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Effects of foot progression angle adjustment on external knee adduction moment and knee adduction angular impulse during stair ascent and descent

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ABSTRACT

Foot progression angle adjustment was shown to reduce external knee adduction moment (EKAM) and knee adduction angular impulse (KAAI) during level ground walking. However, evidence on effects of foot progression angle adjustment on the above surrogate measures of medial knee loading during stair climbing is limited. Hence, this study examined the effects of toe-in and toe-out gait on EKAM and KAAI during stair ascent and descent. Kinematic and kinetic data were collected from thirty-two healthy adults during stair ascent and descent with toe-in, toe-out and natural gait. A repeated measures ANOVA indicated that toe-in gait significantly reduced the first EKAM peak ($P < 0.001$) and KAAI ($P = 0.002$), while toe-out gait significantly increased the first ($P < 0.001$) and second ($P = 0.04$) EKAM peaks and KAAI ($P < 0.001$) when compared with natural gait during stair ascent. During stair descent, toe-in gait significantly reduced the first ($P < 0.001$) and second ($P = 0.032$) EKAM peaks and KAAI ($P < 0.001$), whilst toe-out gait significantly increased the first EKAM peak ($P = 0.022$) and KAAI ($P = 0.028$) when compared with natural gait. In conclusion, toe-in gait was found to be a viable strategy in reducing medial knee loading during stair climbing.

1. Introduction

The knee is one of the most important weight-bearing joints during walking and stair climbing. During gait, 60–80% of the total knee joint loading is distributed to the medial knee compartment (Andriacchi, 1994; Chang et al., 2007; Schipplein & Andriacchi, 1991), leading to a greater incidence of knee osteoarthritis (OA) over the medial compartment than lateral compartment (Jenkyn, Hunt, Jones, Giffin, & Birmingham, 2008). It is estimated that 10–13% of people aged 60 years or above suffer from symptomatic knee OA (Zhang & Jordan, 2010), which is a major cause of disability globally. However, it is difficult to measure the knee loading in the medial compartment *in vivo* and it has been widely accepted that external knee adduction moment (EKAM) is a surrogate measure of the medial compartment load (Cheung, Gossec, & Dougados, 2010; Cheung et al., 2018; Fukaya, Mutsuzaki, & Mori, 2019; Hall et al., 2016), although it is only one of the many predictors for knee OA (Long, Papi, Duffell, & McGregor, 2017).

EKAM is the product of the ground reaction force (GRF) and the knee moment arm (the perpendicular distance between the GRF vector and the knee joint center) in the frontal plane. It is reported that with every one unit (% Nm/Bw*Ht) increase in the EKAM, the risk of progression of medial compartment knee OA will be increased by 6.5 times (Miyazaki et al., 2002). Therefore gait modification has been proposed to manage patients with medial compartment knee OA by lowering peak EKAM (Bennett et al., 2017; Bennour, Ulrich, Legrand, Jolles, & Favre, 2017; Chang et al., 2007; Cheung et al., 2018; Lynn & Costigan, 2008). Previous studies have examined potential strategies to lower EKAM during level ground walking (Cheung et al., 2018; Favre, Erhart-Hledik, Chehab, &

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Andriacchi, 2016; Hunt & Takacs, 2014; Tokuda et al., 2018). Among different strategies, altering foot progression angle, i.e. toe-in or toe-out gait, has been reported to reduce 10.5–20.0% EKAM in both healthy individuals and patients with medial compartment knee OA during level ground walking (Hunt & Takacs, 2014; Shull, Shultz, et al., 2013; Shull, Silder, et al., 2013; Uhlrich, Silder, Beaupre, Shull, & Delp, 2018).

It has been postulated that a decrease in EKAM with adjustments to foot progression angle is brought about by laterally shifting the center of pressure (COP), which in turn shortens the moment arm between the GRF vector and the knee joint center (Hunt, Birmingham, Giffin, & Jenkyn, 2006; Jenkyn et al., 2008; Simic, Wrigley, Hinman, Hunt, & Bennell, 2013). Since toe-in gait shifts the knee joint center medially and the COP laterally during early stance phase (Shull, Shultz, et al., 2013) while toe-out gait shifts the COP laterally during late stance phase (Shull, Silder, et al., 2013), toe-in and toe-out gait were expected to lower the first and the second EKAM peaks during gait respectively (Simic, Hinman, Wrigley, Bennell, & Hunt, 2010; van Den Noort, Schaffers, Snijders, & Harlaar, 2013).

