Effects of Toe-In and Wider Step Width in Stair Ascent with Different Knee Alignments

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ABSTRACT

BENNETT, H. J., S. ZHANG, G. SHEN, J. T. WEINHANDL, M. R. PAQUETTE, J. REINBOLT, and D. P. COE. Effects of Toe-In and Wider Step Width in Stair Ascent with Different Knee Alignments. *Med. Sci. Sports Exerc.*, Vol. 49, No. 3, pp. 563–572, 2017. **Purpose**: Toe-in (TI) and toe-in with wider step width (TIW) gait modifications have successfully reduced the internal peak knee adduction moment (KAM) during level walking and stair ascent tasks, respectively, for healthy and knee osteoarthritis populations. However, the concurrent effects of these modifications have not previously been combined to reduce both the first and the second peak KAM during stair ascent or tested among the different knee alignment groups. Therefore, the purpose of this study was to examine effects of TI and TIW gait modifications on knee biomechanics during stair ascent in individuals with varus, neutral, and valgus knee alignments. **Methods**: Thirty-eight healthy individuals (age 18–30 yr) with varus, neutral, and valgus knee alignments confirmed using radiographs, performed stair ascent in normal, TI, and TIW gait conditions. A 3 × 3 (group × condition) mixed model repeated-measures ANOVA compared alignment groups across the stair ascent gait conditions ($P < 0.05$). **Results**: The TI and the TIW reduced the first peak KAM and KAM impulses compared with normal stair ascent. The TIW also reduced the second peak KAM compared with normal gait and reduced KAM impulses compared with TI. The varus group had increased first peak KAM compared with neutral and valgus groups. The TI and the TIW also reduced peak knee flexion moments compared with normal gait. The TIW also reduced peak external rotation moments compared with normal gait. **Conclusions**: The TIW gait modification seems to be successful in reducing knee joint loading in all three planes during stair ascent, regardless of knee alignment. The success of TIW in varus knee alignments may have important implications for people with medial knee osteoarthritis, or those susceptible to knee osteoarthritis. **Key Words:** KNEE ADDUCTION MOMENT, TOE-IN, TOE-IN WITH WIDER STEP, VARUS ALIGNMENT, VALGUS ALIGNMENT, NEUTRAL ALIGNMENT

Stair negotiation is a normal and somewhat unavoidable activity of daily living for most adults. Stair negotiation is more physically demanding on the lower extremity joints (23) and requires twice the metabolic cost compared with level ground walking (1). Patients with knee osteoarthritis (KOA) find stair ambulation particularly difficult (9). Stair ambulation is also a common measure in functional evaluations of the knee; for example, Western Ontario and McMaster Universities Arthritis Index (6) and Knee Society Scoring System (29). Therefore, it is important to ascertain whether possible interventions can be identified to combat the increased lower extremity demands for KOA populations and individuals who are at risk for KOA.

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The increased difficulty of stair negotiation for KOA patients is possibly due to increases in the external knee adduction moment (KAM) found in stair negotiation compared with level walking (10,23). Stair ascent has been reported to result in 13.2% (10) and 27.9% (23) increases in the first peak KAM, and 24.3% increases in the second peak KAM compared with level walking (10). Stair ascent also involves increased peak knee adduction angles at the time of the peak KAM (41). In regard to the sagittal plane, stair ascent reportedly has two to three times greater peak external knee flexion moments compared with level walking (28,35). These increases in knee flexion moments may also lead to a higher sagittal plane mechanical demand for the knee joint during stair ascent compared with walking. In addition, recent research has shed light on the importance of the peak knee flexion moment in enhancing the accuracy of predictions of medial knee joint loading (20) and as a determinant of the effectiveness of a gait modification in reducing medial knee joint loading (40).

Increased or abnormal KAM is an important variable for KOA patients, as the first peak KAM is related to the incidence (30) and severity (31) of KOA in level walking. Because of the reportedly strong relationship between KAM and medial compartment forces (20,42), increases in the

