Gait & Posture 71 (2019) 163–169

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Influence of foot progression angle on knee adduction and flexion moment during stair climbing in healthy individuals

Rui Tsukagoshi[a,*], Mika Goto[b], Haruka Senoo[b], Riho Honda[c]

[a] Department of Physical Therapy, Faculty of Rehabilitation, Hyogo University of Health Sciences, 1-3-6 Minatojima, Chuo-ku, Kobe, Hyogo, Japan
[b] Division of Rehabilitation, Hakuho Central Hospital, 4-23-1 Higashisonoda-cho, Amagasaki, Hyogo, Japan
[c] Division of Rehabilitation, Amagasaki Daimotsu Hospital, 1-1-1 Higashidaimotsu-cho, Amagasaki, Hyogo, Japan

ARTICLE INFO

Keywords:
Stair climbing
Foot progression angle
Knee adduction moment
Knee flexion moment

1. Introduction

Knee osteoarthritis is the most common musculoskeletal disease affecting middle-aged and older people. Previous studies reported that the factors that influence the progression of knee osteoarthritis are pain [1], age [1], varus-valgus alignment [2] [3], metabolic syndrome [4], obesity [5] [6], and diabetes [7]. Among these factors, varus alignment is one of the most important factors that influence medial compartment knee osteoarthritis [8]. Excessive varus alignment increases the mechanical load to the medial compartment of the knee during activities of daily living such as walking and ascending and descending stairs [9]. Because the contact pressure in the medial knee joint is highly correlated with the knee adduction moment (which is easy to measure with a motion capture system and force plates), the adduction moment has been used as an index of contact pressure in the medial knee joint [10]. Previous research indicated that the knee adduction moment increased during walking more in people with knee osteoarthritis than in subjects with healthy knees [11], and the increase in the knee adduction moment correlated with narrowing of the knee joint space and increased knee pain [12] [13].

It has been reported that the knee adduction moment during walking is influenced not only by varus alignment of the knee but also by the foot progression angle [9] [14]. These studies reported that the toe-out angle explains approximately 10% of the variation in the peak knee adduction moment. Based on these reports, studies have recently focused on modifying the gait pattern to decrease the knee adduction moment while walking. The knee adduction moment during walking is bimodal, and it is divided into a first peak during the early stance phase and a second peak during the late stance phase. Van den Noort and Soobia reported that the toe-in gait reduces the first peak knee adduction moment during walking in healthy subjects [15] [16], and the same effects were confirmed in patients with medial compartment knee osteoarthritis [17] [18]. Several studies have also shown that toe-out gait is effective in reducing the second peak knee adduction moment [19] [20]. In those studies that focused on gait modification, the reason the knee adduction moment decreased was thought to be because the direction of the ground reaction force vector and the position of the center of foot pressure are changed by the toe-in or toe-out gait, and the vector and the center of the knee joint are close to one another. However, there have been only a few reports on stair-climbing motion—a movement used frequently during activities of daily living—which creates a higher load on the knee joint than walking [21] [22]. Because the knee and trunk are more flexed during stair climbing than when walking, changes in the knee adduction moment due to the foot progression angle may also be different between walking and stair climbing.

Guo et al. reported that, during stair climbing, toe-out gait reduced the second peak of the knee adduction moment but increased the first peak [19]. In contrast, Bennet et al. reported that the toe-in gait reduced the first peak knee adduction moment during stair climbing [23]. To our knowledge, however, no reports have directly compared toe-in and toe-out gaits during stair climbing, and it is not clear which action is more effective in reducing the knee adduction moment and angular impulse. Patients with knee osteoarthritis have more pain and difficulty

* Corresponding author.
E-mail addresses: tsukagoshi.rui@huhs.ac.jp (R. Tsukagoshi), pr14013@std.huhs.ac.jp (M. Goto), pr14018@std.huhs.ac.jp (H. Senoo), pr14033@std.huhs.ac.jp (R. Honda).

https://doi.org/10.1016/j.gaitpost.2019.03.015
Received 20 September 2018; Received in revised form 31 January 2019; Accepted 15 March 2019

with stair climbing than with walking and sit-to-stand movements [24], suggesting that a reduced mechanical load on the knee joint during stair climbing might contribute to improving performance and quality of life. In this study, we investigated the influence of the foot progression angle on the knee adduction moment and kinematics during stair climbing in healthy individuals.

2. Methods

2.1. Subjects

Twenty healthy subjects participated in this study (12 men, 8 women; mean ± SD age 21.7 ± 0.6 years; height 168.1 ± 9.2 cm; body weight 58.9 ± 9.1 kg). They were recruited from the student population of Hyogo University of Health Sciences. The inclusion criteria were healthy young adults aged 20–30 years without a history of diabetes or musculoskeletal, neurological, or cardiovascular disorders. Subjects were excluded if they had any pain in the lower extremity or trunk joints. All subjects provided written informed consent for the study. All test protocols were approved by the Ethics Review Board of Hyogo University of Health Sciences.

