Original Article

Toe-out Landing Position Increases Medial Ground Reaction Force during Walking in Young Individuals

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Running title: Toe-out gait on ground reaction force vectors

Abstract

Objective. The purpose of this study was to determine how toe-out foot landing position influences ground reaction forces (GRF) during gait. **Design.** Values of GRF components recorded with a force platform were used to compare 3D GRF vectors of toe-out and non toe-out (including neutral and toe-in) foot landing positions. **Methods.** Thirty-two healthy males (ranging from 19-21 years old) were repeatedly assigned three foot landing positions: toe-out, toe-in and neutral. Each participant walked with three foot landing positions across a force platform while their three-dimensional motion was captured. **Results.** No differences were observed for vertical or anteroposterior GRF among three foot landing positions ($p > 0.05$). For mediolateral GRF, higher medial loading forces appeared at the first and second peaks in toe-out landing position when compared with non toe-out gaits ($p < 0.05$). Also earlier and later occurrences appeared at the 1st and 2nd peaks in toe-out landing position respectively ($p < 0.05$). **Conclusion.** We provide evidence of toe-out, toe-in and neutral foot landing positions on GRF using a kinetic study. It is suggested that individuals who walk with greater degrees of toe-out angle create greater medial GRF during the contact and propulsive phases.

Key words: ground reaction force, foot landing position, toe-out

Introduction

Toe-out gait is a gait modification that provides a practical and clinically applicable strategy for management of knee osteoarthritis (OA).[1,2] Increasing toe-out angle during gait reduces knee adduction moment through a mechanism of reducing moment arm length of the net ground reaction force (GRF) vector with respect to the knee joint in the frontal plane.[3,4] Therefore, greater toe-out angle has been inversely related to knee adduction moment during the late stance phase of gait to unload the medial compartment of the knee in people with healthy knees and in those with knee OA.[5]

It is commonly assumed that GRF plot shape is a direct reflection of net moments of forces generated by the muscles around the ankle, knee and hip joints. GRF values may be influenced by the angle formed between the long axis of the foot and the direction of walking. The product of the GRF vector in the frontal plane and the perpendicular distance from the GRF vector to the knee joint centre of rotation (the frontal plane moment arm) is a major determinant of the magnitude of knee adduction moment.[5] However, there is little evidence from kinetic studies to evaluate vectors of GRF including mediolateral, vertical and anteroposterior forces on toe-out gait, which might help elucidate the efficacy and biomechanics of toe-out gait modification in preventing or managing knee OA.

The aim of the current investigation, therefore, was to determine the effects of toe-out foot landing position on the vectors of GRF during walking compared with those of non toe-out gait. Based on the findings of the previous studies [3-5], we tested the hypothesis that increased toe-out angle is associated with a reduced likelihood of magnitude of GRF vector in frontal plane as assessed by a force platform.

Materials and Methods

Subjects

Thirty-two healthy male volunteers with a mean age of 19.6±0.67 (ranging from 19-21) years, height of 170.0±5.46 cm (ranging from 157-179 cm) and weight of 67.4±9.40 kg (ranging from 53-90 kg) participated in the study. Subjects were screened for lower extremity pathology and neuromuscular disease and demonstrated no clinical signs of abnormal gait. Informed consent was obtained from each subject prior to testing and study protocol conformed to the ethical guidelines of the 1996 Declaration of Helsinki (the 4th amendment) as reflected in a prior approval by the human research committee of National Chung Hsing University.

Equipments

A 60 × 40 cm^2 Bertec force platform (FP4060, Bertec Corporation, OH, USA), mounted at the mid-point of a 10 m walkway, was connected to a PC via a six channel Bertec type AM6501 charge amplifier (Bertec Corporation, OH, USA) and a 12-bit Analog to Digital converter. Mediolateral (Fx), vertical (Fy) and anteroposterior (Fz) force data were sampled at a rate of 2000 Hz. The frequency response of the platform was 200 Hz.

Procedures

Subjects were required to perform three foot landing positions; at neutral, maximum toe-in and maximum toe-out paces. The neutral landing position indicated the subject's comfortable walking pattern at the usual foot landing angle. Three conditions involved walking at a self-selected pace over a 9 m walkway covered with paper. The paper (0.90×9 m^2) obscured the force platform mounted at the midpoint of the walkway. The starting position of each subject was modified such that their preferred foot would arrive at the target area on their seventh step without notable alterations in their gait pattern. Subjects were permitted to use visual guidance in attempting to perform the targeting task and were instructed to terminate their gait on a line at the end of the walkway.

