

Article

Not peer-reviewed version

Influence of Internal and External Foot Rotation on Peak Knee Adduction Moments and Ankle Moments during Gait in Individuals with Knee Osteoarthritis

[Yongwook Kim](#) *

Posted Date: 23 February 2024

doi: 10.20944/preprints202402.1343.v1

Keywords: adduction moment; foot progression angle; knee joint; osteoarthritis



Preprints.org is a free multidiscipline platform providing preprint service that is dedicated to making early versions of research outputs permanently available and citable. Preprints posted at Preprints.org appear in Web of Science, Crossref, Google Scholar, Scilit, Europe PMC.

Copyright: This is an open access article distributed under the Creative Commons Attribution License which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Article

Influence of Internal and External Foot Rotation on Peak Knee Adduction Moments and Ankle Moments during Gait in Individuals with Knee Osteoarthritis

Yongwook Kim

ptkim@jj.ac.kr

Abstract: Biomechanical changes such as increased knee adduction moment (KAM) during walking are known to be involved in the development and severity of knee osteoarthritis (OA). Although various foot progression angle (FPA) modifications during gait have been applied to reduce peak KAM, few studies have investigated effects of applying toe-in or toe-out walking modifications for knee OA on peak KAM and three-dimensional (3D) moments of the ankle joint. Kinetic moment variables were acquired from 35 individuals with medial knee compartment OA. A 3D motion analysis system and two force platforms were used to acquire KAM and 3D moments of both ankle joints during gait. Visual3D motion analysis program was used to obtain final moment data for statistical processing. Repeated-measures analysis of variance with Bonferroni adjustment was used to compare kinetic and kinematic values for each FPA walking condition. The first peak KAM of an internal rotation foot position of the FPA walking condition showed significant decrease compared to normal foot position walking ($p < 0.01$). The second peak KAM of an external rotation foot position walking showed significant decrease compared to normal foot position walking ($p < 0.01$). Compared to a normal foot position, peak ankle inversion moment of the external rotation foot position walking showed a significantly decrease ($p < 0.05$). There were no interactive effects between FPA condition and limb sides for any KAM values ($p > 0.05$). These results suggest that clinical application of toe-in or toe-out gait modification walking in individuals with knee OA should be performed based on biomechanical evaluations such as peak KAM.

Keywords: adduction moment; foot progression angle; knee joint; osteoarthritis

1. Introduction

Knee osteoarthritis (OA), one of the degenerative diseases, is rapidly increasing due to recent increase in human average lifespan and an aging society [1,2]. In Korea, knee OA is a common disease that occurs in about one-third of people over the age of 60, with a prevalence rate of 20.2% in men and 50.1% in women [3]. Biomechanical changes such as increases of knee adduction moment (KAM) and knee varus shear force during walking are known to be involved in the development and severity of knee OA [4–6]. Because it is generally difficult to measure joint loads directly, joint moments such as KAM are often used as alternative measures of the force applied to a joint [7]. Knee moments that occur in real time during the stance phase, when the body weight is supported on the ground while walking, are biomechanical variables calculated by multiplying the magnitude of the three-dimensional ground reaction force and the lever arm distance from the knee joint center. Clinically, KAM is used for diagnosing knee OA and predicting knee pain, knee deformity, and the degree of knee OA progression [8,9]. KAM is a coronal kinetic variable. It typically has two distinct peaks during the stance phase of gait. The first peak occurs around the 25% stance phase during walking. The second peak elicits around the 75% stance phase [3]. The first peak KAM is typically greater than the second one. It is larger for patients with medial knee OA than for age-matched healthy individuals [10]. Peak KAMs during walking are determined by various factors such as gait pattern, knee pain avoidance strategy, and foot progression angle (FPA). Abnormally increased KAM during gait is closely related to worsening of musculoskeletal diseases such as knee OA [4,11,12].

From a biomechanical perspective, changes in kinematic and kinetic variables of any joints or segments during gait may affect ergonomic variables of all other connected joints and segments of

the musculoskeletal system [13,14]. Therefore, changes in FPA such as internal rotation or external rotation of the foot in contact with the floor during the stance phase of gait may affect the KAM [6,14]. Since a study of Wang et al. [15], many studies have been conducted on biomechanical effects of lower extremity joints according to changes in FPA during walking. A previous study has demonstrated that the effect of FPA on KAM, in particular, self-selected over 15° of increasing toe-out angle in pain free individuals with knee OA, can significantly decrease the second peak KAM during gait except the first peak [6]. Additionally, the first KAM in internal rotation of FPA during gait is significantly decreased in patients with medial compartment knee OA [16]. Although many previous studies have reported that tiptoe walking and tiptoe walking interventions can reduce first and second peak KAMs in patients with medial compartment osteoarthritis of the knee joint, peak KAM change varies significantly between individuals in response to the achievement of the target FPA, anatomical variations, and biomechanical influence of the motor link [5]. Therefore, limiting exogenous variables that have a negative impact on measurement and evaluating objective and quantitative peak KAMs according to changes in FPA during gait are important for obtaining positive clinical outcomes of patients with knee OA.

Studies verifying effects of foot rotation modifications during gait have mainly focused on effects of FPA during gait on biomechanics of the knee joint [7,17]. There is a need to evaluate effects of these modifications on other lower extremity joints. Most of related studies have mainly examined effects of gait modification on KAM and biomechanical values of the hip joint [7,18,19]. However, there have been few studies on effects of foot modification angle during walking on kinematics and kinetics of the ankle joint along with its effect on KAM. Although it is not known how FPA changes affect the ankle joint, increased ankle joint moments in three dimensional planes of motion may increase biomechanical loads on soft tissues around the ankle joint and increase the incidence of musculoskeletal disorders such as ankle OA [20]. Therefore, the purpose of this study was to investigate effects of different FPA conditions during free walking on kinetics of the ankle and knee joints in pain-free individuals with knee osteoarthritis using a 3D motion analysis system with two force platforms.

