Figure 2. Logic diagram of insole customization
(a) Size design; (b) Arch support area location design; (c) MP design; (d) Heel cup design

Insoles for Measurements

A total of three insoles were tested in this study. The CI had no insole construction and simulated the prefabricated insoles that come with daily purchased shoes. The ASI (with ASS) simulated the more common functional insoles currently available. The three insoles were tested kinematically to investigate whether the CDI we designed positively affected lower limb kinematics.

In this experiment, we used three types of insoles in the same experimental shoe for testing. The hardness was measured using a Shore Digital C hardness tester and the three insoles were tested three times on the forefoot, arch and heel, with the average of the three tests being the final hardness result. For the specific parameters of the insole and the experimental shoes are shown in Table 1.

Table 1: Experimental insole parameters

Types of insoles	Front view	Back view	Profile	AAS	Heel cup	MP	Front rear height difference	Remarks
Custom-designed insole (CDI)				√	√	√	6mm (average)	The insole is a lattice structure
Control Insole (CI)				×	×	×	0mm	Unstructured
Arch support Insole (ASI)				√	√	×	1.8mm	Raised structure of the transverse arch of the foot

Types of insoles	Front view	Back view	Profile	AAS	Heel cup	MP	Front rear height difference	Remarks
Experimental shoe							Front heel height 11mm, heel height 25mm, 13mm height difference between front and rear	Total weight 325g

Types of insoles	Forefoot area hardness	Foot arch area hardness	Heel area hardness	Material	Production Technology
Custom-designed insole (CDI)	42°Shore C	38°Shore C	33°Shore C	polymeric elastic material	Digital Light Procession
Arch support Insole (ASI)	50°Shore C	42°Shore C	46°Shore C	EVA (Ethylene Vinyl Acetate Copolymer), Latex gasket support	Moulding
Types of insoles	48°Shore C	48°Shore C	48°Shore C	EVA	One-piece cutting and gluing

Kinematics Measurement

The Vicon Nexus and Vicon Polygon (Vicon vantage, Vicon, UK) software in the Vicon optical motion capture system was used to collect and process participant kinematic data, maintaining a global coordinate axis system throughout the experiment. Lower extremity reflective points were marked as shown in Figure 3. During the experiment, care should be taken to remove or cover the possible reflective items within the shooting range to avoid the influence of sunlight, lights and other reflective items on the camera identification. After the subjects changed into the experimental clothes as required, 16 reflective points were set on the left and right side of the lower limbs (Figure 4(a)): anterior superior iliac spine, posterior superior iliac spine, thigh, knee, tibia, ankle, toe, heel. The eight Vicon cameras were aligned at 45° angles on all four sides of the 10m square test field, with the treadmill placed in the center of the test field, (Figure 4(b)). To strengthen the experimental effect, we introduced the speed and slope factors, in initial conditions, the male walked at the speed of 5km/h and the female walked at the speed of 4km/h under the condition of 0% slope. Speed simulation: +10% PRS, -10% PRS, grade simulation: +5% grade, +10% grade. A three to five minutes warm-up was first provided to participants, then they were asked to wear three different insoles (CDI, CI, ASI) at random. Participants wearing the insoles were required to perform a randomly assigned ramp speed walking task, maintaining rest intervals of 5 minutes during the test. Eventually, after filtering out incomplete measurements, data of 60 seconds after gait stabilization was selected for acquisition into the database.

Figure 3. Schematic diagram of lower limb model reflective points – front, side, back and detail