Other than walking on level ground, stair climbing is another common daily activity encountered by patients with knee OA. Due to the greater peak knee loading during stair climbing than walking, it is usually the first complaint for individuals with knee OA (Costigan, Deluzio, & Wyss, 2002; Taylor, Heller, Bergmann, and Duda, 2004). It is reported that the first EKAM peak was 11.2% and 55.6% greater during stair ascent and descent respectively in patients with medial compartment knee OA when compared to level walking (Guo, Axe, & Manal, 2007). However, only two published papers have reported the effects of foot progression angle adjustment on EKAM during stair climbing (Bennett et al., 2017; Guo et al., 2007). One of the studies suggested that a toe-in stair walking gait may lead to a 40% reduction of the first EKAM peak in healthy subjects (Bennett et al., 2017), while another study found that an additional 15-degree toe-out gait decreased the second EKAM peak by 11% and 6% during stair ascent and descent respectively (Guo et al., 2007). In spite of these important findings, there are several limitations to be considered. For example, only toe-in gait was tested in the first study (Bennett et al., 2017), while the second study only used a single step to collect the kinetics data (Guo et al., 2007) and such arrangement did not allow a complete gait cycle for stair ascent and descent.

In addition to EKAM, the knee adduction angular impulse (KAAI) has also been reported for its potential influence on the initiation and disease progression in patients with knee OA (Baliunas et al., 2002; Miyazaki et al., 2002; Thorp et al., 2006). KAAI represents the accumulated frontal plane loading on the knee joint during stance and it has been associated with cartilage damage (Bennell et al., 2011; Creaby et al., 2010). Some studies even proposed that KAAI is more of a sensitive indicator of medial knee joint loading than EKAM (Kean et al., 2012; Simic et al., 2010). Previous studies have found that KAAI is increased with a toe-in gait, while reduced with a toe-out gait during level-ground walking (Favre et al., 2016; Gerbrands, Pisters, & Vanwanseele, 2014; Simic et al., 2013). However, another study also reported that KAAI might be reduced with a toe-in gait during stair ascent (Bennett et al., 2017).

Hence, we sought to examine the effects of foot progression angle adjustment on EKAM and KAAI during stair ascent and descent in healthy adults. Since EKAM is governed by the GRF and the COP position (Hunt, Birmingham, Giffin, & Jenkyn, 2006), we also examined the changes of GRF and the COP with respect to foot progression angle adjustments, as secondary outcomes. Based on the findings previously reported (Bennett et al., 2017; Henriksen et al., 2012), we hypothesized that toe-in and toe-out gait would reduce the first and the second EKAM peaks respectively during stair ascent and descent when compared to natural gait. We also expected that KAAI would be increased with toe-in gait, while reduced with toe-out gait. For GRF, we hypothesized that there would be no significant difference between the three conditions. We also expected that the COP would shift laterally during early and late stance phase with toe-in and toe-out gait respectively.

2. Methods

2.1. Subjects

Thirty-two healthy adults (16 males, 16 females; age 22.8 ± 3.1 years (Mean ± SD); mass 60.3 ± 10.9 kg; height 1.68 ± 0.08 m) were recruited. Individuals with medial or lateral compartment knee OA, history of lower limb surgery, or any known neurological conditions that may affect gait were excluded. The experimental procedures were reviewed and approved by the institutional review board. Written consent was collected before proceeding to the test.