2. Materials and Methods

2.1. Study Subjects

Thirty-five subjects (9 males and 26 females) diagnosed with knee OA participated in this study. All participants had knee OA without pain. Their average Kellgren-Lawrence grade was 1.8 ± 0.58 (Grade I: n = 10, Grade II: n = 22, Grade III: n = 3). They were recruited from an area orthopedic clinic. The mean illness duration of knee OA after initial diagnosis was 5.2 ± 2.4 years. Inclusion criteria were: 1) no surgical history of knee or ankle joints; 2) no severe pain of the lower extremity joints or segments; 3) Kellgren-Lawrence grade 3 or less; and 4) able to walk free and unaided according to instructions. If participants had neurologic conditions affecting walking, painful knee OA, or systemic rheumatoid arthritis, they were excluded from this study. Participants had an average age of 62.2 years, a height of 159.3 cm, and a weight of 64.8 kg (Table 1). Average walking speeds in NFP, IFP, and EFP gait trials were 1.24 ± 0.20 m/s, 1.21 ± 0.27 m/s, and 1.23 ± 0.19 m/s, respectively. There were no significant differences in walking speed, cadence, or step length between FPA walking conditions (all $p > 0.05$). An experienced researcher fully explained the research purpose and experimental procedures of this study to study subjects. All subjects voluntarily agreed to participate in this study. Written informed consents were obtained from all participants. The study assessment protocol and design were approved by the Institutional Review Board of Jeonju University (jjIRB-200714-HR-2020-0708).

Table 1. General characteristics of study participants (standard deviation (SD) is presented in parentheses).

Characteristics (N=35)	Mean (SD)
Age (yr)	61.2 (2.1)
Height (cm)	159.3 (9.5)
Weight (kg)	64.8 (10.2)
Gender	Male: 9, Female: 26
Foot rotation angle (deg)	NFP: 17.84 (7.12), IFP: -10.09 (5.55), EFP: 42.76 (6.80)
Velocity (m/s)	NFP: 1.19 (0.13), IFP: 1.16 (0.13), EFP: 1.20 (0.14)

NFP: normal foot position; IFP: internal foot position; EFP: external foot position.

2.2. Instrumentation for gait analysis and data acquisition

Biomechanical data during gait were acquired from motion analysis experimental laboratory at Jeonju university. A 3D motion analysis system (Vicon Inc., Oxford, England) based on eight infrared cameras and 8 m walking pathway was used to acquire KAM and 3D moments of both ankle joints during gait (Figure 1). The sampling rate of the motion capture camera system was set at 100 Hz. The lab had two force platforms (AMTI, Watertown, MA, USA) for sampling data at 500 Hz. Those were placed in the center of the walking way to obtain 3D ground reaction force to calculate knee and ankle moments for three different FPA conditions: normal foot position (NFP), maximal possible internal rotation foot position (IFP), and maximal possible external foot position (EFP).

A T-frame bar (0.75 m) was used to recognize the origin of the 3D spatial coordinates of the laboratory and for initial calibration of the object and motion analysis system. Analog kinetic and kinematic data obtained from two force platforms and eight capture cameras were converted to digital data and processed through Nexus program (ver. 1.8.5, Vicon Inc., Oxford, England) on the main computer. Anatomical labeling of reflective markers and a lower limb segment model, which was the basis for gait analysis, were created through the Nexus program [21]. In addition, the final c3d file for each gait trial was created through integrated processing of all kinetic and kinematic data.

Visual3D (C-Motion Inc., Germantown, MD, USA), a motion analysis program, was used with the final c3d data exported in the Nexus program to obtain finals quantitative moment data for statistical processing and 3D graphic results of knee and ankle moments (Figure 2). Visual3D software created a virtual skeletal model for each subject based on reflective marker settings. It was able to analyze knee moment and foot angle for each of the three FPA walking trials (Figure 3). The X-Y-Z Cardan order was used to decide the sequence of rotations according to the Right-Hand Rule about the segment coordinate system’s axes [3]. All biomechanical data were low-pass filtered using a fourth-order Butterworth filter with cutoff frequencies set to 15 Hz and 6 Hz, respectively [22].



Figure 1. Motion analysis laboratory equipped with 3D motion capture cameras and two force platforms embedded in the center of the experimental 8 m walking pathway.