KAM may result in increased loads to the medial compartment of the knee joint. To reduce the KAM and the medial compartment knee load, modifications to foot progression angles (e.g., increased toe-out) and step widths have been performed in healthy and KOA populations during stair ascent and descent tasks (10,25,26). Increasing foot progression, the foot angle in relation to forward progression of the body, from self-selected to an additional 15° toe-out has resulted in significant reductions in the second peak KAM during stair ascent compared with normal ascent gait (10). However, increased toe-out also resulted in significant increases in the first peak KAM compared with normal ascent (10). Increasing step widths from self-selected to 26% and 39% leg lengths have been successful in reducing both the first and second peak KAM in stair ascent (25) and stair descent tasks (26). Although only performed in level walking tasks, toe-in (TI) gait (in contrast to toe-out gait) has resulted in significant decreases in the first peak KAM (32,34,38). TI angles ranging from self-selected maximum (18,38) to 10° (34) have been successful in reducing the first peak KAM. However, the effect of TI gait on the second peak KAM is uncertain. Although several studies have reported no change in the second peak KAM (18,32,38), others have reported increases in the second peak KAM using TI gait (19,34). Therefore, it might be advantageous to combine a TI gait strategy with an increase in step width to reduce both the first and second peak KAM during stair ascent. However, TI gait alone has not been tested in stair negotiation tasks, nor has it been previously combined with increased step width to reduce both the first and second peak KAM in stair ascent. In addition, it is unknown how these modifications may affect the peak external knee flexion moment, which could be a factor for reducing medial knee loading.

Patients with KOA are not alone in exhibiting increased peak KAM during gait tasks. Healthy and KOA individuals with varus knee malalignment have increased peak KAM compared with their neutral and valgus knee alignment counterparts during level walking (13,17,22,37). Up to 42% increase in the first peak KAM have been reported in healthy and KOA individuals with varus compared with neutral and valgus alignments (3,17,22,37). In regard to stair negotiation, no experimental evidence is available about the effects of frontal plane knee malalignment on stair ascent knee biomechanics.

Therefore, the purpose of this study was to determine the effects of TI without controlled step width and toe-in with increased step width (TIW) gait modification strategies during stair ascent on knee biomechanics in healthy individuals with neutral, varus, and valgus frontal plane knee alignments. We hypothesized that 1) the TI gait strategy would reduce the first peak KAM in stair ascent, 2) the TIW gait strategy would reduce both the first and second peak KAM in stair ascent, and 3) the varus alignment group would exhibit increased KAM compared with the neutral and valgus groups during stair ascent similar to level walking.

METHODS

Participants. Thirty-eight healthy individuals (Table 1) were recruited from the university campus. Participant exclusion criteria included major lower extremity musculoskeletal injuries in the past 3 months, knee pain in the past 6 months during activities of daily living, diagnosed lower extremity joint arthritis, or body mass index greater than 35 $kg \cdot m^{-2}$. All participants signed an informed consent form, which was approved by the University of Tennessee institutional review board.

Radiographic knee alignment. Radiographic frontal plane knee alignment was determined from anteroposterior full-limb standing radiographs of each participant, obtained at a local orthopedics clinic. Knee alignment was measured as the knee mechanical axis angle on each radiograph using InteleViewer Software (Intelerad, Montreal, Quebec, Canada). Two raters measured the knee mechanical axis angle independently, which was measured as the medial angle between two lines connecting the center of the femoral head, center of tibial spines, and center of the talus, per standard procedures (12,24,31,39). Knee mechanical axis angles of 0° ± 2° were determined as neutral, $<-2°$ were determined as varus, and $>2°$ were determined as valgus alignments (14,31). There was excellent agreement among raters for knee mechanical axis angles (intraclass correlation = 0.99) (7). The knee of each participant with the most neutral, varus, or valgus knee mechanical axis angle was used in biomechanical testing of stair ascent (Table 1).

Instrumentation. A nine-camera motion capture system (240 Hz; Vicon Motion Analysis Inc., Oxford, UK) was used to collect three-dimensional (3-D) kinematics. All participants wore reflective anatomical markers placed bilaterally on the acromion processes, iliac crests, anterior superior iliac spines (ASIS), posterior superior iliac spines, greater trochanters, femoral epicondyles, malleoli, first and fifth metatarsal heads, and second toes. Clusters of four tracking markers were attached to the posterior trunk, pelvis, thighs, and shanks. Three discrete tracking markers were secured to the posterior and lateral heel of standard laboratory shoes. All participants wore a pair of standardized laboratory shoes (Noveto, Adidas). An instrumented three-step staircase (FP-stairs; Advanced Technology Inc., MA) was attached to two force platforms (1200 Hz, BP600600 and OR-6-7; Advanced Mechanical Technology, Inc., Watertown, MA) and two additional noninstrumented steps and used to collect ground reaction force (GRF) values during stair ascent (Fig. 1A and B) (25,36).

TABLE 1. Demographic data, knee mechanical axis angle, and ascent speed of the three alignment groups (mean ± SD).

