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The dynamic characteristics of the center of pressure for toe-out gait: implications for footwear design

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Abstract

Background: Toe-out gait is often used as a conservative technique to reduce knee adduction moment, which has been targeted to modify knee osteoarthritis progression. The center of pressure (COP) can not only be used to evaluate gait stability, but is also more reliable and practical than local plantar pressures as it does not depend on accurate foot zone divisions. However, to the authors' knowledge, few study has reported the influence of the foot progression angle on the dynamic characteristics of the COP.

Research question: The aim of the study was to investigate the effects of the deliberately toe-out gait on the COP trajectory and stability during walking in healthy individuals.

Methods: Thirty healthy young adults were asked to walk along an 8-m walkway. A Footscan 1 m pressure plate was used to measure the center of pressure during walking.

Results: Compared to the normal gait, the COP of the toe-out gait shifted laterally during the initial contact phase, and shifted laterally and anteriorly during the forefoot contact phase. The mean anterior–posterior velocity of COP reduced by 0.109 m/s during the foot flat phase and the duration of the foot flat phase and forefoot push off phase increased by 4.5% and reduced by 7.0%, respectively.

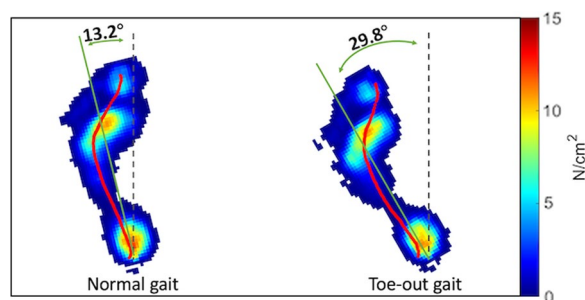
Significance: Compared to the normal gait, the findings of this study suggest that biomechanical alteration of foot under our experimental conditions may decrease gait stability and increase forefoot load during toe-out walking. The situation may be improved by well-designed footwear or custom-made insole and the biomechanics analysis method can be used to test the efficacy of therapeutic footwear or insole for individuals with deliberately toe-out walking.

Keywords: Toe-out, Center of pressure, Walking, Velocity

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Graphical Abstract



1 Introduction

The knee joint bears and transmits weight during daily activities, but excessive knee loading increases the risk of knee osteoarthritis (OA) [1]. The lifetime risk of symptomatic knee OA is 44.7% [2]. The high prevalence and burden of knee OA have led to increased efforts to investigate factors underlying knee OA pathology, progression and intervention [3]. The medial compartment of the knee transmits the majority of load during walking in healthy knees. Consequently, medial knee OA is more prevalent than lateral knee OA, due to excessive loading in the medial compartment of knee [4].

Knee adduction moment (KAM) is a well-acknowledged representative measure of knee joint loading [1] and lowering the KAM has therefore been targeted to manage knee OA progression. The knee adduction moment is the product of the ground reaction force (GRF) vector in the frontal plane and the perpendicular distance from this vector to the knee joint center [4]. One of the conservative techniques to reduce KAM is altering the gait pattern, commonly called gait modification/retraining technique, which includes modification in walking speed and changing the foot progression angle. Toe-out gait, which increases the foot progression angle, shifts the GRF vector closer to the knee joint center, decreasing the knee adduction moment arm. In such way, the KAM can be reduced [4]. The foot progression angle is potentially modifiable using gait training or foot orthotics of 2 weeks [5]. More specifically, toe-out gait decreases the adduction moment during the late stance of gait to reduce the loading on the medial compartment of knee in individuals with medial knee OA [6].

A toe-out gait can be theoretically caused by any combination of increased external rotation of the thigh, lower leg, or foot segments [7]. The entire lower limbs acts as a linked kinetic and kinematic unit; hence, alterations at any joint can have an influence on loading patterns of lower limbs during walking [8]. Though a toe-out gait is

benefit for modifying knee osteoarthritis progression, its effect on foot kinetics remains unclear. As walking is the most common activity of daily living [9], investigations are required to evaluate the effect of a toe-out gait on the kinetics of the foot in healthy individuals. The plantar pressure distribution of toe-out walking is well documented for children with and without neuromuscular diseases, adults with and without diabetic foot lesion [10–13]. This pressure distribution is often evaluated by comparing the peak/mean pressure on different plantar regions, which is not time-dependent variables and contain minimal information on the dynamic foot function during gait. Furthermore, the precision of plantar region division has a significant impact on the pressure distribution results [14, 15], but a consistent division across all participants is difficult to achieve. Compared to the regional plantar pressure analysis, the analysis of the center of pressure (COP) trajectory is more practical and reliable, and also represents the plantar pressure distribution over time [16].

A toe-out gait changes the plantar COP trajectory during walking [17]. The positional changes of the COP as small as 2 mm with respect to the subtalar joint axis may alter the balance of moments acting across the subtalar joint axis, so that a normal foot may begin to malfunction and develop pathologies [18]. In addition, the COP variables have been used to investigate medial–lateral stability of the foot [19]. It has been reported that toe-out would increase fall risk when combined with knee brace [20]. However, to the authors' knowledge, few study has reported the influence of the foot progression angle on the stability during walking.