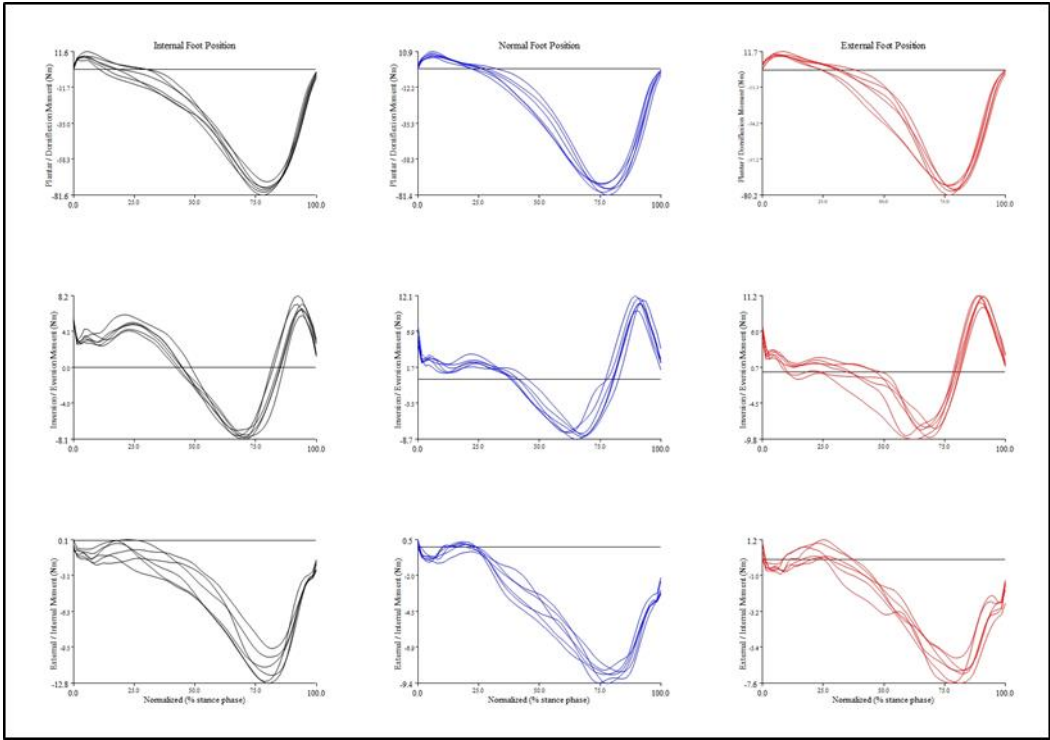


Figure 2. Intra-individual variability in three-dimensional ankle joint net moments according to each foot position condition during walking trials.

Ten reflective markers (14 mm) were attached bilaterally on the medial and lateral malleoli, medial and lateral femoral epicondyles, and greater trochanters to create joint positions. Four cluster markers were attached bilaterally on the lower leg and thigh segments according to six degrees of freedom (6DOF) model to present lower skeletal segments [22]. Additionally, five reflective markers were attached to foot segments to measure FPA. Foot markers were attached onto the first and fifth

metatarsophalangeal joints, the dorsal center of the midfoot, and medial and lateral hind foot. After setting the marker, static calibration was executed to acquire dynamic moment data of the ankle and knee joints. The average FPA value in each walking condition was calculated through 100% of stance phase.

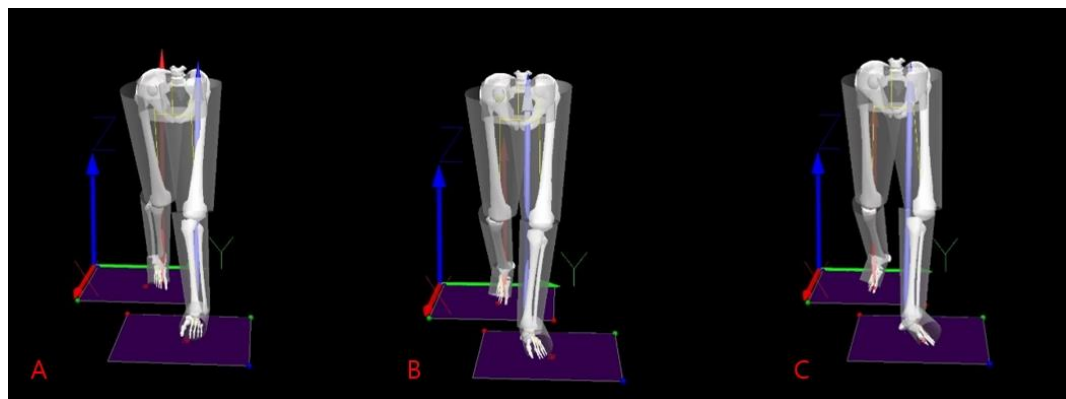


Figure 3. Visual3D representation of virtual musculoskeletal model according to three different foot progression angles in each walking trial. A: Internal rotation foot position; B: Normal foot position; C: External rotation foot position.

2.3. Gait analysis

Before attempting FPA walking trials, static capture of reflective marker settings, which served as the standard for dynamic gait analysis, was performed for each subject. To maintain a consistent foot rotation angle in each FPA walking trial, the foot rotation when each subject walked naturally was set as the baseline NFP. IFP and EFP conditions were then set by adding or subtracting about 20° to this angle [23]. Additionally, to ensure consistent walking speed and step width, a tape line was attached to the walking pathway so that each subject could know the degree of FPA rotation achieved during walking practice. For each walking condition (NFP, IFP, and EFP), a total of 8–10 walking trials that achieved the target FPA line were analyzed. Kinetic and kinematic data were calculated for every walking trial and averaged over each FPA gait condition. If the trial was not completed successfully in an FPA condition, an additional walking trial was performed. We applied a modified anatomical systems technique to analyze biomechanical changes that occurred in the knee and ankle joints during comfortable gait trials in different FPA conditions. All kinetic moment data of the knee and ankle joints were normalized by each participant's body weight and analysis time of moment normalized to 100% of the stance phase during gait. The experimental order of each FPA condition was randomly assigned.

2.4. Statistical analysis

Knee and ankle moments were normalized by subject weight [7]. Knee moments values were compared between main FPA conditions: 1st peak KAM during 0–50% of stance phase, peak KAM at mid stance, and 2nd peak KAM during 50–100% of stance phase. For comparative analysis of ankle moments for each FPA walking condition, characteristic peak moment variables generated in each 3D motion plane were used. Peak ankle moment variables used in the analysis were dorsiflexion, plantar flexion, inversion, eversion, internal rotation, and external rotation moment that occurred in a specific period of stance phase.

