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Toe-in gait reduces the first peak knee adduction moment in patients with medial compartment knee osteoarthritis ☆

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ABSTRACT

The first peak of the knee adduction moment has been linked to the presence, severity, and progression of medial compartment knee osteoarthritis. The objective of this study was to evaluate toe-in gait (decreased foot progression angle from baseline through internal foot rotation) as a means to reduce the first peak of the knee adduction moment in subjects with medial compartment knee osteoarthritis. Additionally, we examined whether the first peak in the knee adduction moment would cause a concomitant increase in the peak external knee flexion moment, which can eliminate reductions in the medial compartment force that result from lowering the knee adduction moment. We tested the following hypotheses: (a) toe-in gait reduces the first peak of the knee adduction moment, and (b) toe-in gait does not increase the peak external knee flexion moment. Twelve patients with medial compartment knee osteoarthritis first performed baseline walking trials and then toe-in gait trials at their self-selected speed on an instrumented treadmill in a motion capture laboratory. Subjects altered their foot progression angle from baseline to toe-in gait by an average of 5° ($p<0.01$), which reduced the first peak of the knee adduction moment by an average of 13% ($p<0.01$). Toe-in gait did not increase the peak external knee flexion moment ($p=0.85$). The reduced knee adduction moment was accompanied by a medially-shifted knee joint center and a laterally-shifted center of pressure during early stance. These results suggest that toe-in gait may be a promising non-surgical treatment for patients with medial compartment knee osteoarthritis.

1. Introduction

Symptomatic knee osteoarthritis (OA) affects 12% of adults over age 60 years (Dillon et al., 2006) and its prevalence is projected to increase as life expectancy and obesity rates rise (Elders, 2000). The medial compartment of the knee is affected ten times more often than the lateral compartment, likely due to greater medial compartment loading during walking (Ahlback, 1968; Schipplein and Andriacchia, 1991). The external knee adduction moment (KAM) during walking gait is a surrogate measure of medial compartment loading (Zhao et al., 2007; Birmingham et al., 2007). The KAM typically has two peaks: a first peak during early stance and a second peak during late stance. The first, and the larger, peak in the KAM has been linked to the presence (Hurwitz et al., 2002), severity (Sharma et al., 1998), and progression (Miyazaki et al., 2002) of knee OA.

Gait modifications to lower the KAM have been suggested as a conservative treatment for patients with medial compartment knee OA. The foot progression angle is defined by the angle between the foot vector (calcaneous to the second metatarsal) and the line of progression (Rutherford et al., 2008). In normal gait, the foot progression angle is around 5°, indicating toes pointing slightly outward (Rutherford et al., 2008; Guo et al., 2007). Toe-out gait, defined as an increase in foot progression angle from baseline through external foot rotation (Wang et al., 1990; Jenkyn et al., 2008), reduces the second peak of the KAM but not the first peak (Guo et al., 2007; Lynn and Costigan, 2008; Lynn et al., 2008; Fregly et al., 2008). During stair climbing, toe-out gait reduces the second

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peak KAM but increases the first peak (Guo et al., 2007). Toe-in gait, defined as a decrease in foot progression angle from baseline through internal foot rotation, has been studied comparatively less. Lynn and Costigan (2008) reported that toe-in gait reduced the first peak KAM in healthy adults, while Lin et al. (2001) reported that toe-in gait did not change the first peak KAM and increased the second peak KAM in healthy children.

Gait modifications that are designed to alter the KAM can also change the external knee flexion moment, which may alter joint contact force (Walter et al., 2010). It is possible that gait modifications may decrease the KAM while simultaneously increasing the external knee flexion moment. An increased external knee flexion moment necessitates greater force development by the quadriceps and can eliminate reductions in the medial compartment force brought about by a reduced KAM (Walter et al., 2010). Thus, there is motivation to develop gait modifications for patients with medial-compartment knee OA that lower the first peak KAM without increasing the peak external knee flexion moment.