Therefore, the aim of the study was to investigate the effects of deliberately walking toe-out on the kinetics of the foot and stability in healthy individuals. Potential findings may provide a better understanding of the biomechanical factors associated with a toe-out gait, which provided a basis of clinical intervention for individuals

with a toe-out gait to attain rational plantar pressure distribution and reduce fall risk. The characteristics of COP trajectories may have implications for assessing footwear or customized insoles of individuals with toe-out walking. As a toe-out gait shifts loading distally during walking [12] and increases fall risk when combined with a knee brace [20], we hypothesized that there was a different displacement of the COP moving in heel-to-toe direction between deliberate toe-out gait and normal gait, and that the former could reduce gait stability.

2 Methods

2.1 Participants

An a priori sample size calculation was performed based on our variability from unpublished pilot data. With a power of 80% and an α level of 0.05, a minimum sample size of 26 participants was required. A total of thirty healthy young adults (25 males and 5 females, with mean \pm SD age: 21.4 ± 0.9 , Body mass index: 21.2 ± 2.4 kg/m²) were recruited from the campus. All of them gave informed consent and participated in this study. None of the participants had any lower extremity injuries for the last 6 months prior to testing.

2.2 Materials and apparatus

When measure from a transducer matrix pressure plate, the COP is determined by calculating the centroid of the total number of active transducers for each data sample collected, the position of the participants' foot is always known [21]. A 1-m Footscan pressure plate (RScan International, Belgium, $1068 \times 418 \times 12$ mm, with 8192 resistive sensors arranged in a 128×64 matrix at a resolution of 2 sensors/cm², sensor dimensions: 5.08 mm \times 7.62 mm, and pressure range: 0–127 N/cm²) was located in the middle of an 8-m walkway to provide the determination of COP and the foot progression angle. The system was used to record COP coordinates at a measurement frequency of 250 Hz. Displacement of COP in the medial–lateral direction was defined with respect to the x-axis, perpendicular to the longitudinal foot axis. This longitudinal foot axis was defined as the line from mid-heel to forefoot, between metatarsal head 2 and 3. Because only the transducers that have contact with the foot are excited, the plantar pressure outline is clarity and the forefoot (or metatarsal head) and heel were easily discernable.

2.3 Procedures

Participants were asked to walk barefoot along an 8-m walkway, with an integrated 1 m pressure plate, at their self-selected speeds. After a period of practice to allow familiarity, participants performed walking trials with their natural foot progression angle. A verbal and visual

demonstration of toe-out gait was provided and participants were then asked to walk with their feet turned outwards intentionally, to a comfortable degree. The angle achieved was therefore self-selected [22]. Five walking trials of each participant in natural foot progression angle and toe-out were recorded.

2.4 Data analysis

According to the study [23, 24], there was no significance difference of COP between left and right foot. The average COP data of selected three steps with the left feet landed on the pressure plate completely of each condition for each participant was used for data analysis. The COP data analyses were performed on the left foot. The toe-out angle is the intersection angle of foot axis direction related to the gait direction and the data were processed using footscan[®] analysis software to determine each individual's normal and self-selected toe-out angle during walking.

The stance phase was divided into four phases from dynamic pressure-based footprints by the footscan[®] analysis software. These phases are the initial contact phase (ICP), the forefoot contact phase (FFCP), the foot flat phase (FFP) and the forefoot push-off phase (FFPOP). The ICP is from the first foot contact until first metatarsal contact with the pressure plate. The FFCP follows the ICP and ends with all metatarsal head areas contacting with the plate. The FFP is the period from all metatarsals contact until the heel is off the plate, and the FFPOP is the last subphase of the stance.

Normalization of the COP medial–lateral and anterior–posterior displacements was performed, with respect to each individual's foot width or foot length, respectively [23]. The medial–lateral and anterior–posterior COP velocity were calculated with the x- and y-coordinates displacements divided by the elapsed time between measurements respectively. Mean displacements of the COP were plotted on the “standard foot”, which was calculated as the average of foot length and width of all participants [25]. When comparing the time spending on the sub-phase of gait, all trials were normalized to the total contact time. The range of the COP excursion and velocity was calculated as the absolute difference between the largest and smallest x-, y-coordinate and COP velocity respectively during the corresponding phase. The x- and y coordinates were calculated to the relative x-, y-coordinates and plotted as COP trajectory with polynomial interpolation in Matlab version 2009b (Mathworks Inc.).

Statistical analyses were performed using SPSS version 22. Each parameter was evaluated for normality, if a measure did not achieve normality after transformation, Wilcoxon Signed Ranks Test were performed. Paired

samples t-test was only used to test the foot rotation angle between two conditions. The test was performed to ensure that the foot progression angles between two conditions were statistically different. Differences between toe-out and normal gait were assessed using paired samples t-test to determine the effect of the toe-out gait on the walking speed and COP characteristics. Significant differences between the two conditions were considered

if $p < 0.05$. Cohen's *d* effect size (ESd) was calculated, where effect sizes between 0.20 and 0.33 were considered small, between 0.33 and 0.50 were medium and above 0.5 were considered high [26].