G*Power (version 3.1.9.7) analysis was used to estimate the appropriate sample size. A sample size of 25 was obtained based on an effect size enough to identify the estimated significance based on a previous study [5] that examined effects of toe-in and toe-out gait retraining on biomechanical variables. Because all analysis variables satisfied the parametric test, the Kolmogorov-Smirnov test used to verify normal distribution, two-way repeated-measures analysis of variance (ANOVA) with

Bonferroni adjustment was used to compare biomechanical values for each FPA walking condition. If the significance of the main effect (FPA condition or limb side) was confirmed in the ANOVA, pairwise comparisons were performed using post hoc tests. All analyses were performed using SPSS version 26 (IBM Corp, Armonk, NY, USA).

3. Results

3.1. Peak knee moments occurring in coronal motion plane

All knee joint moment data required for analysis satisfied Mauchly's sphericity assumption. There were significant differences in repeated measures ANOVA results of the peak knee moment occurring in the coronal plane during the stance phase depending on FPA gait and bilateral knee conditions ($p < 0.01$) (Table 2). Specifically, the first peak KAM ($F = 9.753, p = 0.004$) and the second peak KAM ($F = 27.624, p = 0.00006$) were significantly different according to FPA walking trials (Table 2). The first peak KAM of the IFP walking condition showed a significant decrease compared to that of the NFP condition ($p < 0.01$) (Table 3, Figure 4). Additionally, the second peak KAM of the EFP condition showed a significant decrease compared to that of the NFP condition ($p < 0.01$) (Table 3, Figure 4). There were no significant differences in knee coronal moment variables among all other FPA walking conditions ($p > 0.05$). There were no interactive effects between FPA condition and knee sides for any KAM values ($p > 0.05$) (Table 2).

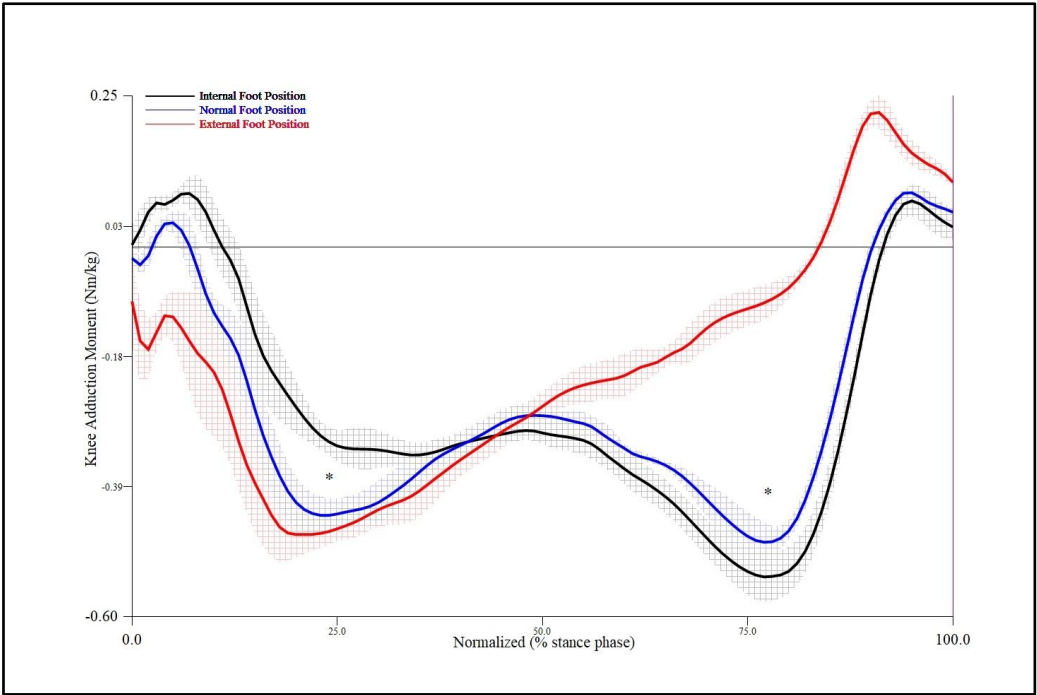


Figure 4. Mean and standard deviation of knee adduction moment for all three foot rotation positions in stance phase during gait. *, Significant main effect for foot progression angle position at $p < 0.01$.

Table 2. Comparisons of peak knee moments of coronal plane by foot progression angle and knee side in stance phase during gait.

Moment values	Level	F	p-value
Knee adduction moment ait 1st peak 0-25% stance (Nm/kg)	Foot positions	9.753	0.003
	Knee sides	1.375	0.218
	Positions*sides	2.540	0.101
	Foot positions	0.984	0.326

Knee adducton moment at mid stance 25-70% stance (Nm/kg)	Knee sides	0.077	0.734
	Positions*sides	0.183	0.657
Knee adduction moment at 2nd peak 75-100% stance (Nm/kg)	Foot positions	27.624	0.000
	Knee sides	1.779	0.166
	Positions*sides	1.343	0.255

Table 3. Mean (SD) values of knee adduction moments presented for all three foot progression conditons in stance phase during gait.