The mechanism linking changes in foot progression angle to changes in the KAM is not fully understood. It is thought that toe-out gait causes the center of pressure to move laterally, shifting the line of action of the ground reaction force toward the knee joint center (Guo et al., 2007; Jenkyn et al., 2008). This change could reduce the lever arm of the ground reaction force (Hunt et al., 2006) and reduce the magnitude of the KAM; however, experimental data supporting this theory have not been reported. A prior study, in which subjects were instructed to make modifications only to the foot progression angle and separately to make modifications only to the frontal plane tibia angle, found that foot progression and frontal plane tibia angles were moderately correlated ($r=0.60$, Shull et al., 2010). This suggests that an instructed change in foot progression angle could be accompanied by a frontal plane tibia angle change, which could shift the knee joint center medially for toe-in gait. Thus, it may be too simplistic to assume that changes in the KAM from an altered foot progression angle arise from a change in the center of pressure alone.

We undertook this study to determine the effect of toe-in gait on the first peak knee adduction moment and the peak external knee flexion moment in patients with medial compartment knee osteoarthritis. We hypothesized that: (a) toe-in gait reduces the first peak knee adduction moment, and (b) toe-in gait does not increase the peak external knee flexion moment. We expected that reductions in the knee adduction moment would occur as the knee joint center moved medially and the center of pressure moved laterally, thereby reducing the lever arm of the ground reaction force vector.

2. Methods

2.1. Subjects

Twelve subjects (Table 1) with symptomatic, medial-compartment knee OA participated in this study after giving informed consent in accordance with Stanford University's Institutional Review Board. A priori pairwise sample size calculation (power: 95%, alpha: 5%), based on a cohort of healthy subjects from a previous study (Shull et al., 2011), was used to determine that twelve subjects were sufficient to detect a 10% reduction in the KAM. To be included, subjects were required to have radiographic evidence of medial compartment knee OA defined as Kellgren & Lawrence (K/L) Grade >1. The K/L scale is comprised of four levels of increasing severity (Kellgren and Lawrence, 1957), Grade 1: doubtful narrowing of joint space and possible osteophytic lipping, Grade 2: definite osteophytes and possible narrowing of joint space, Grade 3: moderate multiple osteophytes, definite narrowing of joint space and some sclerosis and possible deformity of bone ends, and Grade 4: large osteophytes, marked narrowing of joint space, severe sclerosis and definite deformity of bone ends. Subjects were also required to have self-reported medial compartment knee pain at least one day per week during the six weeks prior to participation ("yes/no" question with "yes" indicating presence of pain), to be older than 18 years, and to be able to walk unaided for at least 25 consecutive minutes. Exclusion criteria included: body mass index greater than 35 (difficult to accurately place motion capture markers); inability to adopt a new gait due to previous injury or surgery on the foot, ankle, knee, hip or back; use of a shoe insert or hinged knee brace; corticosteroid injection within the previous six weeks; or age greater than 80 years. Gait retraining was focused on the limb with greatest self-reported knee pain (5 right legs, 7 left legs). On the day of testing and before performing walking trials, subjects completed the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) to assess OA pain and function (Bellamy et al., 1988).

Table 1
Demographics of patients with symptomatic knee osteoarthritis. Standard deviation values reported in parentheses. Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) levels reported on a scale from 0 to 100 with 100 indicating no pain and perfect function (Bellamy et al., 1988).

Characteristic	Mean (SD)
Age (yr)	59.8 (12.0)
Height (cm)	171 (8)
Mass (kg)	77.7 (18.0)
BMI (kg/m^2)	26.5 (4.2)
Gender	F: 5, M: 7
Kellgren and Lawrence Grade	II: 4, III: 7, IV: 1
WOMAC—Pain	74.2 (19.0)
WOMAC—Function	81.7 (21.6)

2.2. Baseline gait

A static calibration trial was performed with markers placed at the following locations: calcaneous, head of second metatarsal, head of the fifth metatarsal, lateral and medial malleoli, lateral and medial femoral epicondyles, lateral mid-shaft shank (2 markers), greater trochanter, lateral mid-shaft femur (2 markers), left and right anterior superior iliac spines, left and right posterior superior iliac spines, left and right acromion, and seventh cervical vertebrae. Medial malleolus and medial epicondyle markers were removed for subsequent walking trials. Subjects walked on a split belt instrumented treadmill (Bertec Corporation; Columbus, OH, USA) for two minutes to warm up and establish a preferred treadmill walking speed (average$=1.23\pm0.21$ m/s). Following the warm up, subjects were instructed to walk normally for two minutes during a baseline trial. The last ten steps of this trial were averaged to establish the following baseline parameters: external knee adduction moment, external knee flexion moment, lever arm of the ground reaction force vector, magnitude of the resultant ground reaction force vector, foot progression angle, tibia angle, and lateral trunk sway angle (definitions below in *Data analysis* section). Marker trajectories were recorded with an eight-camera motion capture system (Vicon, Oxford Metrics Group, Oxford, UK) at 60 Hz, and treadmill forces and moments were recorded at 1200 Hz.