	Neutral	Valgus	Varus	*P*
No. subjects	15	13	10	–
Age (yr)	23.7 ± 0.8	22.3 ± 1.0	24.7 ± 0.9	0.208
Height (m)	1.75 ± 0.1	1.74 ± 0.1	1.77 ± 0.1	0.620
Mass (kg)	72.8 ± 14.7	72.2 ± 12.6	73.4 ± 14.8	0.980
Body mass index ($kg \cdot m^{-2}$)	23.6 ± 3.1	23.7 ± 2.5	23.3 ± 4.1	0.940
Knee mechanical axis angle (°)	−0.4 ± 0.7	3.6 ± 1.0	−6.0 ± 1.4	**<0.001**
Ascent speed ($m \cdot s^{-1}$)	1.67 ± 0.21	1.58 ± 0.20	1.60 ± 0.25	0.583

The *P* value in bold was for significant difference among all alignment groups ($P < 0.05$).

FIGURE 1—A, Experimental setup of instrumented staircase. An instrumented three-step staircase (first three steps) was used to collect GRF during stair ascent. Adhesive tape strips were placed at 10° angles to the forward progression of the staircase and at 26% of each participant's leg length on each step. Participants were instructed to place one foot on each step for all conditions, as closely as possible to the 10° angles for both TI and TIW conditions, and outside the tapes for the TIW condition. B, Experimental setup of participant and tracking markers worn during stair ascent.

Data from the second step (instrumented) were used for biomechanical analyses. Participants' stair ascent speeds were determined and monitored by a set of two photocells (63501 IR; Lafayette Instrument Inc., Lafayette, IN) and electronic timers (54035A, Lafayette Instrument Inc.).

Experimental procedures. After collecting a static trial, all anatomical markers were removed. Participants then performed a warm-up on a stationary cycle, followed by the stair ascent task. Participants performed several practice stair ascent trials, during which their average self-selected speeds were recorded. Participants performed five successful stair ascent trials under each of three gait conditions: self-selected normal, increased TI to a target of 10° with their own self-selected step width, and increased TI to a target of 10° with a step width set at 26% leg length (TIW) measured from the ASIS to the medial malleoli (10,11). The test conditions were randomized for each participant. All trials were performed at ±5% of their average self-selected speeds. Adhesive tape strips were placed at 10° angles to the forward progression of the steps, and at the measured 26% leg length to control step width (Fig. 1). For the TI and the TIW gaits, participants were instructed to attain the 10° TI angle but were allowed to internally rotate to a comfortable angle (34,38). Participants were also instructed to place their foot outside the tapes (step width) and as close to the 10° angle as possible for the TIW gait. Participants' foot angles were calculated as the angle between the heel to the second toe and forward progression of the stairs. Stance phase TI angles were monitored during the data collection using Visual 3-D biomechanical analysis suite (5.0; C-Motion, Inc., Germantown, MD).

Participants were allowed sufficient practice trials for the TI and the TIW conditions to successfully perform the gait patterns. A successful trial was denoted as a trial with its ascent speed within the 5% range of the mean self-selected speed, TI or TIW trials performed with greater than 5° TI angle, and/or TIW trials performed with the participant stepping outside the tapes on the stairs, indicating stepping at the instructed step width. A minimum of 5° was set so that the TI angles matched minimum magnitudes found in the literature (18,19,32,34,38).

Data analyses. All kinematic and GRF data were imported into and processed in Visual 3-D. Three-dimensional marker trajectories and GRF values were filtered at a cutoff frequency of 8 Hz for joint kinetic calculations using a zero-lag fourth-order Butterworth low-pass filter. The GRF values were also filtered separately at 50 Hz with a zero-lag fourth-order Butterworth low-pass filter for the purposes of identifying peak GRF values. To predict hip joint centers, the ASIS and the posterior superior iliac spines markers were used for the Bell (5) method. Knee and ankle joint centers were defined as the midpoint of the epicondyles and malleoli, respectively. For all conditions, step width was determined as the mediolateral distance between the foot centers of masses during mid stance of the second and third steps. An *X–Y–Z* (extension–adduction–rotation) Cardan rotational sequence was used for 3-D angular kinematics computations. The conventions of 3-D kinematic and kinetic variables were determined

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with the right-hand rule. The GRF values were normalized to body weight. The joint moments were normalized to body mass (N·m·kg^{-1}) and calculated as external moments expressed in the proximal segment. Knee adduction angular impulse was calculated as the area under the normalized KAM curves. Variables of interest included first and second peak GRF, peak knee extension, abduction, and external rotation angles, flexion, and abduction range of motion (ROM) from max to min, peak knee adduction, flexion, and external rotation moments, and knee adduction impulses. Two customized programs (VB_V3D and VB_Table; MS VisualBasic, Redmond, WA) were used to determine discrete values for variables of interest.