2.2. Instrumentation

Three-dimensional kinematics were recorded using an eight-camera motion capture system (Vicon Nexus; Oxford Metrics Ltd., Oxford, UK) at a sampling rate of 200 Hz, and a four-force plate (BP400600; AMTI, Watertown, MA, USA) at a sampling rate of 1000 Hz. Participants wore close-fitting shorts and t-shirts but no shoes. Reflective markers (14 mm diameter) were placed at the following locations according to the Vicon Plug-in-gait full-body model marker placement protocol (Vicon; Oxford Metrics Ltd., Oxford, UK): jugular notch, xiphoid process of the sternum, seventh cervical and tenth thoracic vertebrae, left and right acromioclavicular joints, lateral humeral epicondyle, ulnar styloid process, radial styloid process, third metacarpal head, anterior superior iliac spine, distal one-third of the lateral thigh, lateral femoral epicondyle, mid-point of the lateral shank, lateral malleolus, second metatarsal head, above the tuber of the calcaneus. The stairs consisted of two steps placed on a force plate. The height of the first and second steps were 16.5 cm and 33.0 cm, respectively. The treads of the steps were 40 cm. Ground reaction force data from the first step were used for kinematic and kinetic analyses.

All subjects could perform the ascending trials without support. Subjects started ascending the stairs from a standing position. They were instructed to stand at the position of the first toe 10 cm apart from the proximal edge of the first step and 10 cm apart from the center line (Fig. 1.). They were also instructed to ascend at a constant cadence of 90 steps/min. The cadence was determined and monitored using a digital metronome.

2.3. Experimental procedures

Prior to the stair ascent trial, participants performed several practice trials to adjust to the same cadence at 90 steps/min, and they performed at least five practice trials under each of three foot progression angles: self-selected normal angle (normal), 15° greater than the self-selected normal angle (toe-out), and 15° less than the self-selected normal angle (toe-in) according to the adhesive tape strips placed on the first step. They were instructed to perform the ascending motion while looking at the target tapes. The participants then performed three successful trials under each of the three foot-progression angles. The order of the three foot-progression angle conditions were randomized for each participant.

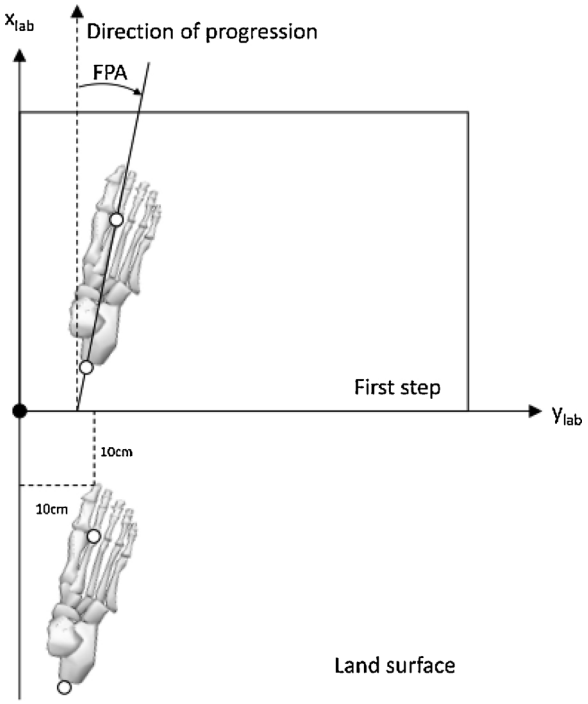

Fig. 1. Foot positions when starting (standing on the Land surface) and when on the first step. The X_{lab} and Y_{lab} axes show the laboratory coordinates. The X_{lab} axis is the center line of the steps, and the Y_{lab} axis is the proximal edge of the first step. The white circles identify the calcaneus and second metatarsal head markers. FPA = foot progression angle.

2.4. Data analyses

All kinematic and kinetic data were calculated using Vicon nexus software. Marker trajectories were low-pass filtered at 6 Hz. Force plate data were filtered at 50 Hz using a zero-lag fourth-order Butterworth filter.

Foot progression angles during the stance phase of the first step were calculated as the angle between the line connecting the calcaneus and second metatarsal head and the line of forward progression of the stairs. Stance time was determined as the trial time from the point at which the right foot initially contacted the first step to the time it was completely off the first step. We analyzed the calcaneus and second metatarsal head marker positions at mid-stance (50% point of the stance phase), the center of pressure position, and the ground reaction force with three components. The positions of the marker and center of pressure were expressed by the x coordinate axis indicating the direction of movement and the y coordinate axis representing the horizontal direction. The two axes were orthogonal at the center line and the proximal edge of the first step (Fig. 1).

Joint kinematics and kinetics were generated using an inverse dynamics analysis. Ground reaction forces and joint moments were normalized to body weight, and joint moments were expressed as external moments. The knee adduction angular impulse was calculated as the area under the normalized knee adduction moment curve over the stance phase. Variables of interest were peak anterior and posterior ground reaction forces, first and second peaks of the medial and vertical ground reaction forces, peak hip flexion, adduction and knee flexion angles, peak hip flexion, adduction, and knee flexion, first and second peak knee adduction moments during the stance phase, and knee adduction angular impulses. The first and second peak values of the medial and vertical ground reaction forces and the knee adduction moments were identified as the maximum values during the 0–50% and 50–100% of the stance phase, respectively. The center of pressure positions at the time of the knee adduction moment, indicating the first

and second peaks, were also calculated.