2.3. Toe-in gait modification

Subjects then performed a toe-in gait trial, at the same speed as the baseline trial on the same instrumented treadmill for two minutes. During pilot testing prior to this study, individuals with medial-compartment knee OA demonstrated that two minutes was a sufficient amount of time to learn toe-in gait. Real-time haptic (touch) feedback, shown previously to be effective for gait training (Shull et al., 2011), was used to instruct toe-in gait during the trial through the use of a vibration motor (Engineering Acoustics, Inc., FL, USA) placed on the lateral-proximal aspect of the fibula. Subjects were informed that during the trial they should attempt to point their toes more inward relative to their normal walking foot progression angle. They were instructed that a vibration pulse on their leg during the stance phase of a given step indicated the toes should be pointed more inwardly on the next step and no vibration indicated that no correction was needed. Because foot progression angle and tibia angle are moderately correlated (Shull et al., 2010), and because it is easier for subjects to sense vibrations from a motor placed on the shank than from one placed on the shoes (Jirattigalachote et al., 2011), real-time feedback was computed based on tibia angle. Thus, tibia angle was a surrogate measure for training foot progression angle. While it is possible that subjects could change the tibia angle without changing foot progression angle (such as widening stance width), a previous study which trained tibia angle changes in healthy subjects (Shull et al., 2011) and pilot testing on individuals with knee OA demonstrated that tibia angle changes do lead to foot progression angle changes. During each step, tibia angle was computed in real-time during the first half of stance, and feedback was administered during the last half of stance of the same step. Vibration pulses were intended to train a decrease in tibia angle from each subject's baseline value by approximately 1°. This decrease in tibia angle was anticipated to decrease the foot progression angle by roughly 5–6° based on a prior relationship between tibia and foot progression angle established for healthy subjects (Shull et al., 2011). The approximately 5° decrease in foot progression angle was chosen based on pilot testing, which demonstrated that this amount of change significantly reduced the first peak of the KAM. The last ten steps of the toe-in gait trial were averaged for comparison with baseline values, and the standard deviation of the last ten steps was compared between toe-in and baseline trials to assess degree of kinematic variation in foot progression, tibia, and lateral trunk sway angles (definitions below in *Data analysis* section).

2.4. Data analysis

Marker data were low-pass filtered at 6 Hz and force plate data at 50 Hz using a fourth-order, Butterworth filter with phase correction. Joint angles were calculated by using the joint coordinate system defined by Grood and Suntay (1983) and Wu et al. (2002). The line of forward progression was aligned with the long axis of the treadmill and pointed in the direction subjects walked. The laboratory vertical axis was perpendicular to the treadmill. Foot progression angle was defined in the laboratory horizontal plane as the angle between the line connecting the calcaneous and second metatarsal head and the line of forward progress. Foot progression angles in which the second metatarsal head was lateral of the calcaneous were considered positive. Toe-out gait was defined as increased foot progression angle from baseline, and toe-in gait was defined as decreased foot progression angle from baseline. Tibia angle was defined in the laboratory frontal plane as the angle between the line connecting the lateral malleolus and lateral femoral epicondyle and the line of the laboratory vertical axis. Tibia angles lateral of vertical were considered positive. Lateral trunk sway angle was defined in the laboratory frontal plane as the angle between the line connecting the midpoint of the left and right posterior superior iliac spines and the seventh cervical vertebrae and the line of the laboratory vertical axis. Trunk sway angles lateral of vertical toward the leg of interest were considered positive. The knee joint center was the midpoint between the lateral and medial femoral epicondyles. Center of pressure and knee joint center position were both reported with respect to the pelvis. Specifically, the centroid of the left and right anterior superior iliac spines and left and right posterior superior iliac spines was chosen as a reference since that position is relatively unaffected during pelvic rotation. Center of pressure and knee joint center position lateral of the pelvis were considered positive. External knee adduction and knee flexion moments were expressed in the tibial reference frame. The lever arm of the ground reaction force vector was calculated as the shortest distance between the line of action of the ground reaction force vector and the knee joint center in the frontal plane of the tibial reference frame. Moments were reported as a percentage of each subject's height times body weight and forces were reported as a percentage of body weight.