Statistical analyses. A one-way ANOVA was used to determine demographic, knee mechanical axis angle, and ascent speed differences between groups. A 3 × 3 (Group × Condition) mixed model repeated-measures ANOVA was used to determine differences between varus, neutral, and valgus alignment groups under normal, TI, and TIW gait patterns during stair ascent (JMP®, Version 11; SAS Institute Inc., Cary, NC). In the presence of a significant interaction or main effect, *post hoc* paired sample *t*-tests with Bonferroni corrections were used to determine mean separations (main effects, $P < 0.0167$; interaction, $P < 0.005$). The significance level was set at $P < 0.05$ *a priori*. Shapiro–Wilk tests were used to assess normality of the selected variables (test statistic: W).

RESULTS

Age, height, mass, body mass index, and stair ascent speeds were not different between alignment groups (Table 1). The Shapiro–Wilk tests showed kinematic or kinetic variables were all normally distributed (all $W \geq 0.92$, $P > 0.05$). Overall, internal foot rotation angles were decreased in the varus compared with the valgus group ($P = 0.005$, Table 2). Both TI and TIW increased internal foot rotation angles compared with normal (both $P < 0.001$). Step width was greater in TIW compared with both TI and normal (both $P < 0.001$) and in TI compared with normal ($P < 0.001$, Table 2).

Peak knee extension angles were decreased in TIW compared with normal ($P = 0.007$, Table 3). Knee flexion ROM was decreased in both TI and TIW compared with normal (both $P < 0.001$) and in TIW compared with TI ($P < 0.001$). Peak knee abduction angles were greater for both valgus ($P < 0.001$) and neutral ($P = 0.001$) groups compared with the varus group, and for the valgus compared with the neutral group ($P = 0.011$, Table 4). Both TI and TIW increased peak knee abduction angles compared with normal (both $P < 0.001$). Knee abduction ROM was greater in the varus compared with the valgus group ($P = 0.016$). Knee abduction ROM was reduced in both TI and TIW compared with normal (both $P < 0.001$) and in TIW compared with TI ($P = 0.013$). The peak knee external rotation angles were decreased for both TI and TIW compared with normal (both $P < 0.001$, Table 2).

TABLE 2. Foot rotation angles (°), step widths (cm), and peak knee external rotation angles (°) and external rotation moments (N·m·kg^{-1}) for subject groups and conditions (mean ± SD).

	Neutral			Valgus			Varus			F, P		
	Normal	TI	TIW	Normal	TI	TIW	Normal	TI	TIW	Group	Condition	Interaction
Foot rotation angle[a,b,c]	−5.6 ± 6.0	13.8 ± 5.5	13.4 ± 4.6	0.4 ± 10.1	16.8 ± 6.3	16.8 ± 7.4	−8.1 ± 7.7	12.4 ± 2.7	11.1 ± 2.6	4.48, **0.0186**	226.86, **<0.0001**	0.72, 0.5800
Step width[b,c,d]	17.4 ± 4.6	24.4 ± 5.7	33.5 ± 4.4	17.4 ± 4.0	22.3 ± 7.0	31.4 ± 3.1	17.8 ± 4.7	27.0 ± 5.8	33.8 ± 2.9	0.11, 0.9000	226.86, **<0.0001**	2.1, 0.0897
Peak external rotation angle[b,c]	−7.1 ± 5.4	−2.1 ± 5.8	−1.2 ± 5.4	−9.1 ± 5.6	−2.3 ± 2.6	−1.6 ± 3.1	−9.2 ± 6.5	−2.1 ± 5.8	−1.7 ± 6.1	0.09, 0.9100	73.29, **<0.0001**	0.74, 0.5700
Peak external rotation moment[c]	−0.30 ± 0.23	−0.26 ± 0.22	−0.23 ± 0.21	−0.40 ± 0.23	−0.40 ± 0.24	−0.38 ± 0.23	−0.31 ± 0.24	−0.29 ± 0.24	−0.29 ± 0.24	1.02, 0.3700	8.5, **0.0005**	1.89, 0.1200

Internal foot rotation is positive and external foot rotation is negative. Polarity of joint angles and moments is determined according to the right-hand rule. The *P* values in bold were significant ($P < 0.05$).
[a]Different between valgus and varus.
[b]Different between normal and TI.
[c]Different between normal and TIW.
[d]Different between TI and TIW.

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TABLE 3. Peak vertical GRF (body weight), peak knee extension angle (°), ROM (°), and knee flexor moments (N·m·kg^{-1}) for subject groups and conditions (mean ± SD).