3 Results

There was a significant difference in the self-selected walking speed between two conditions ($p = 0.013$, $ESd = 0.48$), with 0.98 ± 0.12 m/s for toe-out and 1.02 ± 0.1 m/s for normal gait. The foot progression angle of toe-out walking was significantly higher ($p < 0.001$, $ESd = 3.19$) than normal gait, with $29.8 \pm 5.7^\circ$ for toe-out and $13.2 \pm 5.5^\circ$ for normal gait.

Foot length and foot width for all participants were averaged as the "standard foot" with foot length 25.3 ± 1.3 cm and foot width 7.0 ± 1.1 cm. The trajectory of COP for the toe-out and the normal gait are shown in Fig. 1. Comparisons in the medial-lateral and anterior-posterior COP parameters between the toe-out and the normal gait are shown in Tables 1 and 2, respectively.

The y-axis is the longitudinal axis of the foot, and x-axis is perpendicular to the longitudinal foot axis. Sub-classified phases are ICP, FFCP, FFP and FFPOP.

Compared to the normal gait, the toe-out gait shifted the COP trajectory laterally during the first half and then medially during the second half of the stance phase. More specifically, with a toe-out gait, the mean and maximum displacements of COP in medial-lateral direction for toe-out were increased by 3.2 mm

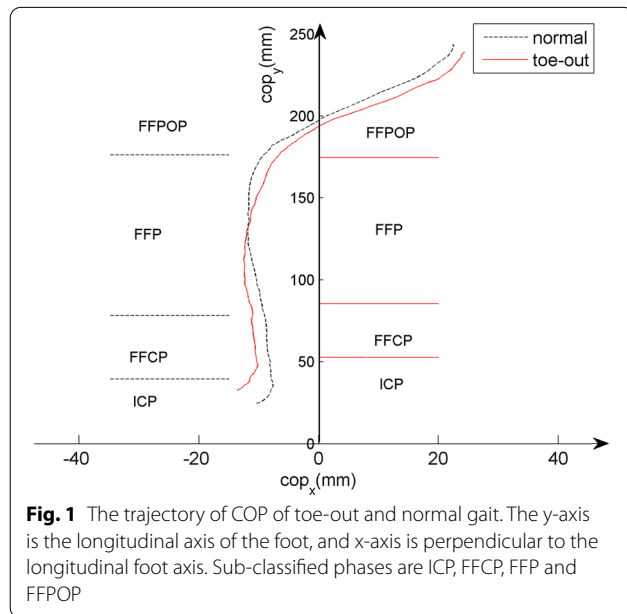


Fig. 1 The trajectory of COP of toe-out and normal gait. The y-axis is the longitudinal axis of the foot, and x-axis is perpendicular to the longitudinal foot axis. Sub-classified phases are ICP, FFCP, FFP and FFPOP

Table 1 Comparison of ML-COP deviation and velocity between toe-out and normal gait

	Deviation (mm)				Velocity (m/s)			
	Toe-out	Normal	<i>p</i>	ES _d	Toe-out	Normal	<i>p</i>	ES _d
<i>ML-COP mean</i>								
ICP	11.9 ± 5.9	8.7 ± 4.2	0.000**	0.68	0.170 ± 0.098	0.160 ± 0.089	0.639	0.09
FFCP	12.0 ± 5.5	8.9 ± 3.8	0.001**	0.72	0.082 ± 0.044	0.073 ± 0.026	0.228	0.22
FFP	11.5 ± 5.9	11.4 ± 5.7	0.925	0.02	0.066 ± 0.038	0.075 ± 0.03	0.212	0.23
FFPOP	8.9 ± 2.6	8.1 ± 2.9	0.135	0.28	0.155 ± 0.038	0.147 ± 0.041	0.255	0.21
<i>ML-COP max</i>								
ICP	14.2 ± 6.4	11.1 ± 4.5	0.002**	0.56	0.560 ± 0.326	0.516 ± 0.295	0.545	0.11
FFCP	14.0 ± 6.5	10.6 ± 4.4	0.003**	0.62	0.341 ± 0.355	0.248 ± 0.129	0.145	0.29
FFP	14.8 ± 5.9	14.6 ± 6.3	0.873	0.03	0.312 ± 0.286	0.304 ± 0.152	0.887	0.04
FFPOP	26.0 ± 7.2	25.0 ± 8.1	0.318	0.10	1.128 ± 0.569	1.234 ± 0.484	0.327	0.18
<i>ML-COP range</i>								
ICP	4.2 ± 2.7	4.0 ± 1.9	0.700	0.07	0.765 ± 0.476	0.700 ± 0.365	0.559	0.11
FFCP	4.3 ± 3.4	3.5 ± 2.4	0.254	0.21	0.481 ± 0.399	0.382 ± 0.215	0.134	0.02
FFP	8 ± 4.5	7.5 ± 4	0.686	0.11	0.464 ± 0.313	0.514 ± 0.276	0.473	0.13
FFPOP	33.6 ± 11.1	33.7 ± 12.6	0.938	0.01	1.486 ± 0.739	1.628 ± 0.599	0.339	0.18