Kinematic and kinetic data were analyzed at the peak during stance phase and at the points of the first and second peak KAM. Four patients did not show a distinct second peak KAM, and for these subjects the time of the second peak of the vertical ground reaction force was used instead (Guo et al., 2007). Differences between baseline and toe-in values were determined with paired Student's *t*-tests at the $p < 0.05$ significance level, and differences in standard deviation over the final ten trial steps were determined through Wilcoxon signed rank test at the $p < 0.05$ significance level.

3. Results

Subjects, on average, reduced their foot progression angle by 5° ($p < 0.01$) during toe-in trials compared to baseline walking trials (Fig. 1, Table 2). Toe-in gait reduced the first peak of the KAM ($p < 0.01$) by an average of 13% (Fig. 2, Table 2). Toe-in gait did not change the ground reaction force vector magnitude ($p = 0.30$) but shortened the lever arm of the ground reaction

Fig. 1. Typical subject walking with (left) baseline gait and (right) toe-in gait. Foot progression angle was defined as the angle between the line connecting the calcaneous marker and second metatarsal head and the line of forward progress. Toe-in gait was defined as a decreased foot progression angle from baseline through internal rotation of the foot with respect to the line of progression. On average, toe-in gait decreased the foot progression angle by 5° and reduced the first peak of the knee adduction moment by 13%.

Table 2
Average baseline and toe-in gait mechanics for all subjects. Standard deviation values reported in parentheses. Foot progression angle was defined as the angle between the line connecting the calcaneous and second metatarsal head and the line of forward progress. Foot progression angles in which the second metatarsal head was lateral of the calcaneous were considered positive. Foot progression angles reported here are by definition smaller than if they would have been calculated from a line between the calcaneous and fifth metatarsal. Bold p-values denote 5% significance levels. (GRF: ground reaction force).

Measurement	**At first peak knee add. moment**			**At second peak knee add. moment**		
	Baseline	Toe-In	p-val	Baseline	Toe-In	p-val
Knee add. moment (%BW*HT)	3.28 (1.37)	2.90 (1.38)	< **0.01**	1.98 (1.14)	1.94 (1.09)	0.48
Foot progression angle (deg)	3.3 (4.5)	−2.1 (6.3)	< **0.01**	3.9 (4.6)	−1.4 (6.4)	< **0.01**
Lever arm (mm)	55 (22)	47 (20)	< **0.01**	37 (22)	37 (21)	0.89
Knee joint center position (mm)	86 (25)	82 (26)	**0.01**	84 (19)	86 (22)	0.31
Center of pressure (mm)	27 (77)	33 (79)	**0.04**	30 (83)	30 (80)	0.96
GRF vector magnitude (%BW)	106 (13)	108 (14)	0.30	100 (5)	100 (6)	0.79
Knee flex. moment (%BW*HT)	1.48 (1.45)	1.29 (1.39)	0.36	−1.95 (0.93)	−1.78 (1.00)	0.18
Tibia angle (deg)	2.8 (5.6)	1.8 (4.4)	0.06	3.0 (6.3)	2.3 (5.3)	0.10
Lateral trunk sway angle (deg)	0.5 (2.3)	0.2 (2.0)	0.44	0.6 (1.2)	0.4 (1.3)	0.48

force vector ($p<0.01$) by an average of 13% (Fig. 2, Table 2). The tibia angle was not significantly different, though it trended toward a reduction during early stance for toe-in gait ($p=0.06$) (Table 2). In early stance the knee joint center position shifted medially ($p=0.01$) and the center of pressure shifted laterally ($p=0.04$), while in late stance both knee joint center position and center of pressure were unchanged ($p=0.31$ and $p=0.96$, respectively) (Fig. 3).