2.5. Statistical analyses

The average values of the three successful trials for each participant were used for statistical analyses. The Shapiro–Wilk test was used to determine whether datasets were normally distributed. According to the normality results, a one-way repeated measures analysis of variance or Friedman's test was used to analyze the effect of test conditions (normal, toe-out, toe-in). When a significant effect of the condition was observed, paired t-tests or Wilcoxon signed-rank tests with Bonferroni corrections were used to determine significant differences between the three test conditions. The level of statistical significance was set at 5%. All statistical tests were performed using SPSS statistical software (version 20.0; IBM, Inc., Armonk, NY, USA). The effect size of Cohen's d was calculated for kinematic and kinetic variables. Effect size was interpreted in which an effect size of d = 20 was seen as a small effect, d = 0.50 a medium effect, d = 0.80 a large effect, and d = 1.30 a very large effect [25].

3. Results

According to the results of the Shapiro–Wilk test, the peak knee flexion angle and peak external hip flexion moment were not normally distributed. Therefore, the Friedman test and Wilcoxon's signed-rank test with Bonferroni corrections were used for these two variables.

3.1. Foot progression angles, stance times, and marker positions

The mean ± SD of the foot progression angles for normal, toe-out, and toe-in conditions were 4.9° ± 3.3°, 19.1° ± 6.5°, and −7.8° ± 4.1° respectively. Stance times were not different between the three-foot progression angle conditions. The x coordinates of the calcaneus markers were not significantly different among the three conditions at mid-stance. The y coordinates of the second metatarsal head marker were smallest to largest (and significantly different) in the order of toe-in, normal, and toe-out (Table 1, Fig. 1).

3.2. Ground reaction forces and center of pressure positions

There were no significant differences among the three conditions for the peak anterior, posterior, and vertical ground reaction forces. The first and second peak medial ground reaction forces were smallest to greatest (and significantly different) in the order of toe-in, normal, and toe-out. The x coordinate of the center of pressure at the first peak of the knee adduction moment of the toe-out condition was significantly smaller than the normal and toe-in conditions. In contrast, the y coordinate of the center of pressure at the first peak of the knee adduction moment of the toe-out condition was significantly larger than the normal and toe-in conditions. At the second peak of the knee adduction moment, the x coordinate of the center of the pressure, from smallest to largest was significantly different, in the order of toe-out, normal, and toe-in. As for the first peak of the knee adduction moment, the y coordinate of the toe-out condition was significantly larger than for the normal and toe-in conditions (Table 2, Fig. 2).

3.3. Kinematic and kinetic variables

During the stance phase, the hip joint was significantly more flexed in the toe-in condition than in the toe-out condition ($p < 0.01$, $d = 0.31$). Peak hip adduction angles were greatest to smallest (and significantly different) in the order of toe-in, normal, and toe-out (normal vs. toe-out, $d = 0.96$; normal vs. toe-in, $d = 1.03$; toe-out vs. toe-in, $d = 2.21$). In contrast, peak knee adduction angles were smallest to greatest (and significantly different) in the same order (normal vs. toe-out, $d = 0.29$; normal vs. toe-in, $d = 0.41$; toe-out vs. toe-in, $d = 0.72$). The knee joint was significantly more flexed in the normal condition compared with the toe-out condition during the stance phase ($p = 0.016$, $d = 0.33$).

The peak external hip flexion moment was significantly greater during the toe-in condition than during the toe-out condition ($p < 0.01$, $d = 0.28$). The peak external knee flexion moment of the toe-in condition was significantly decreased compared with the normal and toe-out conditions ($p < 0.01$ for both conditions) (normal vs. toe-in, $d = 0.31$; toe-out vs. toe-in, $d = 0.37$) (Fig. 2). The first peak knee adduction moment during the toe-in condition was significantly decreased by about 21% compared with the normal condition ($p < 0.01$, $d = 0.59$, range −15% to 48%) and by about 33% compared with the toe-out condition ($p < 0.01$, $d = 1.03$, range 2%–56%), whereas that of the toe-out condition was significantly increased by about 21% compared with the normal condition ($p < 0.01$, $d = 0.50$, range −26% to 58%). The knee adduction angular impulse during the toe-in condition showed significant reduction compared with the toe-out condition ($p = 0.01$, $d = 0.37$). The peak hip adduction moment and second peak knee adduction moment did not show significant differences among the three conditions (Table 3, Fig. 3).

4. Discussion

In this study, the foot progression angle was set at normal, 15° toe-in, and 15° toe-out, and the stair climbing motion was analyzed. The actual foot progression angle was 4.9° for normal, 19.1° for toe-out, and −7.8° for toe-in; and the difference between normal and toe-in was 12.7° and for normal and toe-out 14.2°. Therefore, the subjects performed the stair climbing motion with the foot progression angle slightly smaller than the prescribed 15° during both toe-in and toe-out conditions. The foot progression angle of 15° set in this study was the angle used in previous studies, and it was an angle that can easily be implemented as toe-in and toe-out. Although other, previous studies used a foot progression angle of 20° greater than normal, the excessive foot progression angle is unlikely to be realistic for knee osteoarthritis patients because excessive knee rotation caused by foot rotation can

Table 1
Foot progression angle, stance time and marker positions at mid-stance.