2.2. Experimental procedures

Reflective markers were firmly affixed onto specific bony landmarks according to a previously established model (Cappozzo, Catani, Della Croce, & Leardini, 1995). A 10-camera motion capturing system (V series, Vicon, Oxford, UK) at 100 Hz was used to collect kinematic data. Kinetic data were collected using two force plates (4060-NC, Bertic Corp., Columbus, Ohio, USA) installed in the second and third steps of a four-step wooden staircase (step height: 17 cm, tread depth: 30 cm) at 1000 Hz. Each subject was asked to ascend and descend stairs using step-through gait with standard footwear (ARHL002, Li Ning, Beijing, China) with natural, increased, and decreased foot progression angle in a randomized sequence. The foot progression angle in each condition was self-selected by individual subjects and no extra instruction was given. In order to capture a complete stair gait cycle, the second step of the staircase was selected to collect kinetic data. All subjects were required to walk one step on the level ground and staircase platform then start ascending and descending stairs with their right leg respectively. In each foot progression angle condition, a total of five trials were collected. Based on previous studies (Aliberti, Costa, Passaro, Arnone, & Sacco, 2010; Mian, Narici, Minetti, & Baltzopoulos, 2007), the cadence of stair ascent and descent was controlled by a metronome set at 1.5 Hz. The stair ascent gait cycle began with initial foot contact on the second step and finished when the same foot contacted the fourth step. Similarly, the stair descent gait cycle started with initial foot contact on the second step and finished when the same foot contacted the level ground.

2.3. Data analyses

A fourth-order Butterworth low-pass filter with a cut-off frequency of 6 Hz and 25 Hz were used respectively to remove noisy signals for kinematic and kinetic data (Jones, Zhang, Laxton, Findlow, & Liu, 2013). The kinematic and kinetic data were conducted using Visual 3D (V5, C-Motion, Germantown, MD, USA). The foot progression angle was calculated as the angle between the axis of foot (the line between the second metatarsal marker and the heel marker) and the direction of progression (relative to the global coordinate system). The joint moment was expressed as external joint moment and normalized to body mass and the GRF was normalized to body weight. Joint moment and GRF were time-normalized to 100% stance. The first and second EKAM peaks and maximum GRF were extracted from each trial and averaged across the five trials in each condition. Additionally, the position of the right foot's COP (relative to the local coordinate system of the foot) at the corresponding first and second EKAM peaks were also extracted from the COP trajectory during each trial and they were averaged across the five trials in each condition.

2.4. Statistical analyses

Only data from the right leg were analyzed to satisfy the independence assumption of statistical analysis (Menz, 2004). Shapiro-Wilk tests were used to assess normality of the selected parameters. The One-way repeated measures ANOVA was used to examine the difference in foot progression angle, EKAM, KAAI, GRF and COP between the three conditions. Pairwise comparison was performed with Bonferroni correction, if necessary. All statistical analyses were performed in SPSS (Version 20, SPSS Inc., Chicago, IL, USA) with a global alpha level of 0.05.

3. Results

The Shapiro-Wilk tests showed kinematic and kinetic data were normally distributed ($P > 0.05$). The foot progression angle during stair ascent and descent in each condition are shown in Table 1.

3.1. Stair ascent

We found significant differences across the three foot progression angle conditions in the first EKAM peak ($F = 97.205$, $P < 0.001$, Table 2, Fig. 1) and the second EKAM peak ($F = 3.984$, $P = 0.047$, Table 2, Fig. 1). Toe-in gait significantly reduced the first EKAM peak by 31.3% ($P < 0.001$), while toe-out gait significantly increased the first EKAM peak by 40.6% when compared with natural gait ($P < 0.001$). For the second EKAM peak, no significant difference was shown in toe-in gait, while toe-out gait significantly increased the second EKAM peak by 12.0% when compared with natural gait ($P = 0.04$). Similarly, there were significant differences in KAAI across the three foot progression angle conditions ($F = 44.959$, $P < 0.001$, Table 2). Toe-in gait reduced KAAI by 15.4% ($P = 0.002$) whereas toe-out gait increased KAAI by 38.4% when compared to natural gait ($P < 0.001$).

There was no significant difference in the GRF across the three foot progression angle conditions ($F = 1.567$, $P = 0.221$, Fig. 2). For the COP, significant differences were found across the three conditions in both the first peak ($F = 28.930$, $P < 0.001$, Table 2) and the second peak ($F = 9.130$, $P = 0.001$, Table 2). When compared with natural gait, toe-in gait significantly shifted the COP laterally (the first peak: $P < 0.001$; the second peak: $P < 0.009$), while toe-out gait significantly shifted the COP medially (the first peak: $P < 0.001$).