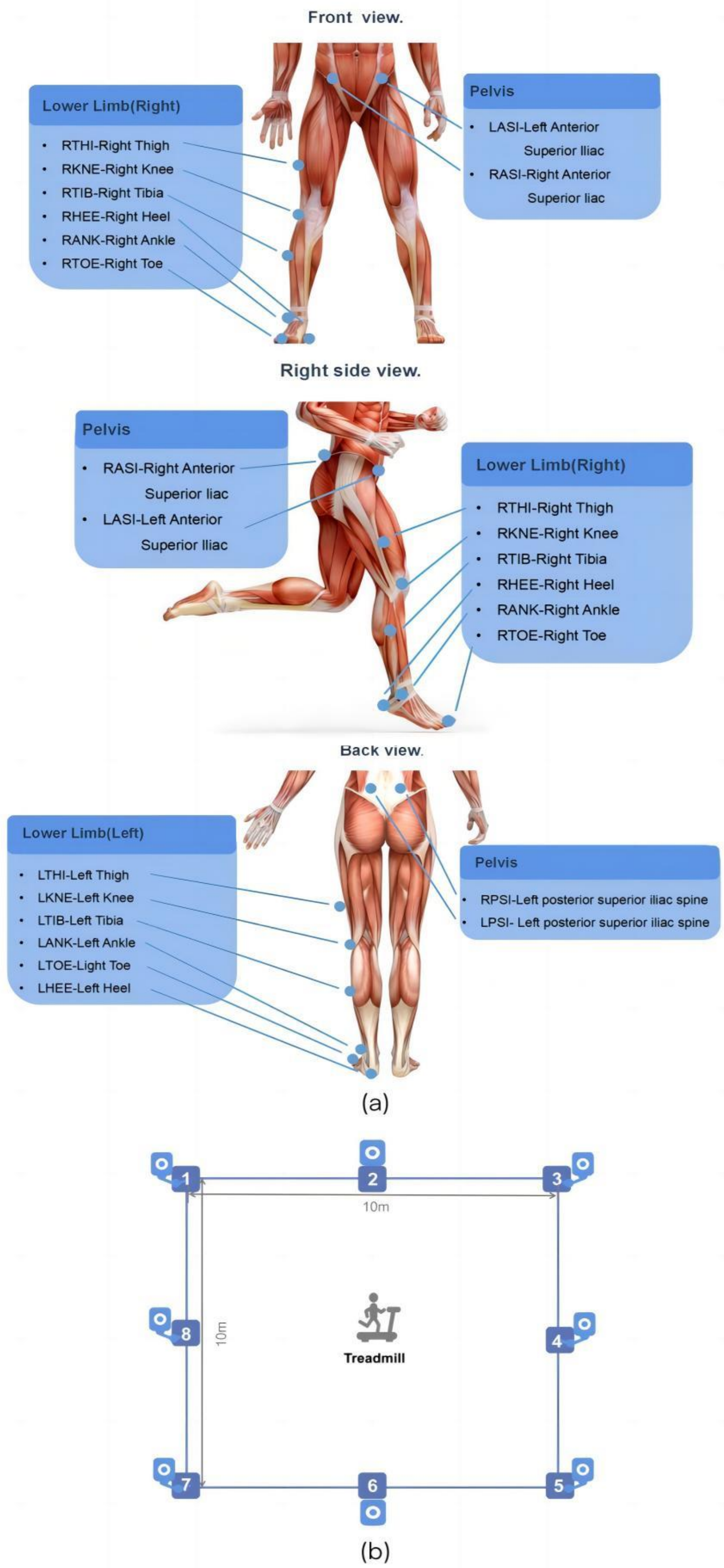

Figure 4. Schematic diagram of insole measurement.
(a) Vicon schematic diagram of reflective points; (b) Schematic diagram of the test site

Data Processing

Using a right-handed coordinate system, each joint is divided into three planes: X (sagittal plane), Y (transverse plane), Z (frontal plane). Since the insole mainly affected motion in X and Z, we chose the sagittal plane and frontal plane for data analysis. Directions were defined for each joint as below: ankles sagittal plane: positive is dorsiflexion and the negative is plantarflexion; ankle's frontal plane: positive is inversion and the negative eversion. The sagittal plane of knee and hip: positive is flexion and the negative is extension; the frontal plane of knee and hip: positive represents adduction and negative represents abduction.

Three complete consecutive strides per phase were used for data analysis, where a complete gait period was defined as from the moment the ipsilateral foot left the ground (the beginning of the gait period) to the moment the second foot left the ground (the end of the gait period) [12]. In terms of the joint angle change evaluation, time-series data were first filtered by a Data filter module of Origin (Origin 8.0, OriginLab, USA) with a 6 Hz cut-off frequency, three complete gait cycles were selected for each case, and then MATLAB (version R2021a, MathWorks, USA) was used to create a 100 points time-normalized gait cycle (GC). The data were normalized for ease of data processing and better observation of data trends, with the algorithm processing logic (Eq. (1)):

$$\alpha=(x-min)/(max-min) \quad (1)$$

where x represents joint angle of each point, min represents valley angle and max represents peak angle.

We first plotted the relationship between the angle and gait cycle in each joint and then UNIANOVA analysis was used at each gait cycle point to explore the influence of slope, speed and slope&speed on the results. Dependent variables were the joint angle, fix factors were insoles, random factors were slope and speed. Within insole's group variances were tested by the Bonferroni model from *post hoc* analysis. Significant differences ($p < 0.05$) from 100 variance analyses were summarized and we used the percentage of significant to indicate the degree of variance. The statistical analyses were performed using SPSS (IBM SPSS Statistics26, SPSS, USA) and α was set as 0.05.