A modified version of the foot printing method outlined by Stuberg et al.[6] was used to obtain a permanent record of each subject's step length. Moleskin squares (20×20 mm^2 and 1 mm thick) soaked in water-soluble ink were adhered to the plantar surface of both heels. Similarly, ink-soaked triangles ($15 \times 15 \times 15$ mm^3 and 1mm thick) were adhered to the plantar surface of the second phalanx unilaterally. Testing began after the participant practiced walking until they felt comfortable and could consistently maintain their target velocity (this involved a 10 min familiarisation period). Data were collected once the between-trial stance phase duration of each subject varied by less than 50 ms. Following the application of ink markers, subjects were required to perform one walking trial using each gait condition. Trial order was randomized among subjects. Trials were repeated if the target step was not contained entirely within the force platform.

Stride analysis

The degree of foot landing position including toe-out, toe-in and neutral angle was recorded following each trial in each subject. Measurements of stride variables were made using drafting equipment and were recorded to the nearest millimeter. Step length was measured directly from the midpoint of successive ink marks using the XY coordinates of a drawing board. Repeated measures, performed on a randomly selected gait trial for each subject, were used to investigate the intra-rater reliability of the technique. The mean step length was calculated for each step along the walkway by averaging the corresponding step in trials for each condition. The mean contact period from the onset of foot contact to the leaving of the force platform was calculated for each condition.

Statistical analysis of ground reaction forces

In total, 96 trials (32 subjects × 1 trials × 3 landing positions) were processed by calculating both stride and GRF time-domain parameters. Three trials were repeated due to incomplete placement of the entire foot within the force platform.

In order to allow comparisons to previous time domain studies, three commonly used GRF parameters (Fx; Fy; Fz) were normalized to body weight and their relative times were expressed as percentages of the stance phase. The magnitudes and occurrence time of the first and second GRF peaks (including the positive and negative maximum GRF) were also analyzed. These variables were used in repeated measures of ANOVA to determine whether GRF was dependent on the three foot landing positions. All statistical tests, including *post hoc* Tukey's HSD tests, were evaluated at $p < 0.05$. All statistical analyses were performed using the Statistical Package for the Social Sciences Version 12.0 for Windows (SPSS Inc., Chicago, IL, USA).

Results

Stride analysis

Foot landing angle, step length and contact period on the platform for all subjects are demonstrated in Table 1. The mean maximum toe-out, toe-in and neutral landing angles were 41.8±25.5, -14.3±9.0 and 13.4±11.9, respectively. There was no statistically significant difference in step length or foot contact period of platform among toe-out, neutral and toe-in foot landing positions (repeated ANOVA, $p > 0.05$).

GRF analysis

1. Force-time pattern

The interposition ensemble curves of the GRF for vertical, anteroposterior and mediolateral directions are shown in Figure 1 for three foot landing positions. The typical plots of the GRF in three directions and three foot landing positions reveal two peaks. The first and second peaks appeared at the periods of 0%-50% and 51%-100% of stance phase, respectively. For vertical (Fz) and anteroposterior (Fy) directions, the force-time patterns of GRF curves were visually similar, but significant differences were seen among three foot landing positions, particularly the toe-in positions. The mediolateral axis appeared to be most sensitive to different foot landing positions. For measure of the area of the force-time curve, that is equal to the total impulse (Ns, calculated by weight × time), the area in medial direction was obviously larger in the toe-out position than in the other non toe-out positions. This resulted in greater medial impulses for the GRF in the toe-out positions (Figure 1).

2. Loading force of peak GRF vectors

The mean magnitudes of the first and second peaks in each landing position for Fx, Fy and Fz are shown in Table 2. For vertical and anteroposterior directions, there were no statistical differences for magnitudes of the first or second GRF peak loading among the three foot landing positions (repeated measures of ANOVA, Fz; 1st peak: $p > 0.05$; 2nd peak: $p > 0.05$; Fy; 1st peak: $p > 0.05$; 2nd peak: $p > 0.05$; Table 2). In the mediolateral direction, the Fx was significantly different among the three foot landing positions (repeated measures of ANOVA, $p < 0.05$, Table 2). There was a higher loading force at the first and second peaks in toe-out landing position when compared with non toe-out gaits (Tukey's HSD test, for 1st peak, toe-out vs. neutral: $p < 0.01$, toe-out vs. toe-in: $p < 0.05$; for 2nd peak, toe-out vs. neutral: $p < 0.01$, toe-out vs. toe-in: $p < 0.01$; Figure 2). The toe-out Fx exhibited significantly greater magnitudes of medial direction than the non toe-out positions in both first and second Fx peaks.