Moment values (Nm·kg ⁻¹)	NFP	IFP	EFP	p-value
1st peak knee adduction moment at around 25% stance	-0.42* (0.11)	-0.34 (0.08)	-0.47 (0.10)	0.003
Knee adducton moment at mid 50% stance	-0.27 (0.09)	-0.30 (0.08)	-0.27 (0.09)	0.326
2nd peak knee adduction moment at around 75% stance	-0.44† (0.14)	-0.50 (0.16)	-0.11 (0.11)	0.000

*Significant difference between NFP and IFP conditions, $p < 0.01$. †Significant difference between NFP and EFP conditions, $p < 0.01$. NFP: normal foot position; IFP: internal foot position; EFP: external foot position.

3.2. Moment results of ankle joint according to FPA condition

There was a significant difference only in the peak inversion moment generated at the ankle joint in the stance phase during walking depending on FPA conditions ($F = 6.107$, $p = 0.019$) (Table 4). Table 5 shows mean and standard deviation of peak moments occurring at the ankle joint according to the three FPA conditions in the stance phase during walking. Compared to the NFP condition, the peak inversion moment of the EFP walking condition generated at 50-75% stance phase showed a significantly decrease moment ($p = 0.034$, 95% CI = -0.07 ~ -0.01) (Table 5). On the other hand, except for the inversion peak moment value, there were no significant differences in other ankle peak moment values according to FPA walking conditions ($p > 0.05$). There were no interactive effects between FPA condition and ankle sides for any ankle moment variables ($p > 0.05$) (Table 4).

Table 4. Repeated measures ANOVA comparing three-dimensional ankle movement by foot rotation conditions and foot side during gait.

Ankle moment (Nm·kg ⁻¹)	Level	F	p-value
Dorsiflexion moment peak 0-50% stance	Foot position	0.761	0.486
	Ankle sides	1.122	0.299
	Positions*sides	2.744	0.078
Plantar flexion moment peak 50-100% stance	Foot position	0.529	0.571
	Ankle sides	1.161	0.254
	Positions*sides	0.188	0.815
Inversion moment peak 50-75% stance	Foot position	6.107	0.019
	Ankle sides	1.230	0.281
	Positions*sides	0.019	0.843
Eversion moment peak 0-50% stance	Foot position	2.347	0.102
	Ankle sides	0.294	0.758
	Positions*sides	1.003	0.359
	Foot position	0.888	0.390

Internal rotation moment peak	Ankle sides	0.554	0.568
0-50% stance	Positions*sides	0.290	0.692
External rotation moment peak	Foot position	1.453	0.197
50-100% stance	Ankle sides	0.482	0.475
	Positions*sides	2.111	0.120

Table 5. Mean (SD) ankle moment values presented for all three foot progression coditions in stance phase during gait.

Ankle moment (Nm·kg ⁻¹)	NFP	IFP	EFP
Dorsiflexion peak 0-50% stance	0.18 (0.08)	0.18 (0.09)	0.17 (0.09)
Plantarflexion peak 50-100% stance	-1.34 (0.26)	-1.34 (0.27)	-1.37 (0.26)
Inersion peak 50-75% stance	-0.09* (0.04)	-0.11 (0.06)	-0.04 (0.05)
Eversion peak 0-50% stance	0.32 (0.26)	0.32 (0.25)	0.30 (0.26)
Internal rotation peak 0-50% stance	0.05 (0.08)	0.05 (0.07)	0.03 (0.05)
External rotation peak 50-100% stance	-0.24 (0.16)	-0.27 (0.19)	0.23 (0.16)

*Significant difference between NFP and EFP conditions, p < 0.05. NFP: normal foot position; IFP: internal foot position; EFP: external foot position.

4. Discussion

This study was conducted to determine effects of gait modifications such as toe-in and toe-out walking on knee KAM and 3D moment characteristics occurring at the ankle joint during the stance phase in subjects with knee osteoarthritis. Increased KAM during walking not only increases the loading force imposed on the medial compartment of the knee joint, but also promotes the development of clinical symptoms of knee OA such as pain and inflammation [24–26]. Therefore, various gait modification methods such as medial knee thrust, lateral trunk lean, and toe-in or out gait have been applied to patients with knee OA to reduce KAM and alleviate clinical symptoms [16,27–29]. Comparison of effects between gait modifications in previous studies is limited by diverse sample characteristics and difficulties in consistently applying gait modifications [27,30]. To complement these methodological limitations of previous studies, this study clearly established inclusion criteria for study participants with knee osteoarthritis through pain severity and clinical evaluation as the Kellgren-Lawrence test. Additionally, guidelines were set for the walking pathway so that three different FPA walking conditions were applied as equally and consistently as possible to all participants.

This study analyzed how changes in FPA conditions affected knee joint and ankle joint moments during walking in 35 patients with medial knee osteoarthritis. Results of this study showed that the first peak value of KAM in the IFP walking condition was significantly decreased by 19.1% compared to that of NFP as the baseline walking condition. These results demonstrate the clinical effectiveness of specific gait modifications in reducing knee joint discomfort during walking, in which participants who have a choice of different gait modifications prefer toe-in gait the most [27,29,31]. In general, the value of the first peak of the KAM that occurred in the early stance phase was greater than the second peak of the KAM. Results of this study showed that toe-in gait modification was closely related to the decrease in the first peak of the KAM. The reason why the FPA condition of toe-in gait significantly reduced the first peak of the KAM was because the loading center moved to the lateral side as the knee joint central axis moved medially [16]. The second peak of the KAM (-0.50 Nm/kg) of the FPA condition of toe-in gait tended to increase compared to that of the NFP condition (-0.44 Nm/kg), although they showed no significant difference. In a study on the second peak KAM

according to the application of FPA in 50 patients with knee osteoarthritis, both the 10° toe-in gait and the baseline gait showed the same moment value (-0.46 Nm/kg) without a significant difference [7]. In addition, like the current study, there was no significant difference between the two FPA walking conditions on the second peak KAM during toe-in gait and baseline gait in twelve patients with medial compartment knee osteoarthritis [16]. However, Lynn et al. [23] reported a significantly greater KAM value of the late stance in internal foot position walking than in normal foot position walking. The reason for such conflicting results of the second peak KAM might be because Lynn et al.'s study was conducted with a small number of healthy individuals without knee OA.