3.2. Stair descent

During stair descent, there were significant differences across the three conditions in both the first ($F = 46.068$, $P < 0.001$, Table 2, Fig. 3) and the second ($F = 10.310$, $P = 0.002$, Table 2, Fig. 3) EKAM peaks. Toe-in gait reduced the first and second EKAM peaks significantly by 29.2% ($P < 0.001$) and 13.8% ($P = 0.032$) respectively, while toe-out gait significantly increased the first EKAM peak by 6.3% ($P = 0.022$) during the first peak when compared to natural gait. KAAI was significantly different across the three conditions ($F = 29.174$, $P < 0.001$, Table 2). Toe-in gait significantly reduced KAAI by 31.3% ($P < 0.001$) and toe-out gait significantly increased it by 12.5% ($P = 0.028$) when compared to natural gait.

When compared with toe-out gait, toe-in gait significantly increased GRF by 4.48% in the first peak ($P = 0.011$, Fig. 2) and significantly reduced GRF by 2.53% in the second peak ($P = 0.027$, Fig. 2). For the COP, there were significant differences across the three conditions in both the first peak ($F = 23.912$, $P < 0.001$, Table 2) and the second peak ($F = 51.282$, $P < 0.001$, Table 2).

Table 1
Foot progression angle (FPA) in each condition during stair ascent and descent.

		Toe-in	Natural	Toe-out	*P* value
FPA (°)	Ascent	−7.80 ± 6.96	14.58 ± 5.35	33.38 ± 6.40	< 0.001
	Descent	−5.37 ± 7.61	17.13 ± 5.77	34.94 ± 5.93	< 0 0.001

Table 2
External knee adduction moment (EKAM), knee adduction angular impulse (KAAI) and position of center of pressure (COP) during stair ascent and descent.

	Parameters		TI	NG	TO	*P* value		
						Main effect	TI *vs* NG	TO *vs* NG
Stair ascent	EKAM (Nm/kg)	Peak 1	0.22 ± 0.09	0.32 ± 0.12	0.45 ± 0.16	< 0.001	< 0.001	< 0.001
		Peak 2	0.25 ± 0.12	0.25 ± 0.09	0.28 ± 0.09	0.047	1.000	0.004
	KAAI (Nm*s/kg)	–	0.11 ± 0.06	0.13 ± 0.07	0.18 ± 0.07	< 0.001	0.002	< 0.001
	COP (m)[Note]	Peak 1	0.012 ± 0.007	0.006 ± 0.006	0.001 ± 0.007	< 0.001	0.001	< 0 0.001
		Peak 2	0.009 ± 0.006	0.005 ± 0.007	0.003 ± 0.009	0.001	0.009	0.273
Stair descent	EKAM (Nm/kg)	Peak 1	0.34 ± 0.14	0.48 ± 0.17	0.51 ± 0.18	< 0 0.001	< 0 0.001	0.022
		Peak 2	0.25 ± 0.13	0.29 ± 0.13	0.31 ± 0.13	< 0.001	0.032	0.110
	KAAI (Nm*s/kg)	–	0.11 ± 0.07	0.16 ± 0.08	0.18 ± 0.08	< 0.001	< 0 0.001	0.028
	COP (m)	Peak 1	0.009 ± 0.008	0.003 ± 0.006	0.002 ± 0.007	< 0.001	0.001	< 0 0.001
		Peak 2	0.006 ± 0.011	−0.005 ± 0.009	−0.009 ± 0.008	< 0.001	< 0.001	0.037

TI: toe-in, NG: natural gait and TO: toe-out.
Note: A greater COP value refers to a more laterally located COP.

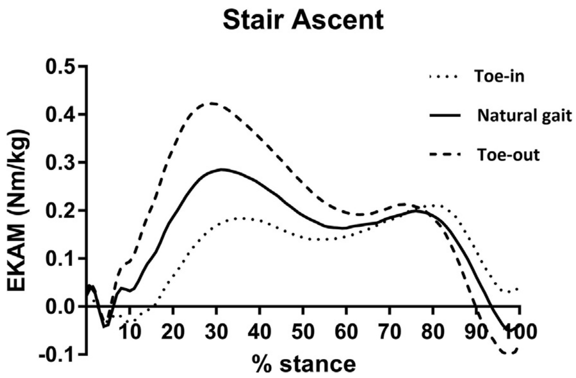

Fig. 1. Mean external knee adduction moment (EKAM) during stair ascent in different foot progression angles.