RESULTS

The Insole Lower Limb Kinematic Performance

Similar effects were found for those three insoles in the sagittal plane (Figure 5(a)). During 1–40% GC, CDI and the other two insoles were similar in dorsiflexion and plantarflexion movement, but dorsiflexion of CDI was lower than other groups. In the frontal plane, a higher inverse in the stance phase was found in CDI and ASI during 10% - 50% GC, in contrast with CI; meanwhile, the degree of eversion was lower in CDI and ASI than CI. Variance analyses between CDI and ASI showed that inversion angle of CDI was higher than ASI during single support phase (10-40% GC); further, CDI had minimal ROM (Range of motion) in the frontal plane.

Kinematic parameters of the knee joint in the sagittal plane (Figure 5(b)). CDI and CI showed a similar tendency in flexion angles since the onset of foot contact. During most phases of gait (20-50% GC), the ASI exhibits less knee extension. When heeled off, CDI demonstrated high flexion and continued into the swing phase. In the frontal plane, we observed that CDI was effective in controlling knee adduction mid-to-late stance phase (20-55% GC), where the adductor angle of the knee is noticeably smaller than that of the other two insoles.

In terms of the hip in both the sagittal and frontal plane, variances within three insoles were smaller than the ankle and knee (Figure 5(c)). However, CDI exhibited larger hip extension degrees during early stance of the moment of landing (1-15% GC); while hip extension angle was suppressed during heel off. In the frontal plane, both CDI and ASI showed greater hip abduction angles in the pre-stance phase (1-20% GC), and CDI effectively controlled the degree of hip abduction (21 GC-50% GC) as the gait moved into the mid-stance phase.