	Neutral			Valgus			Varus			F, P		
	Normal	TI	TIW	Normal	TI	TIW	Normal	TI	TIW	Group	Condition	Interaction
First peak VGRF[a,b]	1.13 ± 0.07	1.09 ± 0.07	1.06 ± 0.08	1.10 ± 0.04	1.08 ± 0.04	1.08 ± 0.07	1.11 ± 0.07	1.11 ± 0.06	1.09 ± 0.05	0.23, 0.790	12.53, **<0.001**	2.26, 0.070
Second peak VGRF[a,b]	1.23 ± 0.10	1.27 ± 0.12	1.27 ± 0.11	1.19 ± 0.14	1.22 ± 0.12	1.24 ± 013	1.16 ± 0.08	1.22 ± 0.09	1.23 ± 0.08	1.17, 0.320	10.16, **<0.001**	0.26, 0.910
Peak extension angle[b]	−10.3 ± 4.3	−10.2 ± 4.5	−10.4 ± 4.2	−6.0 ± 4.4	−6.6 ± 3.6	−7.2 ± 5.8	−8.6 ± 3.5	−10.2 ± 4.1	−11.0 ± 3.5	3.02, 0.060	3.84, **0.030**	1.42, 0.240
Flexion ROM[a,b,c]	59.6 ± 4.5	56.1 ± 3.8	54.0 ± 3.9	60.9 ± 5.9	58.4 ± 4.3	55.0 ± 5.0	62.6 ± 5.4	56.7 ± 4.9	54.6 ± 3.6	0.58, 0.570	77.01, **<0.001**	2.24, 0.070
Peak flexion moment[a,b]	−1.72 ± 0.36	−1.61 ± 0.29	−1.56 ± 0.29	−1.60 ± 0.18	−1.47 ± 0.22	−1.49 ± 0.24	−1.60 ± 0.23	−1.59 ± 0.22	−1.56 ± 0.20	0.66, 0.520	8.52, **0.005**	1.65, 0.170

The polarity of joint angles and moments is determined according to the right-hand rule. VGRF, vertical ground reaction force. The *P* values in bold were significant ($P < 0.05$).
[a]Different between normal and TI.
[b]Different between normal and TIW.
[c]Different between TI and TIW.

Both TI ($P = 0.047$) and TIW ($P < 0.0001$) decreased first peak vertical GRF but increased second peak GRF ($P = 0.002$ and $P = 0.001$, respectively) compared with normal gait (Table 3). Peak knee flexion moments were decreased for both TI ($P = 0.001$) and TIW ($P = 0.008$) compared with normal gait (Table 3). Ensemble KAM curves are provided in Figure 2. The varus group had greater first peak KAM compared with both neutral ($P = 0.002$) and valgus ($P = 0.008$) groups (Table 4 and Fig. 2). The first peak KAM values were decreased in both TI and TIW compared with normal (both $P < 0.001$) and in TIW compared with TI ($P = 0.015$; Fig. 2). The second peak KAM values were decreased in TIW compared with normal ($P = 0.001$, Table 4). The KAM impulses were decreased in both TI and TIW compared with normal (both $P < 0.001$) and TIW compared with TI ($P = 0.005$, Table 4). Peak knee external rotation moments were decreased in TIW compared with normal ($P = 0.001$, Table 2).

DISCUSSION

The TI gait decreased the first peak KAM, whereas the TIW gait decreased both the first and the second peak KAM, regardless of knee alignments, which support our first two hypotheses. However, the varus group only showed higher first peak KAM but not second peak KAM compared with the neutral and valgus groups, which only partially support our third hypothesis.

The success of the TIW gait modification to reduce both first and second peak KAM during stair ascent is an important finding, as stair ascent is a difficult task for KOA populations. The first peak KAM were reduced by 40% and 51% by the TI and the TIW modifications, respectively, compared with normal gait. These reductions are superior to the 11.1% and 19.4% reductions found in a previous study by increasing step width alone to 26% and 39% leg length, respectively (25). In addition, both TI gait modifications involved in this study were vastly superior to the toe-out gait modification in stair ascent used previously, as toe-out gait resulted in 11% increases in first peak KAM (10). Although TI gait has not previously been implemented in stair ascent tasks, similar percent reductions of 13% (18,32) to 45% (38) in first peak KAM using TI modifications during level walking were reported in the literature (19,32,38). The reduced first peak KAM by TI and TIW could be due to the reduced first peak vertical GRF compared with normal gait. The reduced first peak vertical GRF in TIW may be due to the increased knee flexion angles during loading response compared with normal. As changes to knee flexion can alter peak vertical GRF and control of lowering the body's center of mass during loading response (8), the increased knee flexion in TIW may have allowed the participants to more slowly lower their centers of mass after initial contact and reduce first peak vertical GRF. However, as the second peak KAM were also reduced by 12% using the TIW, despite an

TABLE 4. Peak frontal plane knee angle (°), ROM (°), moments (N·m·kg^{-1}), and KAM Impulse (N·m·kg^{-1}) for subject groups and conditions (mean ± SD).