	Nomal Mean (SD)	Toe-out Mean (SD)	Toe-in Mean (SD)	ANOVA *P* value
Foot progression angle (°)	4.9 (3.3)	19.1 (6.5)	−7.8 (4.1)	< 0.01[a, b, c]
Stance time (s)	1.13 (0.08)	1.14 (0.07)	1.16 (0.07)	0.34
Calcaneus marker position X (cm)	4.8 (1.8)	4.5 (2.0)	4.4 (1.7)	0.65
Calcaneus marker position Y (cm)	12.6 (2.7)	12.9 (3.1)	14.3 (1.5)	0.03[b]
Second metatarsal head marker position X (cm)	22.6 (1.7)	21.3 (1.6)	22.1 (1.4)	< 0.01[a]
Second metatarsal head marker position Y (cm)	13.8 (2.3)	18.7 (3.6)	11.8 (1.2)	< 0.01[a, b, c]

[a] Significant difference between normal and toe-out in *t*-test with Bonferronni corrections.
[b] Significant difference between normal and toe-in *t*-test with Bonferronni corrections.
[c] Significant difference between toe-out and toe-in *t*-test with Bonferronni corrections.

Table 2
Ground reaction force variables and center of pressure positions during stance phase.

	Nomal Mean (SD)	Toe-out Mean (SD)	Toe-in Mean (SD)	ANOVA *P* value
Peak anterior GRF (%BW)	7.3 (3.9)	8.1 (5.5)	7.2 (3.5)	0.74
Peak posterior GRF (%BW)	8.7 (4.3)	8.8 (4.8)	9.0 (4.4)	0.34
First peak medial GRF (%BW)	9.0 (2.6)	9.8 (2.5)	8.1 (1.7)	< 0.01[a, b, c]
Second peak medial GRF (%BW)	8.1 (1.8)	9.2 (2.0)	7.3 (1.3)	< 0.01[a, b, c]
First peak vertical GRF (%BW)	103.8 (18.4)	104.9 (22.2)	103.0 (17.8)	0.42
Second peak vertical GRF (%BW)	110.3 (16.0)	107.6 (15.3)	111.4 (14.5)	0.05
COP position X at first peak of KAM (cm)	16.5 (2.1)	14.8 (2.2)	16.8 (2.1)	< 0.01[a, c]
COP position Y at first peak of KAM (cm)	14.1 (2.8)	16.8 (3.1)	13.5 (1.5)	< 0.01[a, c]
COP position X at second peak of KAM (cm)	18.0 (3.1)	14.5 (2.4)	19.8 (2.3)	< 0.01[a, b, c]
COP position Y at second peak of KAM (cm)	14.1 (2.8)	16.6 (3.5)	12.8 (1.7)	< 0.01[a, c]

GRF: ground reaction force, BW: body weight, COP: center of pressure, KAM: knee adduction moment.
[a] Significant difference between normal and toe-out in *t*-test with Bonferronni corrections.
[b] Significant difference between normal and toe-in *t*-test with Bonferronni corrections.
[c] Significant difference between toe-out and toe-in *t*-test with Bonferronni corrections.