Values are expressed as mean ± standard deviation ML-COP: COP in medial-lateral direction

ICP: Initial contact phase, FFCP: forefoot contact phase, FFP: foot flat phase, FFPOP: forefoot push off phase

* Significant difference, $p < 0.05$, ** very significant difference, $p < 0.001$

Table 2 Comparison of AP-COP deviation and velocity between toe-out and normal gait

	Deviation (mm)				Velocity (cm/s)			
	Toe-out	Normal	<i>p</i>	ES _d	Toe-out	Normal	<i>p</i>	ES _d
<i>AP-COP mean</i>								
ICP	39.8 ± 31.7	30.6 ± 8.6	0.106	0.36	0.507 ± 0.443	0.214 ± 0.215	0.072	0.44
FFCP	72.9 ± 24.7	59.9 ± 14.4	0.008**	0.53	0.501 ± 0.043	0.570 ± 0.060	0.192	0.17
FFP	126.7 ± 16.9	129.9 ± 20.6	0.658	0.13	0.400 ± 0.032	0.509 ± 0.040	0.000**	0.95
FFPOP	196.5 ± 7.1	197 ± 4.5	0.719	0.08	0.249 ± 0.066	0.238 ± 0.011	0.120	0.29
<i>AP-COP max</i>								
ICP	49.0 ± 31	37.4 ± 9.6	0.008**	0.47	1.571 ± 1.562	0.622 ± 0.837	0.185	0.40
FFCP	90.9 ± 27.7	79.0 ± 23	0.082	0.35	1.880 ± 0.177	1.711 ± 1.65	0.766	0.13
FFP	174.8 ± 14.6	177.7 ± 8.1	0.644	0.18	1.693 ± 0.238	2.261 ± 0.225	0.003**	0.33
FFPOP	236.5 ± 13.8	241.1 ± 12.1	0.020*	0.41	2.057 ± 0.868	1.948 ± 0.095	0.558	0.20
<i>AP-COP range</i>								
ICP	17.1 ± 8	13.5 ± 5.7	0.036*	0.43	1.665 ± 1.604	0.687 ± 0.991	0.072	0.38
FFCP	40.8 ± 19.8	41.0 ± 22.5	0.968	0.01	2.149 ± 0.219	2.009 ± 0.251	0.192	0.08
FFP	86.7 ± 26.5	98.1 ± 23.3	0.081	0.33	1.954 ± 0.261	2.497 ± 0.244	0.000**	0.29
FFPOP	61.2 ± 19.6	63.1 ± 15.4	0.585	0.10	2.268 ± 0.963	2.166 ± 0.117	0.120	0.18

Values are expressed as mean ± standard deviation. ML-COP: COP in medial–lateral direction; AP-COP: COP in anterior–posterior direction

ICP: initial contact phase, FFCP: forefoot contact phase, FFP: foot flat phase, FFPOP: forefoot push off phase

* Significant difference, *p* < 0.05, ** very significant difference, *p* < 0.001

and 3.1 mm during the ICP, respectively; increased by 3.1 mm and 3.4 mm during the FFCP, respectively. There were no significant differences in the range of COP displacements and the COP velocity in medial–lateral direction between toe-out and normal gait.

It has been shown in Table 2 that the anterior–posterior at the terminational contact point of the ICP and the mean of the FFCP for the toe-out gait was increased compared to the normal gait, suggesting that the COP was displaced anteriorly in these two phases. More specifically, the maximum and range displacement of COP in anterior–posterior direction for the toe-out walking was increased by 11.6 and 3.6 mm during the ICP, respectively. The mean displacements of anterior–posterior COP for the toe-out gait was increased by 13.4 mm during the FFCP. The maximum displacement of anterior–posterior COP for the toe-out gait was decreased by 4.6 mm during the FFPOP.

The mean, maximum and range of COP velocity in anterior–posterior direction were reduced by 0.109, 0.568 and 0.543 m/s respectively for the toe-out gait during the FFP, compared to the normal gait.

Comparisons of the time percentage of different phases between two conditions are shown in Table 3. For the toe-out gait, the time spent on the FFP was increased by 4.5% and on the FFPOP was reduced by 7.0%, compared to the normal gait.