As a result of this study, in contrast to toe-in gait that showed a significant decrease in the first peak KAM, the toe-out gait showed a significant reduction in the second peak KAM compared to the NFP condition in individuals with knee OA. However, there was no significant difference in the first peak KAM value between NFP (-0.42 Nm/kg) and EFP (-0.47 Nm/kg) gait conditions. These results were similar to previous studies reporting reduction of the second peak KAM during toe-out gait in patients with knee OA [6,16,32,33]. Unlike results of this study, Lin et al. [34] reported that applying a 30° self-selected toe-out gait to participants caused a significant increase in the first peak KAM. The current study applied a toe-out walking trial, which was increased by 20° compared to NFP angle. Characteristics of the present study subjects were also individuals with knee osteoarthritis, not healthy participants. Peak KAM values of the present study for the FPA toe-out walking condition were somewhat different from previous studies [35–38]. These differences might be attributed to different characteristics of study subjects, clinical severity of knee OA, and variations in study design. Specifically, most subjects of the present study were patients with mild knee OA. However, there were studies conducted on patients with moderate knee osteoarthritis of K-L grade IV or higher [35,36]. There were also studies conducted on knee OA patients with severe clinical symptoms [37,38].

Many studies have determined effects of toe-in or toe-out walking conditions on biomechanical variables of the knee and hip joints in people with medial compartment knee OA. However, very few studies have examined effects of these walking conditions on the moment of the ankle joint. The present study analyzed effects of different walking conditions on 3D ankle moments along with their effects on peak KAM according to FPA during walking in individuals with knee OA. Results showed that there was no significant increase in ankle joint moment value according to changes in FPA walking conditions. Only the peak ankle inversion moment value of the EFP walking condition decreased compared to that of the NFP condition. In a previous study conducted on 15 patients with medial compartment knee OA, there was no change in the peak external ankle inversion moment value (0.02 Nm/kg) of 10° toe-out walking compared to the baseline condition. The peak external ankle inversion moment value (0.01 Nm/kg) of 20° toe-out walking was not changed either [20]. On the other hand, the toe-in gait condition showed an increase of peak inversion moment value (0.04 Nm/kg) of the ankle joint compared to all other FPA conditions [20]. As such, ankle moment results of previous studies in the toe-in gait condition did not match results of this study. The reason for such conflicting results was presumed to be due to differences in the number of study subjects, clinical characteristics of subjects, and inter-individual variability in biomechanical variables such as moments.

Although toe-in gait trials showed a significant decrease in the first peak KAM with a significantly decreased second peak KAM in toe-out walking, clinical application of the FPA walking modification for patients with knee osteoarthritis requires a cautious approach. Because the first peak KAM is more closely related to current clinical symptoms, severity, and prognosis of knee OA than the second peak KAM, the decrease in the first peak KAM is considered more important [16]. However, considering the impact of a 1% increase in KAM on knee OA symptoms [39], it will not be possible to overlook the tendency to increase the first peak KAM during EFP walking condition and the tendency to increase the second peak KAM during IFP walking. Results showed no significant increase in the ankle joint moment value in the stance phase during walking for both 20° toe-in and 20° toe-out modifications. However, in some participants, the IFP gait modification increased the peak ankle adduction moment when ankle joint contact forces peaked. This indicates that for patients

with musculoskeletal deficits of the ankle joint such as ankle OA, the effectiveness of toe-in or toe-out walking trials at the ankle joint should be verified case by case before adopting FPA gait to improve the KAM.

The current study has some strengths. Previous studies related to KAM and FPA modifications have investigated effects of foot internal or external rotation condition on kinematics and kinetics of the knee joint itself during gait [5,6,16,23,40]. The study was performed to determine effects on two peak KAMs and 3D moments of the ankle joint using three different FPA modifications in individuals with knee OA through a reliable and objective 3D motion analysis system and force platforms. The present study showed that in participants with mild or moderate knee OA, FPA walking modifications affected peak KAMs without affecting the increase in peak ankle moment. Therefore, clinical application of FPA modification should be approached cautiously through quantitative analysis of the two peak KAMs in patients with knee osteoarthritis. Although abnormally high the peak KAM is a risk factor for medial compartment knee OA, abnormally reduced peak KAM might also be a risk factor for lateral compartment knee OA [23]. Limitations of this study are as follows. Because most participants had mild knee OA without severe knee pain or clinical symptoms, results of this study cannot be applied to all knee OA patients. In addition, various research methodological techniques were used to apply consistent FPA walking modifications. However, there were difficulties with consistency in some walking trials. Future research will need to verify the impact of clinical application of walking aids such as foot and ankle orthoses or insoles and integrated intervention of gait modification retraining on the first and second peak KAMs and biomechanics of lower extremity joints.