3. Occurrence time of peak GRF vectors

The mean occurrence time of the first and second peaks in each landing position for Fx, Fy and Fz were shown in Table 2. Similar to the results of loading force, there were no significant differences at the occurrence time of the first and second peaks among the three foot landing positions in vertical and anteroposterior (repeated measures of ANOVA, for Fz, 1st peak: $p > 0.05$; 2nd peak: $p > 0.05$; for Fy, 1st peak: $p > 0.05$; 2nd peak: $p > 0.05$; Table 2). For mediolateral direction, there was an earlier occurrence time appearing at 1st peak in toe-out landing position when compared with non toe-out gait (Tukey's HSD test, toe-out vs. neutral: $p < 0.01$, toe-out vs. toe-in: $p < 0.05$; Figure 2). Furthermore, the occurrence time of the second peak GRF occurred later for the toe-out position than the other non toe-out positions (Tukey's HSD test, toe-out vs. neutral: $p < 0.05$, toe-out vs. toe-in: $p < 0.01$; Figure 2).

Discussion

The most common method used by biomechanists and clinicians to assess and evaluate gait via GRF is to utilize minimum and maximum GRF magnitudes and their times of occurrence and impulses. Our results demonstrated that there was only a significantly difference in mediolateral vector of GRF between toe-out and non toe-out foot landing positions. The vertical and anteroposterior vectors of GRF were not affected by foot landing positions. Therefore, the results conflicted with our hypothesis that toe-out gait can reduce medial GRF and result in decrement of knee adduction moment.

As there were no differences among foot landing positions for any the vertical GRF variables, it was concluded that foot landing position did not influence participant ability to attenuate impact forces, accept body weight, or push the body upwards during the propulsive phase. Furthermore, as the magnitude and occurrence of time to maximum vertical GRF were similar among all three foot landing positions, this suggests that no foot landing position was exposed to insufficient or excessive levels of GRF in the skeletal system. In the anteroposterior direction, foot landing position also appeared to have negligible influence on GRF variables. It was concluded that individuals who land in a non-neutral foot landing positions generate similar anteroposterior forces and impulses in the direction of walking.

In mediolateral direction, the foot landing position may be one factor that causes high interparticipant variability for GRF-time patterns for running and walking.[7] In the present study, it is evident that ensemble mediolateral GRF-time patterns were similar among all three foot landing positions, however, there was significant difference in magnitude and temporal characteristics of maximum GRF. These are consistent with those reported by others.[7] For the toe-out position, there exhibited significantly greater medial forces at 16.16% and 71.30% of stance phase (the 1st and 2nd medial maximum GRF). Hence, it is suggested that individuals who walk with greater degrees of toe-out than others are creating greater medial forces during the contact and propulsive phases.

GRF can reflect the force of the human body's contact with its environment; specifically, the foot's contact with the ground.[8] Within a theoretical biomechanical framework, a toe out foot position also reduces the knee adduction moment through a mechanism of reducing moment arm length of the net ground reaction force (GRF) vector with respect to the knee joint center in the frontal plane.[3, 9] This occurs predominantly during the second half of the stance phase, when the net GRF vector is acting through the forefoot.[10] However, there is a weak correlation (r = 0.19) between GRF and knee adduction moment.[11] The medial GRF showed a significant increase when compared with neutral foot landing position in the present study. It should be considered that toe-out gait with increased medial GRF probably impacts the foot-ankle joint rather than the knee joint.

Simpson and Jiang [7] demonstrated that foot landing position could alter mediolateral GRF and influence the resultant in/eversion moments of the foot. Messier et al. [12] also suggested a possible association between the mediolateral GRF and foot pronation thus, affecting the amount and rate of subtalar joint pronation. It has been suggested that alterations of mediolateral GRF may cause movement problems of the frontal plane in the foot-ankle complex. Moreover, an external frontal loading (medial GRF) may act on the tibia and contribute toward the development of stress fracture injury. Creaby and Dixon [13] demonstrated that the medially directed frontal plane force vector observed in the stress fracture group indicates that the moment arm to the tibia is increased. Such an increase would contribute toward a greater medial bending moment acting on the tibia.

~~A high-peak knee adduction torque has also been correlated with increased OA disease severity [14], and an increased rate of OA disease progression [15]. OA knees that progressed had a significantly smaller toe-out angle measured during quantitative gait analysis than knees that did not progress.~~ Walking with the toes pointed outward can reduce the second peak of the adduction torque curve by as much as 40% but has little influence on the first peak.[1, 3, 5, 14] Many researchers suggested that as toe-out increases, orientation of the ground reaction force line of action moves laterally, reducing the frontal plane lever arm at the knee joint, thereby reducing the knee adduction moment.[9] In keeping with this theory, greater toe-out angle is inversely related to the external knee adduction moment during the late stance phase of gait in persons with knee OA.[3, 5] Chang et al.[11] found that odds of medial OA progression was lower in individuals who ambulate with a greater degree of toe-out foot landing position during gait. There is a possibility that a mechanism of the toe-out angle effect may be a reduction in the adduction moment which involves a basic gait modification in patients with knee OA. Although the results of this study obtained from normal young subjects may be not appropriately translated to clinical elder patient with OA knees, the possibility of abnormal joint loading (especially increased GRF vector in the fontal plane) should be considered while applying rehabilitation intervention with toe-out gait modification.