Table 3 Time comparisons between toe-out and normal gait

	Toe-out (%)	Normal (%)	<i>P</i>	ES _d
ICP	6.3 ± 2.5	6.7 ± 2.2	0.262	0.16
FFCP	16.4 ± 7.5	13.6 ± 7.3	0.102	0.31
FFP	38.4 ± 13.8	33.9 ± 10	0.032*	0.49
FFPOP	38.9 ± 9.1	45.9 ± 8.9	0.000**	1.03

Values are expressed as mean ± standard deviation

ICP: Initial contact phase, FFCP: forefoot contact phase, FFP: foot flat phase, FFPOP: forefoot push off phase

* Significant difference, *p* < 0.05

** Very Significant difference, *p* < 0.001

4 Discussion

This study compared the COP trajectory between a toe-out gait and a normal gait. Compared to the normal gait, people walking with a toe-out gait had a slower preferred walking speed, and an altered COP trajectory during walking, which shifted laterally and anteriorly during the ICP and FFCP, and shifted posteriorly at the terminal contact. For the toe-out gait, the COP velocity in the anterior–posterior direction was reduced during the FFP, and the time spent on the FFPOP was shortened.

COP excursions along the medial–lateral direction mainly depend on the inversion–eversion movements of the foot, which influence gait stability control, energy storage, and propulsion efficiency. Such movements

were performed by subtalar and minor foot joints in the frontal and transversal planes [27]. Our results suggested that the COP trajectory showed a lateral shift during the ICP and FFCP with a large effect size, compared to the normal gait. This result agreed with the plantar pressure pattern of the individuals with medial knee osteoarthritis [8], suggesting a higher risk of medial knee osteoarthritis. A lateral shift of the COP revealed that the foot had significant heel inversion. The deliberately toe-out gait inhibited the medial foot contact during the ICP and FFCP, resulting in transferring the load from the rearfoot to forefoot through the lateral side of the foot in comparison with the normal gait. The period of the FFCP almost corresponds with the change from bipedal to unipedal support, which presents a dynamic challenge to balance. The lateral shift of the COP during the FFCP was associated with the decrease of foot stability [28], which agreed with reductions in balance with a toe-out gait in previous studies [20, 29]. Furthermore, individuals with a toe-out gait have a slower walking speed than individuals with a normal gait, which might reflect a compensatory strategies for enhancing gait stability [30].

The change of the COP pattern has different forms and may be showed in different parameter. We found that both mean and maximum of the COP in the anterior–posterior direction were important for evaluating the plantar pressure pattern. For example, significant differences in the maximum values of the COP were found during the ICP in toe-out gait, but not in the mean values of the COP in anterior–posterior direction (Table 2). This trend was reversed for the values during the FFCP. The anterior–posterior direction COP moves forward during the whole stance phase generally, the maximum of COP in anterior–posterior direction was the cumulative result while the mean was the overall condition four phases.

As the COP is, in part, determined by the force application during the stance phase, which represents the spatial relationship between plantar pressure distribution and the entire plantar surface of the foot [31], it is reasonable to consider the displacements of the COP as the reflection of foot loading patterns. Spatial evolution of COP along the longitudinal axis of the foot mainly depended on the articular mobility in the sagittal plane [27]. It has been reported that the forefoot loading was increased in a forwardly displaced COP during gait [32]. Compared to a normal gait, the anterior–posterior COP in a toe-out gait showed an anterior shift during the ICP and FFCP with a medium and large effect size, respectively, which agreed with that of Jenkyn et al [3]. It was indicative of a load shift from the rearfoot/midfoot to the midfoot/forefoot, respectively. The COP movement from the heel to toe and the orientation of GRF permit the lever arm to

stay within the efficient working range of ankle muscles and tendons [33]. During the FFCP, the ankle plantar-flexed [25]. An anterior shift of the COP changed the lever arm of the GRF about the talocrural joint axis [34], resulting in an increased magnitude of joint moment [35]. To maintain equilibrium, there must be an equal moment produced by ankle muscles and tendons. Consequently, this may increase the stress in associated foot structures, contributing to pathologies in ankle [19].

Under the condition of the COP in anterior–posterior direction anterior shift in toe-out during the FFCP. Largest effects were noted with the reduced anterior–posterior mean velocity of COP in the toe-out during the FFP, resulting in the similar anterior–posterior mean position of the COP during the FFP and FFPOP, compared to the normal gait. The subtalar joint inversion locks the transverse tarsal joint, which causes the plantar aponeurosis to create a rigid structure for propulsion during the FFP [25]. Compared to the normal gait, the toe-out gait caused a reduction of the mean anterior–posterior COP velocity during the FFP by as high as 21.4% and did not alter the COP velocity during the remaining three phases. As the reduction of the COP velocity during the FFP was considerably larger than the walking speed reduction, i.e. 3.9%, we believed that this reduction was mainly caused by the toe-out gait instead of the walking speed. A slower anterior–posterior COP velocity during the FFP indicated that there might be a challenge for the foot to change from a flexible to a rigid structure to guarantee an efficient progression of the body when adopting a toe-out gait. With the decreasing anterior–posterior velocity of COP in toe-out during FFP, the duration of load exposure to the forefoot increased, and coupled with the partial load shifting to the forefoot. This indicated that the toe-out pattern tends to put more load on the forefoot. Peripheral neuropathy and increased plantar pressures are the most significant risk factors in the development of foot ulceration, while the main strategy of managing neuropathic ulceration are reduction of plantar pressures. The forefoot usually has high plantar pressures and the partial load shifting to the forefoot may increase the risk of development of ulceration in this discrete region, which may increase the probability of development of ulceration in diabetic population [36].