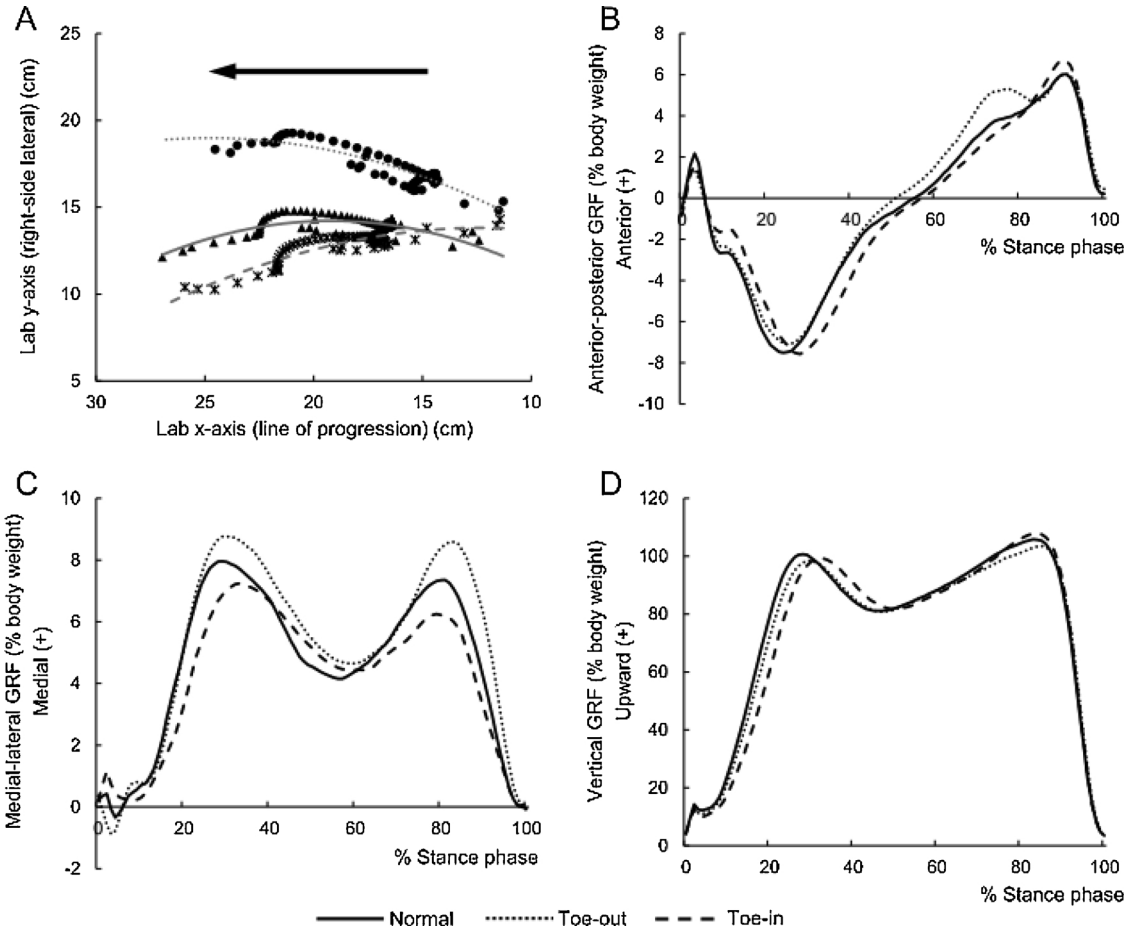

Fig. 2. Change in the position of the center of pressure (COP) and ground reaction forces (GRF) during stance phase. (A) Average paths of the COP for each subject in the normal (triangles), toe-out (circles), and toe-in (asterisks) conditions. The arrow shows the ascending direction of the stairs. Solid line and two dotted lines show approximate curves for each of the three conditions. (B), (C) and (D) indicate the average anteroposterior, mediolateral, and vertical GRF for normal, toe-out, and toe-in conditions. Positive values show anterior, medial, and upward GRF.

lead to pain [26]. Although the knee joint moment is influenced by the gait speed, the stance times were almost the same among the three conditions, so it is possible to compare the joint moment without considering the stance time [27]. During the stair-climbing motion, there was a possibility that the speed of the landing varies depending on the anterior and posterior position of the foot on the step, and that it might also affect the joint moment. Hence, in this study, the position of the markers for the calcaneus and second metatarsal head at mid-stance were calculated. As a result, there was no significant difference in the calcaneus marker positions in the progressive direction among the three conditions. It was therefore considered that there were few influences of the anterior and posterior foot positions on the joint moment.

We found that the first peak knee adduction moment decreased by about 21% (range −14% to 48%) during the toe-in condition compared with the normal condition. In contrast, in the toe-out condition, it increased by about 19% (range −26% to 58%) compared with the normal

Table 3
Kinematic and kinetic variables during stance phase.

	Nomal Mean (SD)	Toe-out Mean (SD)	Toe-in Mean (SD)	ANOVA and Friedman *P* value
Peak hip flexion angle (°)	56.6 (6.3)	56.1 (6.5)	57.6 (6.8)	0.01[c]
Peak hip adduction angle (°)	5.0 (4.0)	1.0 (3.9)	9.0 (3.7)	< 0.01[a, b, c]
Peak knee flexion angle (°)	61.3 (5.6)	59.6 (5.2)	60.2 (4.5)	0.04[a]
Peak knee adduction angle (°)	17.0 (12.3)	20.4 (11.7)	12.3 (11.6)	< 0.01[a, b, c]
Peak external hip flexion moment (Nm/kg)	0.84 (0.38)	0.79 (0.36)	0.89 (0.38)	< 0.01[c]
Peak external hip adduction moment (Nm/kg)	0.73 (0.16)	0.70 (0.16)	0.73 (0.17)	0.06
Peak external knee flexion moment (Nm/kg)	0.82 (0.27)	0.84 (0.30)	0.75 (0.24)	< 0.01[b, c]
First peak external knee adduction moment (Nm/kg)	0.44 (0.15)	0.52 (0.19)	0.35 (0.15)	< 0.01[a, b, c]
Second peak external knee adduction moment (Nm/kg)	0.30 (0.13)	0.31 (0.12)	0.33 (0.14)	0.11
Knee adduction angular impulse (Nm· s/kg)	0.24 (0.10)	0.26 (0.10)	0.23 (0.10)	< 0.01[c]

[a] Significant difference between normal and toe-out in *t*-test or Wilcoxon signed-rank test with Bonferronni corrections.
[b] Significant difference between normal and toe-in *t*-test or Wilcoxon signed-rank test with Bonferronni corrections.
[c] Significant difference between toe-out and toe-in *t*-test or Wilcoxon signed-rank test with Bonferronni corrections.

condition. In both cases, it was a medium effect size. The reason for this result may have been that the hip joint was significantly adducted compared with normal during stair ascent in the toe-in condition. Additionally, the center of the knee joint moved medially, and the moment arm between the ground reaction force vector and the center of the knee joint was shortened. In contrast, in the toe-out condition, it was considered that the distance between the center of the knee joint and the ground reaction force vector increased because the hip joint abducted and the knee joint varus angle increased. In fact, the peak hip adduction angle during the stance phase increased about 4° with toe-in and decreased about 4° with toe-out compared with the normal condition. Likewise, the peak knee adduction angle decreased about 5° in the toe-in condition and increased about 3° in the toe-out condition compared with the normal condition. The fact that the first peak medial ground reaction force of the toe-in condition was significantly smaller than in the other two conditions is considered a factor in the decreased knee adduction moment. In contrast, the center of the pressure horizontal position at the first peak of the knee adduction moment in the toe-out condition was significantly more lateral than in the normal and toe-in conditions, and the first peak of the medial ground reaction force in the toe-out condition was significantly larger than in the other two conditions. Considering the lever arm from the center of the knee joint