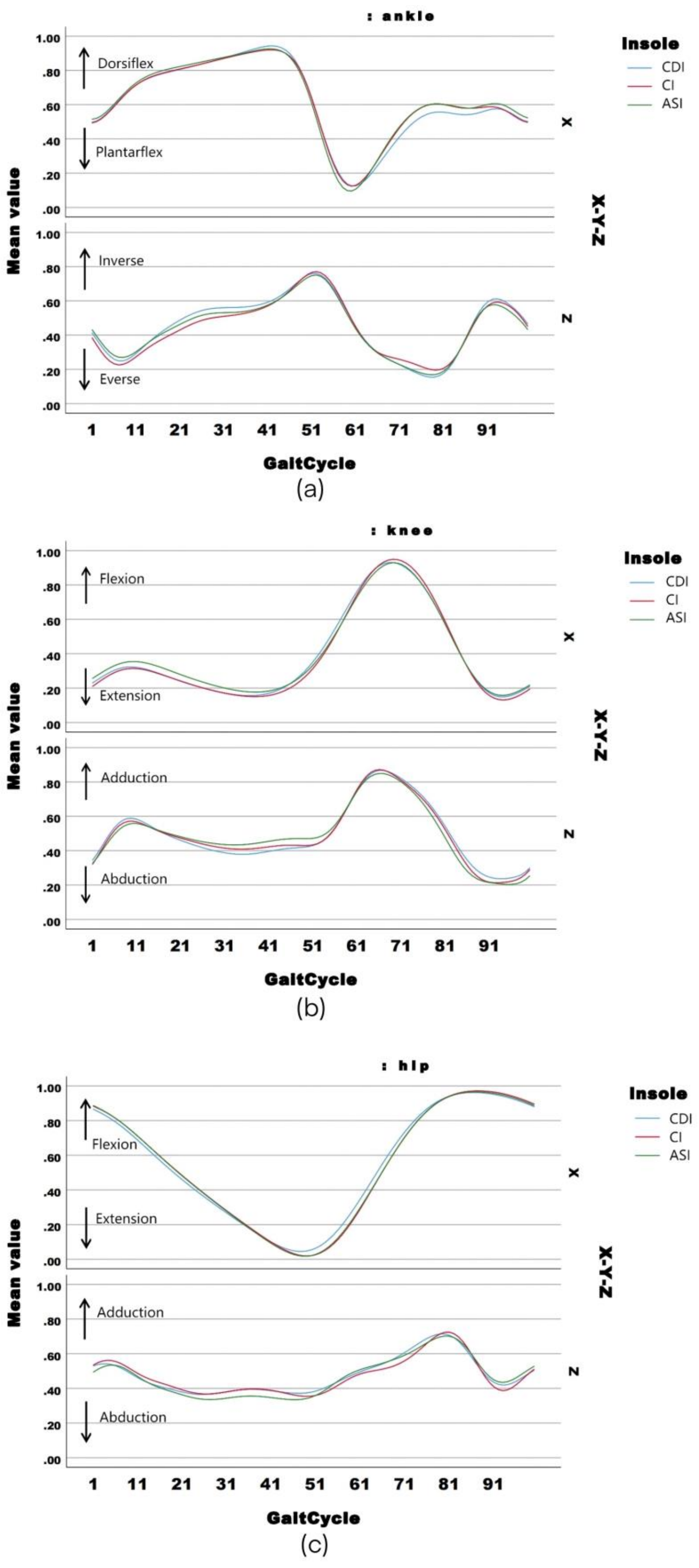

Figure 5. Angle change curve of lower extremity joint.
(a) Sagittal and Frontal plane of ankle joint; (b) Sagittal and Frontal plane of knee joint;
(c) Sagittal and Frontal plane of hip joint

Analysis of Variance

The UNIANOVA results were shown in Table 2. Overall the combined speed*slope factor had a large effect on the lower limb joint kinetic data, particularly for the knee and ankle joints. The effect of slope on sagittal motion of the hip was significant (%sig>30%); speed had a greater effect on sagittal motion of the ankle (%sig>15%), but limited effect on the knee.

The differences between the insoles are mainly between the CDI and the other two insoles. Exceeding 20% differences were found within the two insoles in sagittal plane (CDI V.S CI, CDI V.S ASI), while there were no significant differences in the ASI V.S CI. The results from the frontal plane showed that significant differences in the ankle joint in the CDI V.S CI (%sig>30%) and the knee joint in the CDI V.S ASI.

Table 2: Variance analysis results of lower limb joints

Influence factor		Slope	Speed	Slope*speed
	Ankle	9%	16%	37%
Sagittal plane	Knee	5%	0	37%
	Hip	34%	9%	13%
	Ankle	0%	8%	73%
Frontal plane	Knee	0%	14%	65%
	Hip	0%	19%	39%
Insoles difference		CDI V.S CI	CDI V.S ASI	CI V.S ASI
	Ankle	23%	29%	0
Sagittal plane	Knee	27%	20%	0
	Hip	27%	20%	0
	Ankle	31%	0	0
Frontal plane	Knee	0	15%	2%
	Hip	9%	0	0
	Ankle	31%	0	0
Frontal plane	Knee	0	15%	2%
	Hip	9%	0	0

CDI, Custom-designed insole; CI, Control Insole; ASI, Arch support Insole

DISCUSSION

This study first developed a methodological approach to custom insoles with arch and metatarsal support and then assessed its effectiveness in modifying the lower limb kinematics during walking. Meanwhile, we introduced slope and speed factors to emphasize the effect of the CDI. Our results proved that CDI significantly reduced ankle eversion and dorsiflexion angles during landing; further, we found that CDI not only directly affected ankle motion; but also affected the knee and hip joints, reducing the angle of knee adduction in the frontal plane and effectively controlling the hip abduction angle. Based on the above finding, we postulated that since the CDI with a more precise structural design and better plantar fitting than the other two insoles, a positive effect on lower limb kinematics would be found. In addition, our CDI was combined with 3D scanning, computer modeling [9], and 3D printing technology [13, 14], which made the manufacturing of custom insole more flexible.

Theoretically, reducing ankle valgus contributes to lateral movement of the center of pressure, which reduces medial knee loading and increases body stability. Our findings confirm this, as the CDI effectively reduces the initial valgus angle of the ankle during the stance phase (10-50% GC) and the dorsiflexion angle during the landing phase, and the CDI has a smaller amount of peak ROM during the stance phase than the other two insoles. This is due to the fact that the CDI has structures such as the MP and ASS, which give it a better plantar fit than the control, increasing the contact between the insole and the sole of the foot, thus further improving foot stability during movement. This is consistent with the findings of K.E. Shaw *et al.* [15].