As all trials were normalized to the total contact time, the influence of the walking speed on the duration percentage of four phases of stance was minimal. Foot roll-over timing of four phases of stance enables measurements of the medial–lateral and anterior–posterior behavior of the foot, which is important to distinguish toe-out from normal gait. Foot roll-over time is also important for a comprehensive analysis of foot muscular activities [37]. Compared to normal gait, walking with

toe-out gait had a later heel off with 61.9% of total foot contact time in toe-out against 54.2% in normal gait.

The front part of FFPOP corresponds with the terminal stance, which enables the single limb to support body weight and progress body beyond the supporting foot. A later heel off with toe-out gait indicated a later rearfoot-forefoot body weight transfer, while reduction of weight on the trailing limb allows the ankle to plantar flex. The rear part of FFPOP corresponds with the pre-swing phase, which is the second double stance interval with all the motion and muscle action occurring at this time relate for accelerate progression. Walking speed influences the duration of subdivision of stance, the faster of the walking speed, the longer of single stance and the shorter of the second double stance interval [38]. Compared to normal gait, people walking in toe-out gait had a slower walking speed, but the longer of single stance in FFP and the shorter of the FFPOP appeared. The shorter duration of the FFPOP may induce decrease of propulsive impulse, which reduces walking speed. For finishing the function of the FFPOP in shorter duration, increase the plantarflexor muscular control demand [33]. Compared to the normal gait, this may be related to the reduction of 4.6 mm terminal point of COP in anterior–posterior direction for the toe-out gait.

A toe-out gait is often used as a conservative technique to reduce the progression of knee osteoarthritis, but it also decreases foot stability. It remains unclear whether or not the stability can be improved with well-designed of footwear or custom-made insoles, and which footwear characteristics are important for individuals with a toe-out gait. The effect of footwear/insole on gait stability largely depends on the characteristics of footwear/insole structure. An optimized design of a footwear or custom-made insole can improve plantar pressure distribution and the COP trajectory. Consequently, using the COP parameters as biomechanical feedback can improve footwear/insole design. It is proposed that footwear/insole design modification is required until an optimal COP parameters during gait have been reached [39].

Knowing the biomechanical characteristics of a toe-out gait can provide insights into footwear/insole design to improve gait stability. The heel acts as a rocker during ICP and FFCP [38]. As weight bearing stability is required during the FFCP, it is important to have a good fit between the heel and footwear/insole to ensure the function of the heel rocker. In such situation, a heel cup matching the contour of the heel can improve heel fitting and an arch support can rebound to a smooth continuous forward progression of the COP during FFCP. The medial–lateral displacement of the COP during FFCP has been used as a measure of stability control, which reflected the rocker action [40]. When excessive foot

motions occur, a heel cup may generate forces to restrain it. The foot makes contacts with the arch support at the initial stage of FFCP, which can restrict rapid medial–lateral velocity of COP and make the process of weight transfer more stably and smoothly. The small lateral shift and relatively normal medial–lateral velocity of COP indicates the rocker action flows smoothly, which may improve gait stability and reduce the mechanical risk of knee osteoarthritis [8]. Adding an arch support to a heel lift has also been proven to reduce the medial–lateral velocity of COP, and thus improves gait stability [28].

The results also provide implications for footwear/insole design to improve load distribution of the foot for people with a toe-out gait. A toe-out gait puts more load on the forefoot and increased the demand of ankle plantar flexor muscles control during FFP [39]. The plantar load can be redistributed via biomechanical manipulations of footwear or custom-made insoles [41]. For instance, a well-designed footwear-foot interface shape or custom-made insoles contour may redistribute the plantar pressure. For the midfoot, an arch support has been shown to improve stability control as well as reducing the forefoot load, as it can partially transfer the load from the forefoot to midfoot [28, 42]. For the forefoot, a tilted forefoot inner sole/ a wedged forefoot insole component may shift the load from the lateral to the medial forefoot, to facilitate an efficient load transfer during the FFP and consequently improve foot roll-off function. Altering these structures of a footwear/insole may benefit people who need to adopt a toe-out gait, e.g., patients with knee osteoarthritis. And the proposed biomechanical analysis method can be used to test the efficacy of therapeutic footwear or insole on improving foot dynamic function.

Two limitations arising from the current study should be noted. The participants of this study were young healthy participants with a normal gait pattern. As age has an influence on the COP trajectory, the results of the study are valid only for young adults. The participants of this study had not been systematically trained to walk with a toe-out pattern. As the foot progression angle may be modified by a long-term gait training, further studies are needed to compare the results for healthy individuals before and after a toe-out gait training with providing different foot progression angles [43].