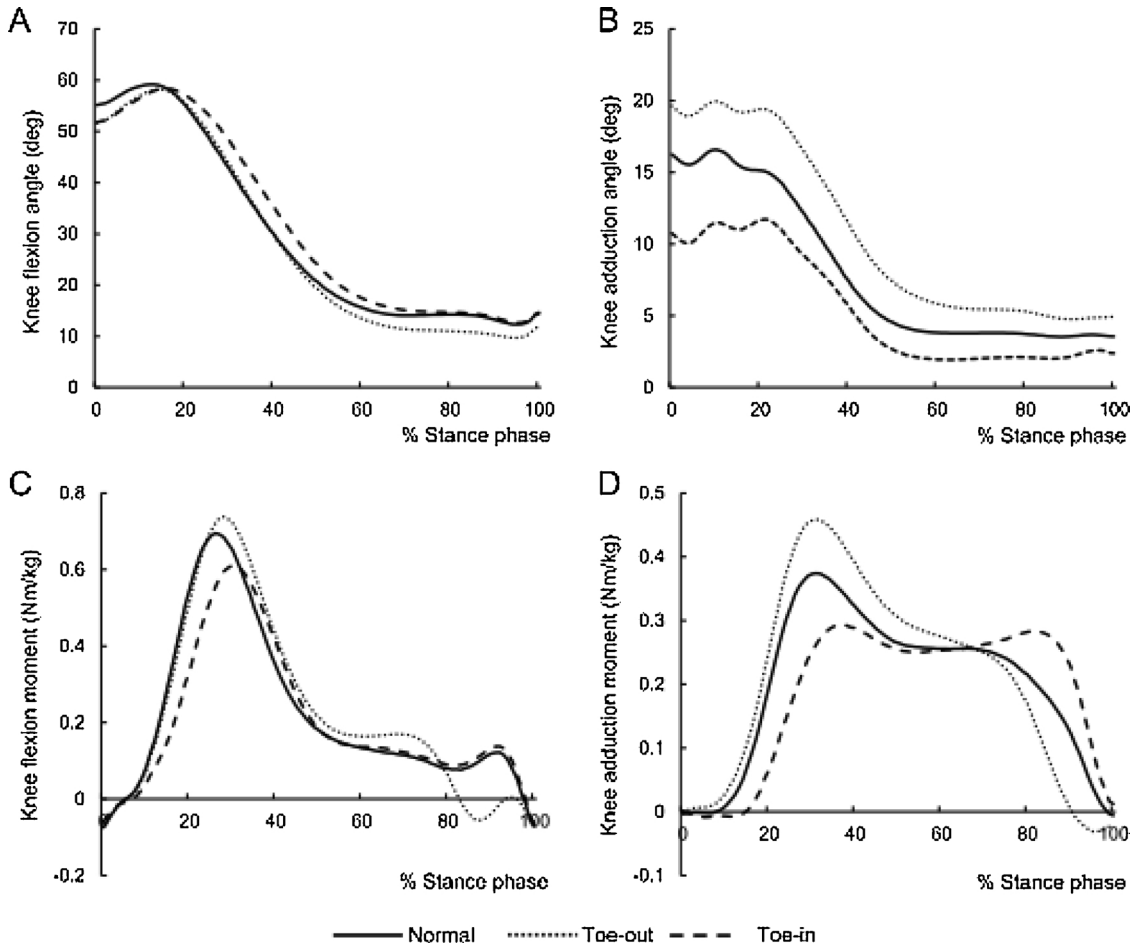

Fig. 3. Average knee flexion angle (A), knee adduction angle (B), external knee flexion moment (C) and external knee adduction moment (D) of the subjects for normal, toe-out, and toe-in conditions during the stance phase.

to the ground reaction force vector, the lateral shift of the center of pressure has a positive effect in reducing the knee adduction moment, but the increased medial ground reaction force is a factor that increases the knee adduction moment. Even if the values for the knee adduction moment are the same, the contact pressure between the femur and tibia is greater as the knee joint flexion angle enlarges [28]. Therefore, the toe-in condition is considered particularly effective for movements that involve large knee flexion angles, such as stair climbing or descending and when moving from sitting to standing. However, there were no significant differences between the three conditions during the second peak of the knee adduction moment. When the knee adduction moment reached the second peak, the knee joint assumed the extended position and was close to the angle of the late stance phase of gait. During walking, it was shown that the second peak of the knee adduction moment decreased with toe-out gait compared with normal gait [15] [18] [29]. The knee adduction angular impulse during the toe-in condition was significantly lower than with the toe-out condition, but there was no statistically significant difference between toe-in and normal conditions. Because Khan et al. [16] and Bennett et al. [30] reported that the toe-in gait internally rotated the foot progression angle by 10°–15° and significantly reduced the knee adduction angular impulse compared with normal gait, the decrease in the knee adduction angular impulse due to the toe-in condition was more likely to occur during walking than stair climbing.

The peak flexion moment of the knee joint was significantly lower in the toe-in condition than in the normal and toe-out conditions. Conversely, the peak hip flexion moment was significantly higher in the toe-in condition than the toe-out condition. Because the peak hip angle was significantly greater in the toe-in condition than in toe-out, during toe-in it was thought that the greater flexion of the hip joint displaced the center of mass forward, with the hip flexion moment increased and the knee flexion moment decreased. Because both the knee flexion and adduction moments had been reported to be associated with knee joint medial compartment contact force [31], it is an important finding that the flexion moment decreased with the toe-in condition.