Our finding further approved the significance of ASS in the insole, it functioned by reducing the initial ankle landing angle, maximizing internal, external rotation angle, and angular deflection [16, 17]. Thereby, orthoses with ASS were widely used in clinical practice to limit abnormal hindfoot rotation angles [18]. Similar functions of insole structure were also reported in literature. Hanatsu *et al*. [19] used medial foot support to reduce knee abduction during walking, thereby reducing patellofemoral pain. There had also been investigations into the significant effect during exercise. The ASS could not only mitigate the indirect effects of knee to ankle external rotation, also reduced hip adduction during support by increasing the ROM in the frontal plane [20]. However, it has also been shown that the ASS structure may increase the stress load on the medial and medial longitudinal arches of the ankle. This may be one of the reasons for the discomfort in insole wear found in previous studies [21] and the poor clinical outcomes produced in randomized clinical trials [22].

In addition, our methodology was featured with a 70% fit design for ASS. According to our previous data, 70% fit support allowed the arch to have a flexible amount of movement during exercise, provided better support for walking comfort and foot posture. In the past few years, there have also been studies that confirm this incomplete fitting of ASS is helpful for physical stability and walking comfort. The flexible mesh structure is used instead of a 100% fitted ASS, the elastic activity of the arch provides better static and dynamic balance for walking and arch support [23].

However, most of insoles on the market were designed with a 100% full-fit arch, which leads to excessive arch elevation and knee hyperextension, affecting lower limb joint flexion and extension stability, and may even affect blood flow and have a negative impact on foot ulcers in diabetic foot patients [24]. The full-fit ASS insole resulted in a large initial dorsiflexion angle, which makes it impossible to balance ankle dorsiflexion and knee flexion in the face of a raised slope, thus inhibiting the caching ability of the arch with large joint changes and making it easy to fall and cause bone damage [25, 26]. This makes it easy to fall and causes bone damage.

Other structures such as MP and lateral wedge with ASS also help to stabilize the lower limbs. Gillian *et al*. [27] further concluded that wearing a lateral wedge with ASS reduced knee moment pulses, which had a positive effect on reducing knee pain and improving knee function in patients. Hanatsu *et al*. [28] proposed that the risk of a fall injury is reduced by adjusting the insole height difference and MP design to assist ankle dorsiflexion and eversion angles.

Our study also introduces a speed-slope factor to investigate the effectiveness of the insole structure in dealing with complex environments. Research shows that the effect of slope was directly on the sagittal plane and the speed factor focused on the sagittal plane of the ankle joint; the combined effect of slope and speed was mainly on the frontal plane of the ankle and knee joints. When walking uphill, the body’s center of gravity was shifted forward to the front of the foot, and a higher gradient at the same speed had a faster step frequency [29]. Due to the shortened support period during uphill walking compared to horizontal walking, the lower limb joints became more flexed during heel landing and more extended during stance [30]. There is evidence that the use of sloping surfaces has a greater impact on the sagittal joint motion [31]. However, the structure of the insole with 70% arch fitting can effectively regulate the natural dorsiflexion angle of the slope, allowing the ankle joint to remain in a relatively neutral position without excessive dorsiflexion in the face of the slope, thus maintaining walking stability [32].

Speed, and the combined effects of speed and slope, had a positive effect on the lower limb ankle joint in the frontal plane. Although the ankle joint was more affected by speed and slope, the knee joint plays a linking role in the lower limb joints, reasonable knee flexion and ROM could provide stability and relief from osteoarthritic knee pain [33]. Therefore, knee angle control is also particularly important for lower limb stability [34]. Kerrigan *et al*. [36] stated that medially supported insoles of different heights all significantly reduced knee inversion torque and peak angles under uphill walking conditions, theoretically explaining that ASS is biomechanically effective in reducing knee joint loading and adjusting knee posture. Hence, our hypothesis was confirmed.

Several limitations were available in this study: firstly, the sample size of the experiment was small. Future research should increase the sample size, and even invite patients with lower limb diseases to test, to better evaluate the impact of insole structure kinematics. Secondly, there are a few types of insoles involved in the study. In the future, we can increase the types of experimental insoles, compare and analyze them with other single variable insoles, and better analyze the functions of various structures of insoles.

CONCLUSIONS

CDI with a more precise structural design and better plantar fitting than the other two insoles, a positive effect on lower limb kinematics has been found and this structural design of customized insoles (70% fit design for ASS) actually enhances the dynamic stability and comfort of the lower limbs and improves sports safety. Our CDI was combined with 3D scanning, computer modeling, and 3D printing technology, which made the manufacturing of custom insole more flexible. This method would make production of "customized" insoles be actually applied in daily life. According to our methodology, an efficient custom insole would be developed.

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