When compared with natural gait, toe-in gait significantly shifted the COP laterally (the first peak: $P < 0.001$; the second peak: $P < 0.001$), while toe-out gait significantly shifted the COP medially (the second peak: $P = 0.037$).

4. Discussion

The main objective of this study was to examine the effects of foot progression angle adjustment on EKAM and KAAI during stair ascent and descent in healthy adults. Our findings showed that during stair ascent, toe-in gait significantly reduced the first EKAM peak as well as KAAI, whilst toe-out gait significantly increased the first and second EKAM peaks and KAAI. During stair descent, toe-in gait significantly reduced both EKAM peaks and KAAI, while toe-out gait significantly increased the first EKAM peak and KAAI. Such observations may be explained by the lateral shift of the COP during toe-in gait and medial shift of the COP during toe-out gait when compared with natural gait during stair climbing.

Compared to natural gait, the first EKAM peak with toe-in gait during stair ascent and descent was reduced by 31.3% and 29.2% respectively. This finding was in accordance with a previous study which reported a 40% reduction in the first EKAM peak by toe-in gait during stair ascent (Bennett et al., 2017). It was generally reported that toe-in gait can significantly reduce the first EKAM peak during level ground walking (Lynn & Costigan, 2008; Shull, Silder, et al., 2013; van Den Noort et al., 2013). Since there was no difference in the GRF between toe-in gait and natural gait, the EKAM reduction could be due to the shortening of the moment arm in toe-in gait. The moment arm reduction could be explained by the lateral shift of the COP (Richards, van den Noort, Dekker, & Harlaar, 2017; Shull, Silder, et al., 2013).

However, the effects of toe-in gait on the second EKAM peak during stair negotiation were inconsistent. Past studies reported either increased or unchanged second EKAM peak during level ground walking with toe-in gait (Lynn, Kajaks, & Costigan, 2008; Simic et al., 2013). Only one study tested toe-in gait in stair ascent and reported no significant change in the second EKAM peak (Bennett et al., 2017), which was similar to our result. However, we found that toe-in gait resulted in a significant reduction in the second EKAM peak during stair descent. The different results between stair ascent and descent may be explained by greater knee flexion during late stance of stair descent (approximately 50°) than that during stair ascent (approximately 10°) (Protopapadaki, Drechsler, Cramp, Coutts, & Scott, 2007). During stair descent with toe-in gait, the tibia and femur tend to be internally rotated in order to reduce foot progression angle and the knee joint was in larger flexion, the knee might be forced into a valgus alignment