	Neutral			Valgus			Varus			F, P		
	Normal	TI	TIW	Normal	TI	TIW	Normal	TI	TIW	Group	Condition	Interaction
Peak abduction angle[a,b,c,d,e]	−0.7 ± 2.5	−5.0 ± 3.2	−5.8 ± 3.8	−5.0 ± 3.0	−7.6 ± 3.2	−8.0 ± 3.8	3.0 ± 2.9	−1.3 ± 1.6	−1.2 ± 2.0	19.25, **<0.001**	108.15, **<0.001**	2.38, 0.060
Abduction ROM[c,d,e,f]	11.0 ± 3.8	6.3 ± 5.2	5.2 ± 5.1	7.5 ± 6.8	2.6 ± 5.9	0.9 ± 6.2	13.9 ± 4.9	7.4 ± 5.8	6.0 ± 5.9	3.32, **0.048**	88.06, **<0.001**	0.96, 0.440
First peak KAM[a,c,d,e,f]	0.36 ± 0.11	0.18 ± 0.15	0.11 ± 0.14	0.33 ± 0.11	0.19 ± 0.14	0.17 ± 0.11	0.55 ± 0.23	0.37 ± 0.23	0.34 ± 0.22	6.5, **0.004**	82.99, **<0.001**	1.11, 0.360
Second peak KAM[e]	0.22 ± 0.20	0.19 ± 0.20	0.18 ± 0.17	0.21 ± 0.14	0.20 ± 0.14	0.21 ± 0.15	0.33 ± 0.20	0.32 ± 0.20	0.27 ± 0.21	1.67, 0.200	5.76, **0.005**	1.55, 0.200
KAM impulse[d,e,f]	0.17 ± 0.10	0.14 ± 0.10	0.13 ± 0.10	0.13 ± 0.05	0.09 ± 0.04	0.09 ± 0.04	0.18 ± 0.07	0.14 ± 0.07	0.12 ± 0.07	1.23, 0.310	66.22, **<0.001**	0.69, 0.600

Polarity of joint angles and moments is determined according to the right-hand rule.
[a]Different between neutral and varus.
[b]Different between neutral and valgus.
[c]Different between valgus and varus.
[d]Different between normal and TI.
[e]Different between normal and TIW.
[f]Different between TI and TIW.

increase in the second peak vertical GRF compared with normal gait, the differences in vertical GRF are likely not the only mechanism for the reduced peak KAM. The frontal plane load reductions by these gait modifications are possibly due to additional changes in knee frontal plane kinematics. Although both TI and TIW increased peak knee abduction angles compared with normal, TIW also decreased knee abduction ROM compared with normal and TI gait. The increased knee abduction motion from normal gait during stair ascent by TI and TIW may have decreased the frontal plane GRF moment arm, and resulted in reduced KAM and adduction impulse. A previous investigation of KOA participants found that TI gait significantly reduced frontal plane GRF moment arms and the peak KAM compared with normal gait (32), without a change in peak vertical GRF. Therefore, the reduction in first peak KAM found here is likely due to a combination of reduced first peak vertical GRF magnitude and a reduction in the GRF moment arm, whereas the second peak KAM reduction is more likely due to a reduced frontal plane GRF moment arm. The reduced second peak KAM values using TIW are similar to the reductions by toe-out stair gait (10) but smaller than the reductions using step width alone (25). Both TI and TIW also reduced KAM impulse by 22% and 30%, respectively, compared with normal gait. The KAM impulse was also 10% lower using TIW compared with TI. The reductions in first and second peak KAM and KAM impulses lend to the efficacy of the TIW gait modification to reduce knee frontal plane loading during stair ascent, as KAM impulse is a more sensitive measure of KOA severity and provides more extensive information on overall frontal plane knee loading during stance (16). The success of the TIW gait in the varus knee alignment group is particularly important for people with KOA, as many people with KOA already have a varus knee alignment (31). Because this study included only healthy participants, future research is warranted to determine the efficacy of the TIW gait in KOA patients.

To our knowledge, this is the first study to compare the effects of a gait modification on knee joint load in all three planes during stair ascent. In this study, both the TI and the TIW gait modifications reduced peak external knee flexion moments by 4.6% and 6.2% compared with normal gait, respectively. The reduced peak knee flexion moments may be due to the decreased knee flexion ROM during TI and TIW and decreased first peak vertical GRF. A decrease in flexion ROM may have reduced the sagittal plane GRF lever arm (27) and, thus, reduced the necessary knee flexion moment, whereas decreased vertical GRF could have reduced the necessary knee flexion moment to control weight acceptance of the stance limb. As increased peak knee flexion moments may attenuate the effectiveness of gait modifications targeting the KAM and medial contact forces (40), the reduced peak knee flexion moments using TI and TIW are important findings. Reduced peak knee flexion moments have also been suggested to decrease compressive loads at the knee joint (15,21) and may be an adaptive response to