In conclusion, the detailed comparison of the COP between toe-out and normal gait suggests that the displacement and velocity of COP in medial–lateral and anterior–posterior direction can be used for the assessment of the gait characteristics for toe-out walking. The results of this study may provide insights into the biomechanical effects of modifying the foot progression angle to lower the knee osteoarthritis incidence rate or modify osteoarthritis progression. Under our experimental

conditions, biomechanical alterations of foot in toe-out gait may cause stability decreases and forefoot load increases, which may be improved by well-designed footwear or custom-made insoles. The approach of analyzing the COP trajectory can be used to test the efficacy of therapeutic footwear or insoles for individuals with a toe-out gait.

Abbreviations

OA: Knee osteoarthritis; KAM: Knee adduction moment; GRF: Ground reaction force; COP: Center of pressure; ICP: Initial contact phase; FFCP: Forefoot contact phase; FFP: Foot flat phase; FFPOP: Forefoot push-off phase; AP-COP: COP in anterior–posterior direction; ML-COP: COP in medial–lateral direction; ESd: Cohen's d effect size.

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Authors' contributions

BL conceived the idea and contributed to the study design and manuscript preparation. XZ contributed to the study design and manuscript revision. Both authors analyzed the experimental result, read and approved the final manuscript.

Authors' information

Bo Li is mainly engaged in the teaching and research of foot biomechanics in Sichuan University. Xianyi Zhang is mainly engaged in the teaching and research of human movement science in Sun Yat-sen University.

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Availability of data and materials

All data generated or analyzed during this study are included in this published article.

Declarations

Competing interests

The authors declare that they have no competing interests.

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References

- Khan SS, Khan SJ, Usman J. Effects of toe-out and toe-in gait with varying walking speeds on knee joint mechanics and lower limb energetics. *Gait Posture*. 2017;53:185–92.
- Murphy L, Schwartz TA, Helmick CG, Renner JB, Tudor G, Koch G, et al. Lifetime risk of symptomatic knee osteoarthritis. *Arthritis Rheum*. 2008;59:1207–13.
- Jenkyn TR, Hunt MA, Jones IC, Giffin JR, Birmingham TB. Toe-out gait in patients with knee osteoarthritis partially transforms external knee adduction moment into flexion moment during early stance phase of gait: a tri-planar kinetic mechanism. *J Biomech*. 2008;41:276–83.
- Chang A, Hurwitz D, Dunlop D, Song J, Cahue S, Hayes K, et al. The relationship between toe-out angle during gait and progression of medial tibiofemoral osteoarthritis. *Ann Rheum Dis*. 2007;66:1271–5.
- Hunt MA, Takacs J. Effects of a 10-week toe-out gait modification intervention in people with medial knee osteoarthritis: a pilot, feasibility study. *Osteoarthritis Cartilage*. 2014;22:904–11.
- Lynn SK, Kajaks T, Costigan PA. The effect of internal and external foot rotation on the adduction moment and lateral-medial shear force at the knee during gait. *J Sci Med Sport*. 2008;11:444–51.
- Cochrane CK, Takacs J, Hunt MA. Biomechanical mechanisms of toe-out gait performance in people with and without knee osteoarthritis. *Clin Biomech*. 2014;29:83–6.
- Lidтке RH, Muehleman C, Kwasny M, Block JA. Foot center of pressure and medial knee osteoarthritis. *J Am Podiatr Med Assoc*. 2010;100:178–84.
- Hunt MA, Birmingham TB, Giffin JR, Jenkyn TR. Associations among knee adduction moment, frontal plane ground reaction force, and lever arm during walking in patients with knee osteoarthritis. *J Biomech*. 2006;39:2213–20.
- Rosenbaum D. Foot loading patterns can be changed by deliberately walking with in-toeing or out-toeing gait modifications. *Gait Posture*. 2013;38:1067–9.
- Chang W-N, Tsirikos AI, Miller F, Schuyler J, Glutting J. Impact of changing foot progression angle on foot pressure measurement in children with neuromuscular diseases. *Gait Posture*. 2004;20:14–9.
- Lai Y-C, Lin H-S, Pan H-F, Chang W-N, Hsu C-J, Renn J-H. Impact of foot progression angle on the distribution of plantar pressure in normal children. *Clin Biomech*. 2014;29:196–200.
- Hastings MK, Gelber JR, Isaac EJ, Bohnert KL, Strube MJ, Sinacore DR. Foot progression angle and medial loading in individuals with diabetes mellitus, peripheral neuropathy, and a foot ulcer. *Gait Posture*. 2010;32:237–41.
- Fernandez-Seguín LM, Diaz Mancha JA, Sanchez Rodriguez R, Escamilla Martinez E, Gomez Martin B, Ramos OJ. Comparison of plantar pressures and contact area between normal and cavus foot. *Gait Posture*. 2014;39:789–92.
- Pataky TC, Caravaggi P, Savage R, Crompton RH. Regional peak plantar pressures are highly sensitive to region boundary definitions. *J Biomech*. 2008;41:2772–5.
- Chiu M-C, Wu H-C, Chang L-Y. Gait speed and gender effects on center of pressure progression during normal walking. *Gait Posture*. 2013;37:43–8.
- Badley EM, et al. Relative importance of musculoskeletal disorders as a cause of chronic health problems, disability, and health care utilization: findings from the 1990 Ontario Health Survey. *J Rheumatol*. 1994;21:505–14.
- Kirby KA, Dpm M. Biomechanics of the normal and abnormal foot. *J Am Podiatr Med Assoc*. 2000;90:1–5.
- Fuller EA. Center of pressure and its theoretical relationship to foot pathology. *J Am Podiatr Med Assoc*. 1999;89:278–91.
- Khan SJ, Khan SS, Usman J, Mokhtar AH, Abu Osman NA. Combined effects of knee brace, laterally wedged insoles, and toe-out gait on knee adduction moment and fall risk in moderate medial knee osteoarthritis patients. *Prosthet Orthot Int*. 2019;43:148–57.
- Cornwall MW, McPoil TG. Velocity of the center of pressure during walk. *J Am Podiatr Med Assoc*. 2000;90:334–8.
- Whelton C, Thomas A, Elson DW, Metcalfe A, Forrest S, Wilson C, et al. Combined effect of toe out gait and high tibial osteotomy on knee adduction moment in patients with varus knee deformity. *Clin Biomech*. 2017;43:109–14.
- De Cock A, Vanrenterghem J, Willems T, Witvrouw E, De Clercq D. The trajectory of the centre of pressure during barefoot running as a potential measure for foot function. *Gait Posture*. 2008;27:669–75.
- Ma CC, Lee YJ, Chen B, Aruin AS. Immediate and short-term effects of wearing a single textured insole on symmetry of stance and gait in healthy adults. *Gait Posture*. 2016;49:190–5.
- Chiu MC, Wu HC, Chang LY, Wu MH. Center of pressure progression characteristics under the plantar region for elderly adults. *Gait Posture*. 2013;37:408–12.
- Cohen J. *Statistical power analysis for the behavioral sciences*. New York: Academic Press; 1977.
- Pan X, Bai J-J, Sun J, Ming Y, Chen L-R, Wang Z. The characteristics of walking strategy in elderly patients with type 2 diabetes. *Int J Nurs Sci*. 2016;3:185–9.