In addition to the foot progression angle, the knee adduction moment was reduced during walking by increasing the leaning of the ipsilateral trunk [14] and widening the step width [30]. Even when ascending stairs, knee adduction and flexion moments may decrease due to strategies such as use of a handrail or trunk flexion. Further research investigating the effects of such strategies is therefore necessary.

There are several limitations in this study. Stair walking includes both ascent and descent, although this study focused only on the ascending motion. Therefore, it is not clear whether the foot progression angle affects the load on the knee joint when descending stairs. In this study, however, the foot progression angles were set at 15° toe- and 15° toe-out, the averages of which were < 15° in both conditions. If the prescribed foot progression angles were perfectly adopted, larger differences might be detected in the kinematic and kinetic variables. We used only steps with a height of 16.5 cm. In environments other than the laboratory, however, steps are of varying heights. Therefore, in the case of very low or very high steps (i.e., < 16.5 cm or > 16.5 cm), the results of this research may not apply. Because this study focused on healthy volunteers and did not take into account the knee's frontal alignment, further studies of patients with medial compartment knee osteoarthritis are needed.

5. Conclusion

The foot progression angle significantly affects hip and knee joint kinematics and kinetics during stair climbing. The toe-in condition significantly changed the hip and knee adduction angles and the medial ground reaction force. It also successfully reduced the first peak knee adduction moment compared with the normal and toe-out conditions. Moreover, the toe-in condition showed a significantly reduced knee adduction angular impulse compared with that in the toe-out condition. In addition, the toe-in condition reduced the peak knee flexion moment, which is related to the contact force in the medial compartment of the knee joint. These results indicate that toe-in is the most advantageous strategy for reducing a medial compartment knee load. In contrast, toe-out gait increased the first peak knee adduction moment compared with that under the normal and toe-in conditions. Therefore, toe-out gait may pose a risk of promoting progression of medial compartment knee osteoarthritis, so care must be taken during stair climbing.

Authorship

All authors made substantial contributions to (1) the conception and design of the study, or acquisition of data, or analysis and interpretation of data; (2) drafting the paper or revising it critically; and (3) final approval of the version to be submitted.

Conflict of interest statement

We certify that no party having a direct interest in the results of the research in this article has or will confer a benefit on us or on any organization with which we are associated.

Acknowledgements

This work was supported by the JSPS KAKENHI Grant Number [JP15K21539]. We thank Peter Mittwede, MD, PhD, from Edanz Group (www.edanzediting.com/ac) for editing a draft of this manuscript.

References

[1] S. Muraki, T. Akune, H. Oka, Y. Ishimoto, K. Nagata, M. Yoshida, et al., Incidence and risk factors for radiographic knee osteoarthritis and knee pain in Japanese men and women: a longitudinal population-based cohort study, Arthritis Rheum. 64 (2012) 1447–1456.
[2] G.M. Brouwer, A.W. van Tol, A.P. Bergink, J.N. Belo, R.M. Bernsen, M. Reijman, et al., Association between valgus and varus alignment and the development and progression of radiographic osteoarthritis of the knee, Arthritis Rheum. 56 (2007) 1204–1211.
[3] L. Sharma, J. Song, D.T. Felson, S. Cahue, E. Shamiyeh, D.D. Dunlop, The role of knee alignment in disease progression and functional decline in knee osteoarthritis, JAMA 286 (2001) 188–195.
[4] N. Yoshimura, S. Muraki, H. Oka, S. Tanaka, H. Kawaguchi, K. Nakamura, et al., Accumulation of metabolic risk factors such as overweight, hypertension, dyslipidaemia, and impaired glucose tolerance raises the risk of occurrence and progression of knee osteoarthritis: a 3-year follow-up of the ROAD study, Osteoarthr. Cartil. 20 (2012) 1217–1226.
[5] E. Yusuf, J. Bijsterbosch, P.E. Slagboom, F.R. Rosendaal, T.W. Huizinga, M. Kloppenburg, Body mass index and alignment and their interaction as risk factors for progression of knees with radiographic signs of osteoarthritis, Osteoarthr. Cartil. 19 (2011) 1117–1122.
[6] A. Hung, E.C. Sayre, A. Guermazi, J.M. Esdaile, J.A. Kopec, A. Thorne, et al., Association of body mass index with incidence and progression of knee effusion on magnetic resonance imaging and on knee examination, Arthritis Care Res (Hoboken) 68 (2016) 511–516.
[7] F. Eymard, C. Parsons, M.H. Edwards, F. Petit-Dop, J.Y. Reginster, O. Bruyere, et al., Diabetes is a risk factor for knee osteoarthritis progression, Osteoarthr. Cartil. 23 (2015) 851–859.
[8] A.N. Bastick, J.N. Belo, J. Runhaar, S.M. Bierma-Zeinstra, What are the prognostic factors for radiographic progression of knee osteoarthritis? A meta-analysis, Clin. Orthop. Relat. Res. 473 (2015) 2969–2989.
[9] D.E. Hurwitz, A.B. Ryals, J.P. Case, J.A. Block, T.P. Andriacchi, The knee adduction moment during gait in subjects with knee osteoarthritis is more closely correlated with static alignment than radiographic disease severity, toe out angle and pain, J. Orthop. Res. 20 (2002) 101–107.
[10] D. Zhao, S.A. Banks, K.H. Mitchell, D.D. D'Lima, C.W. Colwell Jr., B.J. Fregly, Correlation between the knee adduction torque and medial contact force for a variety of gait patterns, J. Orthop. Res. 25 (2007) 789–797.
[11] A.J. Baliunas, D.E. Hurwitz, A.B. Ryals, A. Karrar, J.P. Case, J.A. Block, et al., Increased knee joint loads during walking are present in subjects with knee osteoarthritis, Osteoarthr. Cartil. 10 (2002) 573–579.
[12] T. Miyazaki, M. Wada, H. Kawahara, M. Sato, H. Baba, S. Shimada, Dynamic load at baseline can predict radiographic disease progression in medial compartment knee osteoarthritis, Ann. Rheum. Dis. 61 (2002) 617–622.
[13] S. Amin, N. Luepongsak, C.A. McGibbon, M.P. LaValley, D.E. Krebs, D.T. Felson, Knee adduction moment and development of chronic knee pain in elders, Arthritis Rheum. 51 (2004) 371–376.