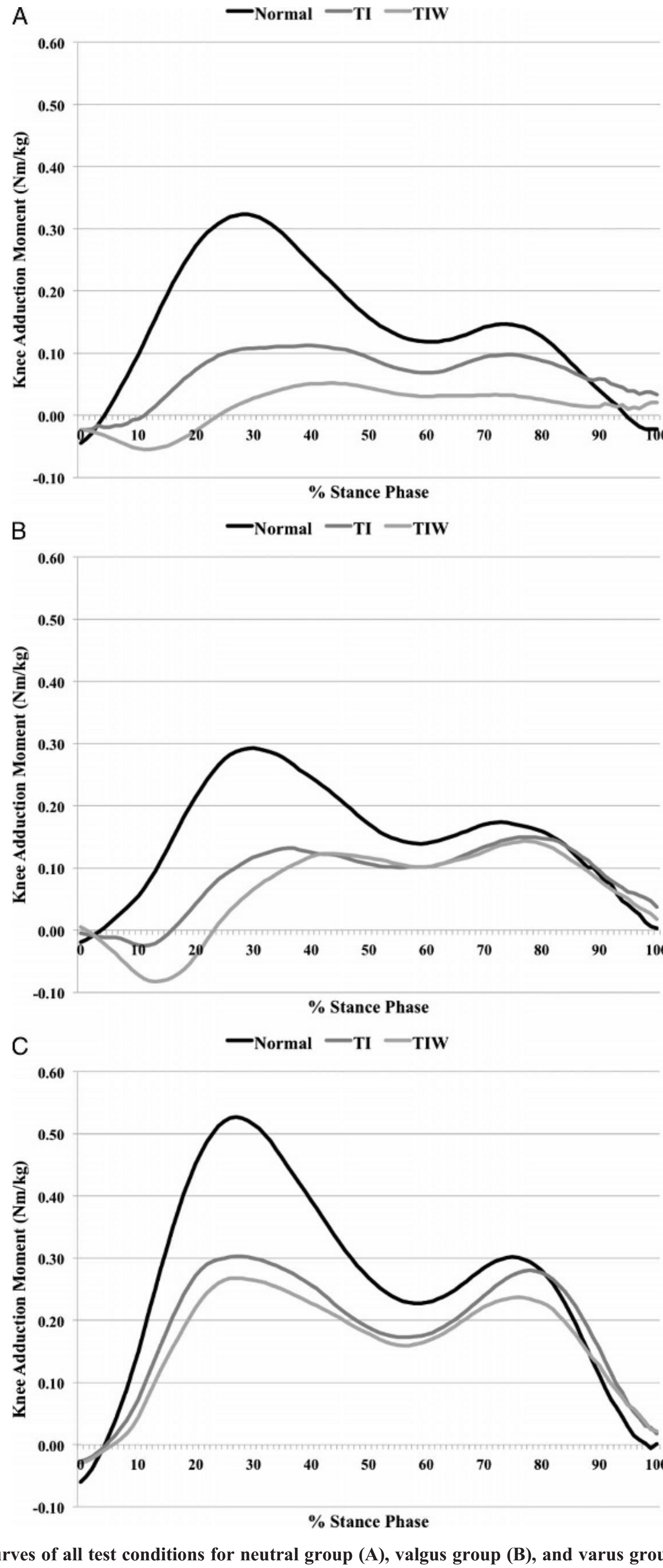

FIGURE 2—Ensemble KAM curves of all test conditions for neutral group (A), valgus group (B), and varus group (C).

reduce pain in KOA populations (15). Coupled with the decreased KAM, the reduced extension moments may be indicative of a decreased overall mechanical load to the knee joint during stair ascent (40). In addition, the TIW gait reduced peak external knee rotation moments by 12.2% compared with normal gait. The reduced external rotation moments in TIW compared with normal may be due to the knee reaching a more neutral alignment in the transverse plane by way of increased TI angles resulting in increased shank internal rotation and reduced external knee rotation angles. The results of this study indicate a reduced load to knee joint in all three planes using the TIW gait. Therefore, it seems the TIW gait modification is superior to TI or wider step width gait modifications in stair ascent gait. However, it is important to note that not all participants responded similarly using the TIW gait. There were 11 individuals (3 neutral, 3 valgus, and 5 varus) that had increased peak knee flexion moments (average increase, 5.9%) using TIW compared with normal gait. There were seven individuals (two neutral, two valgus, and three varus) that had increased peak knee external rotation moments (average increase: 25.1%) using TIW compared with normal gait. Four participants had increased peak knee flexion and rotation moments. Therefore, the TIW modification may not be as successful in all individuals and should be monitored for its affects on sagittal and transverse plane knee loads. Future research using musculoskeletal modeling is warranted to determine whether knee joint contact loads and muscle forces during stair ascent are reduced in the TIW gait modification. Additional experimental research is also needed to determine whether the TIW gait is similarly effective in KOA populations.