Conclusion

In summary, we have provided various evidence of toe-out, neutral, and toe-in foot landing positions on GRF using a kinetic gait study. The clinical implications of these findings indicate that toe-out foot landing position is associated with increased medial GRF vector. It is likely to increase the risk of unnecessary medial loading force on joints of low extremity, especially for ankle-foot joints. However, a possible limitation when interpreting the results of this study was lack of movement information relating to the ankle-foot joint complex and elder individuals investigated in this study. Further studies involving age-matched subjects with OA and kinematic studies relating to ankle-foot joints are needed.

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Figure legends

Figure 1. Group ensemble average curves for ground reaction forces of three foot landing positions as a function of the stance phase (SP).

Figure 2. The mean magnitudes (% body weight, %BW) and occurrences (% stance phase, %SP) of the first and second peak ground reaction force vectors. *: $p < 0.05$ tested by Tukey's HSD test.

正常年輕族群以足外八著地角度行走會增加內側地面反作用力

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目的：本研究目的主要以探討步態進行中足外八著地角度對於地面反作用力的影響。實驗設計：以力板測得的地面反作用力三個方向的參數來比較足外八與非足外八(包括：自然及足內八)著地角度的差異。方法：利用 32 位健康男性(19-21 歲)以足外八、足內八及正中等三種著角度重複測量。每一位受試者均以這三種著地步態踩在力板上並擷取三度空間的力學變化。結果：研究顯示，三種著地角度的垂直與前後的地面反作用力並無明顯差異($p > 0.05$)。而針對內外側的地面反作用力來說，足外八著地角度的第一及第二最大反作用力高峰值較其他兩組明顯增加($p < 0.05$)；且三種步態比較起來，足外八著地步態之第一高峰值出現時間較快、第二高峰值出現時間則較晚 ($p < 0.05$)。討論：本力學研究證明，三種不同的著地角度之地面反作用力表現是不同的。在行進間，足外八著地步態易增加內側地面反作用力。

關鍵字：地面反作用力、著地角度、足外八

Table 1. Means, standard deviation and statistical results of foot landing angles, step length and foot contact periods on a force platform in toe-out, toe-in and neutral positions.

	Toe-out	Toe-in	Neutral	[a]*p* value
Foot landing position (degree)	41.8±25.5	-14.3±9.04	13.4±11.9	$p < 0.05$
Step length (cm)	55.3±14.1	54.5±13.8	54.4±14.0	$p > 0.05$
Contact period (sec)	0.84±0.11	0.89±0.20	0.87±0.16	$p > 0.05$

[a]: tested by repeated measures of ANOVA.

Table 2. Means, standard deviation and statistical results of the occurrence to the critical peak ground reaction force events for the toe-out, toe-in and neutral foot landing positions.

Vector	GRF peak	Toe-out		Toe-in		Neutral		[a]*p* value	
		Loading (% BW)	Occurrence (% SP)	Loading (% BW)	Occurrence (% SP)	Loading (% BW)	Occurrence (% SP)	Loading	Occurrence
Fx	1st	10.28±4.11	16.16±5.35	8.57±2.28	29.57±11.33	6.62±2.53	23.38±11.54	$p < 0.05$	$p< 0.05$
	2nd	8.61±2.50	71.30±11.65	6.14±3.87	64.08±12.87	5.66±4.85	67.84±13.27	$p < 0.05$	$p < 0.05$
Fy	1st	-18.60±6.18	9.51±3.87	-15.00±4.91	9.69±4.27	-14.42±6.56	9.49±5.12	$p > 0.05$	$p > 0.05$
	2nd	17.62±3.46	82.63±3.46	15.56±5.26	80.42±5.68	17.08±5.30	81.92±6.79	$p > 0.05$	$p > 0.05$
Fz	1st	108.75±15.32	23.67±13.53	103.27±12.26	23.69±16.32	107.73±9.79	21.10±14.89	$p > 0.05$	$p > 0.05$
	2nd	106.27±14.55	68.20±10.22	101.19±15.02	68.91±13.23	100.06±0.38	68.56±14.79	$p > 0.05$	$p > 0.05$

[a] : tested by repeated measures of ANOVA. Abbreviations: BW=body weight; SP=Stance phase.