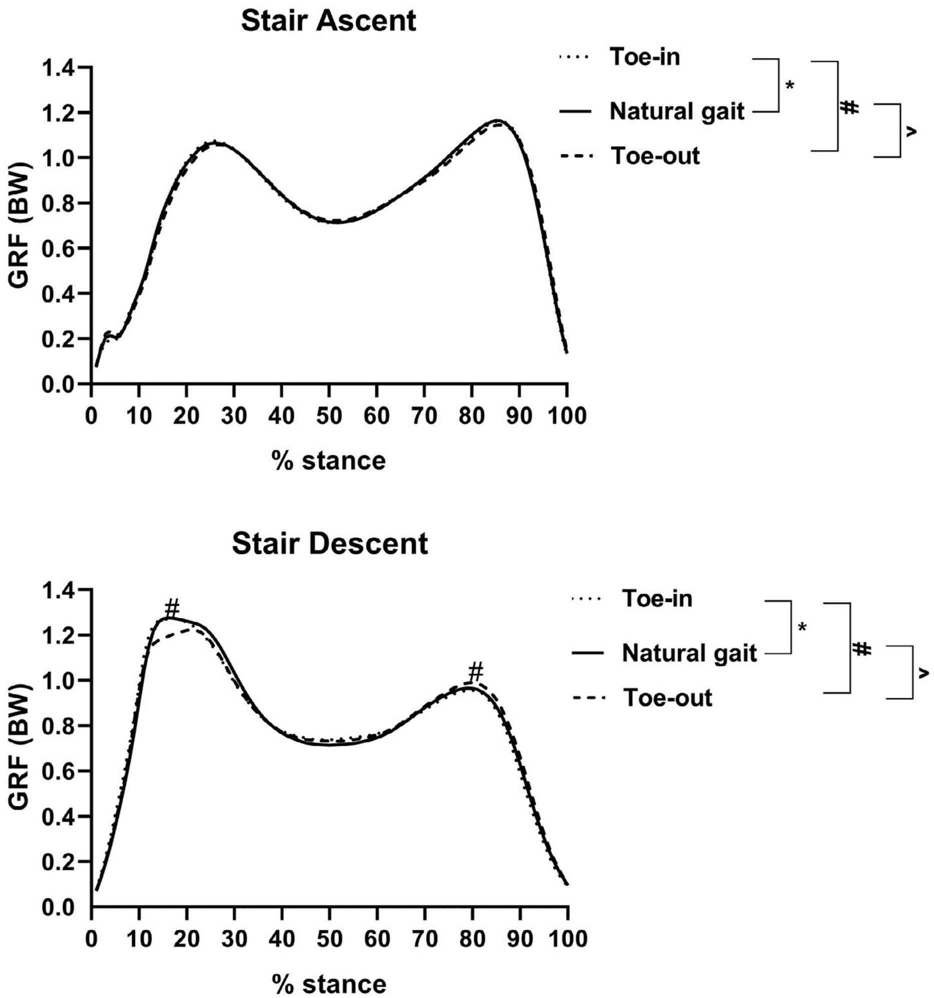

Fig. 2. Ground reaction force (GRF) during stair ascent and descent across conditions *, #, ^ denotes specific significant pairwise comparison between conditions at the two peaks.

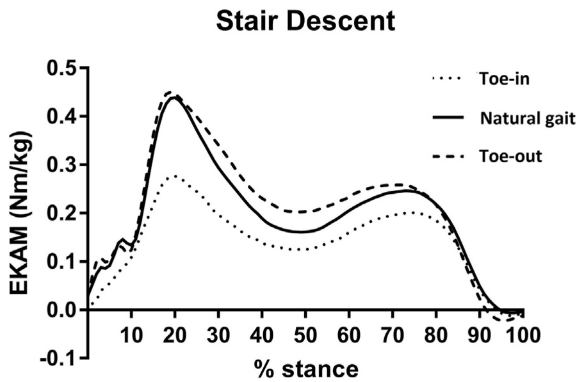

Fig. 3. Mean external knee adduction moment (EKAM) during stair descent in different foot progression angles.

(Barrios, Crossley, & Davis, 2010). With a valgus knee alignment, subjects may experience a valgus thrust, which decreased loading onto the medial compartment (Chang et al., 2010). However, the knee is in a relatively extended position during the late stance of stair ascent, leading to a narrower knee joint space than that of stair descent and absence of valgus (Chang et al., 2010; Ravaud et al., 1996). This may be responsible for the second EKAM peak reduction in stair descent but not in stair ascent.

Our findings did not support our original hypothesis on the effect of toe-out gait in the second EKAM peak during stair climbing.