5. Conclusions

In conclusion, this study showed that IFP walking modification reduced the first peak KAM and that EFP walking reduced the second peak KAM. Additionally, any type of FPA modification conditions did not affect the increase in ankle moment. However, the impact of this FPA walking retraining intervention on other types of knee musculoskeletal disorders such as lateral compartment knee OA cannot be overlooked. Therefore, clinical application of toe-in or toe-out gait modification to patients with knee osteoarthritis should be performed based on biomechanical evaluations such as peak KAM. It is also necessary to consider additional applications of foot and ankle orthoses or modified insoles, which have a positive impact on clinical intervention.

References

1. Yang, G.; Wang, J.; Liu, Y.; Lu, H.; He, L.; Ma, C.; Zhao, Z. Burden of knee osteoarthritis in 204 countries and territories, 1990–2019: Results from the global burden of disease study 2019. *Arthritis Care Res.* **2023**, *75*, 2489–2500.
2. Deshpande, B.R.; Katz, J.N.; Solomon, D.H.; Yelin, E.H.; Hunter, D.J.; Messier, S.P.; Suter, L.G.; Losina, E. Number of persons with symptomatic knee osteoarthritis in the us: impact of race and ethnicity, age, sex, and obesity: symptomatic knee OA in the US. *Arthritis Care Res.* **2016**, *68*, 1743–1750.
3. Kim, Y.; Richards, J.; Lidtke, R.H.; Trede, R. Characteristics of clinical measurements between biomechanical responders and non-responders to a shoe designed for knee osteoarthritis. *Gait Posture* **2018**, *59*, 23–27.
4. D'Souza, N.; Charlton, J.; Grayson, S.; Kobayashi, L.; Hutchison, M.; Hunt, M.; Simic, M. Are biomechanics during gait associated with the structural disease onset and progression of lower limb osteoarthritis? A systematic review and meta-analysis. *Osteoarthritis Cartilage* **2022**, *30*, 381–394.
5. Hutchison, L.; D'Souza, N.; Grayson, J.; Hiller, C.; Kobayashi, S.; Simic, M. Toe-in and toe-out gait retraining interventions to reduce proxy measures of medial knee joint load in people with medial knee osteoarthritis: Protocol for a randomised placebo-controlled trial. *Contemp. Clin. Trials* **2023**, *134*, 107355.
6. Guo, M.; Axe, M.J.; Manal, K. 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* **2007**, *26*, 436–441.
7. Seagers, K.; Uhlich, S.D.; Kolesar, J.A.; Berkson, M.; Kaneda, J.M.; Beaupre, G.S.; Delp, S.L. Changes in foot progression angle during gait reduce the knee adduction moment and do not increase hip moments in individuals with knee osteoarthritis. *J. Biomech.* **2022**, *141*, 111204.