28. Zhang X, Li B, Hu K, Wan Q, Ding Y, Vanwanseele B. Adding an arch support to a heel lift improves stability and comfort during gait. *Gait Posture*. 2017;58:94–7.
29. Khan SJ, Khan SS, Usman J. The effects of toe-out and toe-in postures on static and dynamic balance, risk of fall and TUG score in healthy adults. *Foot*. 2019;39:122–8.
30. Nigg BM, Fisher V, Ronsky JL. Gait characteristics as a function of age and gender. *Gait Posture*. 1994;2:213–20.
31. Wong L, Hunt A, Burns J, Crosbie J. Effect of foot morphology on center-of-pressure excursion during barefoot walking. *J Am Podiatr Med Assoc*. 2008;98:112–7.
32. Melai T, Schaper NC, Ijzerman TH, de Lange TL, Willems PJ, Meijer K, et al. Increased forefoot loading is associated with an increased plantar flexion moment. *Hum Mov Sci*. 2013;32:785–93.
33. Erdemir A, Piazza SJ. Rotational foot placement specifies the lever arm of the ground reaction force during the push-off phase of walking initiation. *Gait Posture*. 2002;15:212–9.
34. Carrier DR, Heglund NOC, Earls KD. Variable gearing during locomotion in the human musculoskeletal system. *Science*. 1994;265:651–3.
35. Haim A, Rozen N, Wolf A. The influence of sagittal center of pressure offset on gait kinematics and kinetics. *J Biomech*. 2010;43:969–77.
36. Raspovic A, Newcombe L, Lloyd J, Dalton E. Effect of customized insoles on vertical plantar pressures in sites of previous neuropathic ulceration in the diabetic foot. *Foot*. 2000;10:133–8.
37. Blanc Y, Balmer C, Landis T, Vingerhoets F. Temporal parameters and patterns of the foot roll over during walking normative data for healthy adults. *Gait Posture*. 1999;10:97–108.
38. Grant AD. Gait analysis: normal and pathological function. *Physiotherapy*. 2010;97:180.
39. Li B, Xiang Q, Zhang X. The center of pressure progression characterizes the dynamic function of high-arched feet during walking. *J Leather Sci Eng*. 2020;2:1–10.
40. Zhang X, Li B. Influence of in-shoe heel lifts on plantar pressure and center of pressure in the medial-lateral direction during walking. *Gait Posture*. 2014;39:1012–6.
41. Khoury M, Wolf A, Debbi EM, Herman A, Haim A. Foot center of pressure trajectory alteration by biomechanical manipulation of shoe design. *Foot Ankle Int*. 2013;34:593–8.
42. Zhang X, Li B, Liang K, Wan Q, Vanwanseele B. An optimized design of in-shoe heel lifts reduces plantar pressure of healthy males. *Gait Posture*. 2016;47:43–7.
43. Chen DKY, Haller M, Besier TF. Wearable lower limb haptic feedback device for retraining foot progression angle and step width. *Gait Posture*. 2017;55:177–83.

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