[14] M.A. Hunt, T.B. Birmingham, D. Bryant, I. Jones, J.R. Giffin, T.R. Jenkyn, et al., Lateral trunk lean explains variation in dynamic knee joint load in patients with medial compartment knee osteoarthritis, Osteoarthr. Cartil. 16 (2008) 591–599.
[15] J.C. van den Noort, I. Schaffers, J. Snijders, J. Harlaar, The effectiveness of voluntary modifications of gait pattern to reduce the knee adduction moment, Hum. Mov. Sci. 32 (2013) 412–424.
[16] S.S. Khan, S.J. Khan, J. Usman, Effects of toe-out and toe-in gait with varying walking speeds on knee joint mechanics and lower limb energetics, Gait Posture 53 (2017) 185–192.
[17] P.B. Shull, R. Shultz, A. Silder, J.L. Dragoo, T.F. Besier, M.R. Cutkosky, et al., Toe-in gait reduces the first peak knee adduction moment in patients with medial compartment knee osteoarthritis, J. Biomech. 46 (2013) 122–128.
[18] M. Simic, T.V. Wrigley, R.S. Hinman, M.A. Hunt, K.L. Bennell, Altering foot progression angle in people with medial knee osteoarthritis: the effects of varying toe-in and toe-out angles are mediated by pain and malalignment, Osteoarthr. Cartil. 21 (2013) 1272–1280.
[19] M. Guo, M.J. Axe, K. Manal, The influence of foot progression angle on the knee adduction moment during walking and stair climbing in pain free individuals with knee osteoarthritis, Gait Posture 26 (2007) 436–441.
[20] T.R. Jenkyn, M.A. Hunt, I.C. Jones, J.R. Giffin, T.B. Birmingham, 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. 41 (2008) 276–283.
[21] M. Hall, E.R. Boyer, J.C. Gillette, G.A. Mirka, Medial knee joint loading during stair ambulation and walking while carrying loads, Gait Posture 37 (2013) 460–462.
[22] S. Gilbert, T. Chen, I.D. Hutchinson, D. Choi, C. Voigt, R.F. Warren, et al., Dynamic contact mechanics on the tibial plateau of the human knee during activities of daily living, J. Biomech. 47 (2014) 2006–2012.
[23] H.J. Bennett, S. Zhang, G. Shen, J.T. Weinhandl, M.R. Paquette, J. Reinbolt, et al., Effects of toe-in and wider step width in stair ascent with different knee alignments, Med. Sci. Sports Exerc. 49 (2017) 563–572.
[24] N. Fukutani, H. Iijima, T. Aoyama, Y. Yamamoto, M. Hiraoka, K. Miyanobu, et al., Knee pain during activities of daily living and its relationship with physical activity in patients with early and severe knee osteoarthritis, Clin. Rheumatol. 35 (2016) 2307–2316.
[25] P.D. Ellis, Thresholds for Interpreting Effect Sizes, (2009), pp. 1–2.
[26] S.K. Lynn, T. Kajaks, P.A. Costigan, 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 11 (2008) 444–451.
[27] S. Telfer, M.J. Lange, A.S.M. Sudduth, Factors influencing knee adduction moment measurement: a systematic review and meta-regression analysis, Gait Posture 58 (2017) 333–339.
[28] K. Engel, G.P. Bruggemann, K. Heinrich, W. Potthast, C. Liebau, Do counteracting external frontal plane moments alter the intraarticular contact force distribution in the loaded human tibiofemoral joint? Knee. 22 (2015) 68–72.
[29] S.K. Lynn, P.A. Costigan, Effect of foot rotation on knee kinetics and hamstring activation in older adults with and without signs of knee osteoarthritis, Clin. Biomech. Bristol Avon (Bristol, Avon) 23 (2008) 779–786.
[30] H.J. Bennett, G. Shen, H.E. Cates, S. Zhang, Effects of toe-in and toe-in with wider step width on level walking knee biomechanics in varus, valgus, and neutral knee alignments, Knee 24 (2017) 1326–1334.
[31] R.E. Richards, M.S. Andersen, J. Harlaar, J.C. van den Noort, Relationship between knee joint contact forces and external knee joint moments in patients with medial knee osteoarthritis: effects of gait modifications, Osteoarthr. Cartil. 26 (2018) 1203–1214.