8. Chehab, E.F.; Favre, J.; Erhart-Hledik, J.C.; Andriacchi, T.P. Baseline knee adduction and flexion moments during walking are both associated with 5-year cartilage changes in patients with medial knee osteoarthritis. *Osteoarthritis Cartilage* **2014**, *22*, 1833–1839.
9. Robbins, S.M.; Birmingham, T.B.; Callaghan, J.P.; Jones, G.R.; Chesworth, B.M.; Maly, M.R. Association of pain with frequency and magnitude of knee loading in knee osteoarthritis. *Arthritis Care Res.* **2011**, *63*, 991–997.
10. Hurwitz, D.E.; Ryals, A.B.; Case, J.P.; Block, J.A.; Andriacchi, T.P. 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.* **2002**, *20*, 101–107., 63, 405–426.
11. Hinman, R.S.; Wrigley, T.V.; Metcalf, B.R.; Hunter, D.J.; Campbell, P.; Paterson, K.; Staples, M.P.; Bennell, K.L. Unloading shoes for osteoarthritis of the knee: protocol for the SHARK randomised controlled trial. *BMC Musculoskelet. Disord.* **2014**, *15*, 48.
12. Simic, M.; Hinman, R.S.; Wrigley, T.V.; Bennell, K.L.; Hunt, M.A. Gait modification strategies for altering medial knee joint load: a systematic review. *Arthritis Care Res. (Hoboken)* **2011**.
13. Kepple, T.M.; Segel, K.L.; Stanhope, S.J. Relative contributions of the lower extremity joint moments to forward progression and support during gait. *Gait Posture* **1997**, *6*, 1–8.
14. Ro, D.H.; Lee, J.; Lee, J.; Park, J.Y.; Han, H.S.; Lee, M.C. Effects of knee osteoarthritis on hip and ankle gait mechanics. *Adv. Orthop.* **2019**, 2019, 9757369.
15. Wang, J.W.; Kuo, K.N.; Andriacchi, T.P.; Galante, J.O. The influence of walking mechanics and time on the results of proximal tibial osteotomy. *J. Bone Joint Surg. Am.* **1990**, *72*, 905–909.
16. Shull, P.B.; Shultz, R.; Silder, A.; Dragoo, J.L.; Besier, T.F.; Cutkosky, M.R.; Delp, S.L. Toe-in gait reduces the first peak knee adduction moment in patients with medial compartment knee osteoarthritis. *J. Biomech.* **2013**, *46*, 122–128.
17. Mündermann, A.; Dyrby, C.O.; Andriacchi, T.P. Secondary gait changes in patients with medial compartment knee osteoarthritis: Increased load at the ankle, knee, and hip during walking. *Arthritis Rheum.* **2005**, *52*, 2835–2844.
18. Legrand, T.; Younesian, H.; Equey, N.; Campeau-Lecours, A.; Turcot, K. Trunk lean and toe out gait strategies impact on lower limb joints. *J. Biomech.* **2021**, *129*, 110740.
19. Wesseling, M.; de Groote, F.; Meyer, C.; Corten, K.; Simon, J.P.; Desloovere, K.; Jonkers, I. Gait alterations to effectively reduce hip contact forces. *J. Orthop. Res.* **2015**, *33*, 1094–1102.
20. Charlton, J.M.; Hatfield, G.L.; Guenette, J.A.; Hunt, M.A. Ankle joint and rearfoot biomechanics during toe-in and toe-out walking in people with medial compartment knee osteoarthritis. *PM R.* **2019**, *11*, 503–511.
21. Kim Y. Effects of foot-toe orthoses on moment and range of motion of knee joint in individuals with hallux valgus. *Life (Basel)* **2023**, *13*, 1162.
22. Collins T.D.; Ghousayni, S.N.; Ewins, D.J.; Kent, J.A. A six degrees-of-freedom marker set for gait analysis: repeatability and comparison with a modified Helen Hayes set. *Gait Posture* **2009**, *30*, 173–180.
23. Lynn, S.K.; Kajaks, T.; Costigan, P.A. 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*, 444–451.
24. Dainese, P.; Wyngaert, K.V.; De Mits, S.; Wittoek, R.; Van Ginckel, A.; Calders, P. Association between knee inflammation and knee pain in patients with knee osteoarthritis: a systematic review. *Osteoarthritis Cartilage* **2022**, *30*, 516–534.
25. Hall, M.; Bennell, K.L.; Wrigley, T.V.; Metcalf, B.R.; Campbell, P.K.; Kasza, J.; Paterson, K.L.; Hunter, D.J.; Hinman, R.S. The knee adduction moment and knee osteoarthritis symptoms: relationships according to radiographic disease severity. *Osteoarthritis Cartilage* **2017**, *25*, 34–41.
26. Thorp, L.E.; Sumner, D.R.; Block, J.A.; Moisio, K.C.; Shott, S.; Wimmer, M.A. Knee joint loading differs in individuals with mild compared with moderate medial knee osteoarthritis. *Arthritis Rheum.* **2006**, *54*, 3842–3849.
27. Lindsey, B.; Eddo, O.; Caswell, S.V.; Prebble, M.; Cortes, N. Reductions in peak knee abduction moment in three previously studied gait modification strategies. *Knee* **2020**, *27*, 102–110.
28. Hunt, M.A.; Simic, M.; Hinman, R.S.; Bennell, K.L.; Wrigley, T.V. Feasibility of a gait retraining strategy for reducing knee joint loading: increased trunk lean guided by realtime biofeedback. *J. Biomech.* **2011**, *44*, 943–947.
29. Shull, P.B.; Silder, A.; Shultz, R.; Dragoo, J.L.; Besier, T.F.; Delp, S.L.; Cutkosky, M.R. Six-week gait retraining program reduces knee adduction moment, reduces pain, and improves function for individuals with medial compartment knee osteoarthritis. *J. Orthop. Res.* **2013**, *31*, 1020–1025.
30. Eddo, O.; Lindsey, B.; Caswell, S.V.; Cortes, N. Current evidence of gait modification with real-time biofeedback to alter kinetic, temporospatial, and function-related outcomes: a review. *International Journal of Kinesiology and Sports Science* **2017**, *5*, 35–55.

31. Wheeler, J.W.; Shull, P.B.; Besier, T.F. Real-time knee adduction moment feedback for gait retraining through visual and tactile displays. *J. Biomech. Eng.* **2011**, *133*, 041007.
32. Lynn, S.K.; Costigan, P.A. Effect of foot rotation on knee kinetics and hamstring activation in older adults with and without signs of knee osteoarthritis. *Clin. Biomech. (Bristol, Avon)* **2008**, *23*, 779–786.
33. Hurwitz, D.E.; Ryals, A.B.; Case, J.P.; Block, J.A.; Andriacchi, T.P. 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.* **2002**, *20*, 101–107.
34. Lin, C.J.; Lai, K.A.; Chou, Y.L.; Ho, C.S. The effect of changing the foot progression angle on the knee adduction moment in normal teenagers. *Gait Posture* **2001**, *14*, 85–91.
35. Baliunas, A.J.; Hurwitz, D.E.; Ryals, A.B.; Karrar, A.; Case, J.P.; Block, J.A.; Andriacchi, T.P. Increased knee joint loads during walking are present in subjects with knee osteoarthritis. *Osteoarthritis Cartilage*. **2002**, *10*, 573–579.
36. Costigan, P.A.; Deluzio, K.J.; Wyss, U.P. Knee and hip kinetics during normal stair climbing. *Gait Posture* **2002**, *16*, 31–37.
37. Gok, H.; Ergin, S.; Yavuzer, G. Kinetic and kinematic characteristics of gait in patients with medial knee arthrosis. *Acta. Orthop. Scand.* **2002**, *73*, 647–52.
38. Kaufman, K.R.; Hughes, C.; Morrey, B.F.; Morrey, M.; An, K.N. Gait characteristics of patients with knee osteoarthritis. *J. Biomech.* **2001**, *34*, 907–915.
39. Baghaei Roodsari, R.; Esteki, A.; Aminian, G.; Ebrahimi, I.; Mousavi, M.E.; Majdoleslami, B.; Bahramian, F. The effect of orthotic devices on knee adduction moment, pain and function in medial compartment knee osteoarthritis: A literature review. *Disabil. Rehabil. Assist. Technol.* **2017**, *12*, 441–449.
40. Simic, M.; Wrigley, T.V.; Hinman, R.S.; Hunt, M.A.; Bennell, K.L. 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. *Osteoarthritis Cartilage* **2013**, *21*, 1272–1280.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.