Previous studies have shown that a subject-specific increase in the foot progression angle may reduce the second peak EKAM during level ground walking due to a lateral shift of the COP at later stance (Richards et al., 2017; Uhlrich et al., 2018). Another study has reported walking with an additional 15-degree toe-out gait increased first EKAM peak and reduced second EKAM peak during stair ascent but did not change first and second EKAM peaks during stair descent in patients with medial compartment knee OA (Guo et al., 2007). Our study showed different findings from these studies. Compared to natural gait, the first and second EKAM peaks with toe-out gait during stair ascent were increased by 40.6% and 12.0% respectively, while the first EKAM peak of stair descent was increased by 6.3%. Since there was no significant difference in the GRF between natural gait and toe-out gait during both stair ascent and descent, our findings on toe-out gait may be explained by the medial shift of the COP during toe-out gait, which lengthened the moment arm between GRF and the center of knee joint. However, significant medial shift of the COP was only found in the first EKAM peak during stair ascent and the second EKAM peak during stair descent. The peaks showing significant increase in EKAM with toe-out gait were different from the peaks showing significant medial shift of the COP. We suggested that other factors besides medial shift of the COP might have contributed to the increase in EKAM with toe-out gait in this study. The different findings in toe-out gait may be due to the following two factors. First, lateral trunk lean contributes to dynamic knee joint loading (Hunt et al., 2008). Increased lateral trunk lean was reported to reduce ipsilateral EKAM and KAAI (Simic, Hunt, Bennell, Hinman, & Wrigley, 2012). However, the degree of trunk lean was not controlled in our study, which might potentially increase EKAM and KAAI with a reduced lateral trunk lean in toe-out gait. It has been reported that healthy old adults demonstrate significantly greater lateral trunk lean during stair climbing when compared with healthy young adults who have better balance skills (Lee & Chou, 2007). Therefore, walking with toe-out gait during stair climbing may reduce lateral trunk lean in healthy young adults in the present study and this may be the reason why the first and second EKAM peaks increased during stair descent and ascent respectively without significant medial shift of the COP. Second, the tibia and femur may be externally rotated to maintain walking with toe-out gait and these could result in higher medial knee loading (Barrios et al., 2010).

As hypothesized, no significant difference was found in both the first and second peaks of GRF across foot progression angle conditions during stair ascent. However, the first GRF peak was significantly greater in toe-in gait than in toe-out gait during stair descent. Despite this, the overall EKAM was still significantly smaller in toe-in gait than in toe-out gait. Since there was significant lateral shift of the COP during toe-in gait in stair descent, we suggested that changes to EKAM were more dependent on the COP position (i.e. moment arm length), which was supported by a previous study (Guo et al., 2007). Our explanation was further supported by findings from Hunt et al. that EKAM was weakly associated with GRF, whilst stronger correlation was reported between moment arm length and EKAM (Hunt et al., 2006). The second GRF peak was significantly lower in toe-in gait than in toe-out gait. Although smaller GRF might have contributed to the reduction in the second EKAM peak, based on the above findings, we suggested that the effect of GRF on EKAM was minimal. As the KAAI represents the accumulated medial knee loading during stance, it is expected that toe-in gait significantly reduced the KAAI while the toe-out gait significantly increased the KAAI when compared with natural gait.

EKAM was shown to be positively-correlated with the initiation and progression of knee OA (Karamanidis & Arampatzis, 2011). It was found in a previous single-blinded randomized controlled trial that real-time EKAM feedback gait retraining program was safe and effective in reducing EKAM and improving symptoms of early knee OA; and most of participants in that study modified foot progression angle following training (Cheung et al., 2018). Our study showed that toe-in gait effectively reduced the EKAM peak during stair climbing. Therefore, we hypothesized that toe-in gait may be useful as a stair negotiation strategy for patients with medial compartment knee OA. With our preliminary findings among healthy young adults, such hypotheses should be tested in patient cohort before conducting another randomized controlled trial.

There were several limitations in our study. First, the foot progression angle in each condition was self-adjusted. The relationship between foot progression angle and EKAM was subject-specific and non-linear (Uhlrich et al., 2018). We suggested adopting subject-specific foot progression angle in future study by providing real-time biofeedback on EKAM. Second, our study recruited healthy young adults only. Our findings should be further examined on patients with medial compartment knee OA. Finally, we did not measure lateral trunk lean in this study as the effect of trunk posture on knee mechanics during stair climbing in healthy young adults is trivial (Lee & Chou, 2007). We should also collect and analyze the data of lateral trunk lean in knee OA patients since older patients may have larger trunk sway to regulate their balance during stair climbing.

5. Conclusion

Toe-in gait significantly reduced the first peak of EKAM and KAAI in stair ascent, and significantly reduced both peaks of EKAM and KAAI during stair descent. In contrast, toe-out gait was shown to increase both peaks of EKAM and KAAI in both stair ascent and descent, which was different from the findings of previous studies. We suggested that toe-in gait may potentially be a viable strategy in reducing medial knee loading during stair climbing for individuals with medial compartment knee OA.

Declaration of interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.humov.2019.02.004.

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