This is also the first study to experimentally compare gait biomechanics between neutral, valgus, and varus knee alignment groups during a stair ascent task. In agreement with previous studies comparing alignment groups in level walking (22,37), we found only group differences in the frontal plane. Previous studies have found 35% (2) to 42% (4) increases in overall peak KAM in varus compared with neutral healthy adults in level walking. In stair ascent, a more difficult and demanding task, we found the varus group had 193% and 183% greater first peak KAM compared with the neutral and valgus groups, respectively. In addition to the increased first peak KAM, reduced knee abduction angles and ROM exhibited by the varus group compared with neutral and valgus groups are similar to gait patterns found in level walking (22,37). The increased KAM and more adducted knee joint in the varus group may provide insight into the reasons stair ascent is a difficult task for KOA patients. Because KAM values are reportedly larger during stair ascent compared with level walking (10,23), there may be additional increases in KAM for people with varus alignments. With increased peak KAM and KAM impulses and no reductions in sagittal or transverse plane loads, the varus group may also have increased medial compartment knee joint loading compared with the neutral and valgus groups. Although comparisons of knee alignment have not been previously performed experimentally, similar results have been found using musculoskeletal modeling (11). Through modifications of a standard model's frontal plane knee alignment from neutral to 10° varus and 8° valgus during normal stair ascent gait, it was found that the first and the second peak KAM values were significantly increased in varus and decreased in valgus compared with neutral knee alignment (11). Although this study was a simulation, its results provide support that frontal plane knee alignment can be indicative of frontal plane knee loading during stair ascent. Future musculoskeletal modeling research is warranted to determine alignment-specific knee joint contact loads and muscle forces during stair ascent tasks, which may be especially important for understanding knee joint loads in people with KOA and varus alignment.

This study is limited in that we performed only a short-term assessment of TI and TIW gait modifications. Future research is warranted to determine the effects of training and metabolic costs of these gait modifications in healthy participants, especially in people with varus alignments as they have increased risks of developing KOA. As progressive gait training using TI and trunk sway gait modifications KOA has been successful in reducing the first peak KAM in people with KOA at one-month follow up (33), gait training of TIW could also be feasible and beneficial for both stair ascent and descent. Although stair negotiation is less common than level walking, it is important to investigate gait-training methods for reducing the knee mechanical load of stair negotiation because of the greater demands on the knee joint during stair ascent and descent compared with level walking (28). However, the current literature is limited on the efficacy of gait training for stair ascent in the KOA population. In addition, because this study did not involve KOA participants, future research of TIW gait should focus on the KOA population, especially those with medial KOA. With the previous success of implementing TI gait in level walking (32,34) and wider step width gait during stair ascent (25) in moderate to severe KOA populations with no adverse affects on pain scales, it is likely that implementing the combination of TI with wider step width would not pose much difficulty for the KOA population. Although the goal was to increase step width to 26% leg length for the TIW modification, our participants in the study reached a step width of 37% leg length. Interestingly, the participants also chose to increase step width to 28% leg length using the TI modification, without instruction. Although the step width in TIW was larger than our targeted step width, it is possible that the larger step width was necessary to result in significant decreases in second peak KAM, as reductions were not found with the increased step width in TI. Our results are in agreement with a previous study that found increased step width to 39% leg length resulted in an additional 16.7% decrease in second peak KAM compared with 26% leg length (25). Therefore, the increased step width to 39%, instead of 26%, leg length combined with TI seems to be necessary to reduce both first and second peak KAM. Future research should investigate the effectiveness of TIW gait training in both healthy and KOA populations. Finally, although our alignment groups were not equal in sample size, we reached observed powers greater than 0.99 for both group and condition comparisons for first peak KAM.

CONCLUSION

The TI and the TIW gait modifications were successful in reducing first peak KAM and KAM impulses compared with normal gait during stair ascent. The TIW modification was also successful in reducing second peak KAM compared with normal gait. In addition, the TIW gait reduced both peak knee flexor moments and external rotation moment, indicating reduced overall load to the knee joint during stair ascent. The varus group had decreased knee abduction angles and increased first peak KAM compared with neutral and valgus groups. The results indicate that TIW is the most advantageous gait modification for reducing frontal plane and overall knee loads and may be especially important for people with varus knee alignment who are more susceptible to developing medial KOA in the future.

There were no conflicts of interest to report for this work. The results of the current study do not constitute endorsement by the American College of Sports Medicine The authors declare that the results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

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