Toe-in gait did not increase the peak external knee flexion moment (baseline: 2.04 ± 0.82%BW*HT, toe-in: 2.01 ± 0.91%BW*HT, $p=0.85$). Similarly, the external knee flexion moment was not different at the first or second peak KAM (Fig. 4, Table 2). Peak lateral trunk sway angle (baseline: $1.5\pm1.6°$, toe-in: $1.3\pm0.5°$), knee flexion angle (baseline: $15.0\pm6.7°$, toe-in: $16.4\pm6.3°$), and internal hip rotation angle (baseline: $3.2\pm3.8°$, toe-in: $4.1\pm4.1°$) were unchanged during toe-in gait ($p=0.49$, $p=0.08$, and $p=0.18$, respectively). The standard deviation of the foot progression angle over the last ten trial steps increased by 1° for toe-in gait during early and late stance (Table 3). Toe-in gait did not affect the standard deviation of the tibia angle or lateral trunk sway angle (Table 3).

4. Discussion

The purpose of this study was to determine whether toe-in gait reduces the first peak of the KAM without increasing the peak external knee flexion moment in patients with medial compartment knee OA. In support of our first hypothesis, toe-in gait significantly reduced the first peak of the knee adduction moment, which occurred as the knee joint center shifted medially and the center of pressure shifted laterally. The second hypothesis was also supported; toe-in gait did not increase the peak external knee flexion moment.

Toe-out gait has been shown to reduce the second peak of the KAM in individuals with knee OA (Guo et al., 2007; Lynn and Costigan 2008; Fregly et al., 2008). In contrast, the results of this study show that toe-in gait reduces the first peak KAM for individuals with knee OA without affecting the second peak (Table 2, Fig. 2). This finding supports previous studies that have shown that toe-in gait reduces the first peak of the KAM for healthy, asymptomatic adults (Shull et al., 2011; Lynn and Costigan, 2008) and extends these results to patients with knee OA. A previous study involving healthy children found that toe-in gait did not change the first peak KAM from baseline and increased the second peak KAM (Lin et al., 2001). It has long been known that skeletal structure and body proportions are different in children and adults (Chenoweth and Selkirk, 1937), and thus the relationship between altered kinematics and knee loading may be dissimilar between adults and adolescents. Since the first peak of the KAM has been linked to the presence (Hurwitz et al., 2002), severity (Sharma et al., 1998), and progression (Miyazaki et al., 2002) of knee OA, reducing the first peak may be more important than reducing the second peak for individuals with knee OA. Our results suggest that toe-in gait is an effective means to achieve this goal.

An increased peak external knee flexion moment can eliminate the potential medial compartment force reduction from the decrease in the KAM (Walter et al., 2010). An increased knee flexion moment causes both medial and lateral compartment forces to increase. Thus, interventions that simultaneously decrease the KAM and increase the knee flexion moment may create no net force change on the medial compartment, while increasing force on the lateral compartment. This may be the case for gait modifications that seek to move the knees medially without changing the foot progression angle (Fregly et al., 2007; Barrios et al., 2010). These modifications produce significant reductions in the KAM, but can also cause increased knee flexion angles and knee flexion moments (Walter, et al. 2010). In contrast, toe-in gait achieves the desired reduction in KAM without increasing external knee flexion moments.

Toe-in gait was accompanied by a medial shift in the knee joint center position and a lateral shift in the center of pressure. Although subjects were instructed and trained to toe-in, they were not taught how to accomplish this. It is possible to toe-in by keeping the heel medio-lateral position constant and internally rotating the toes. It is also possible to toe-in by keeping the toe medio-lateral position constant and externally rotating the heel. In the former case, internally rotating toes would likely be accompanied by a medial shift in knee joint center position, because the knee flexion angle is non-zero during stance. In the latter case, an externally rotating heel would likely be accompanied by a lateral shift in the center of pressure. As the results in this study demonstrated, both a medial knee position shift and a lateral center of pressure shift in early stance (Fig. 3), it may be that subjects chose to use these two approaches in combination. The net result of a medially shifting knee joint center position and a laterally shifting center of pressure was a reduced lever arm of the ground reaction force vector in early stance (Fig. 2).

Tibia angle was not significantly different between baseline and toe-in gait (Table 2). However, there was a trend toward a reduced tibia angle in early stance ($p=0.06$). Based on the previously-reported moderate correlation between foot progression angle and tibia angle ($r=0.60$, Shull et al., 2010), it is likely that a greater reduction in foot progression angle would result in a statistically significant change in tibia angle.

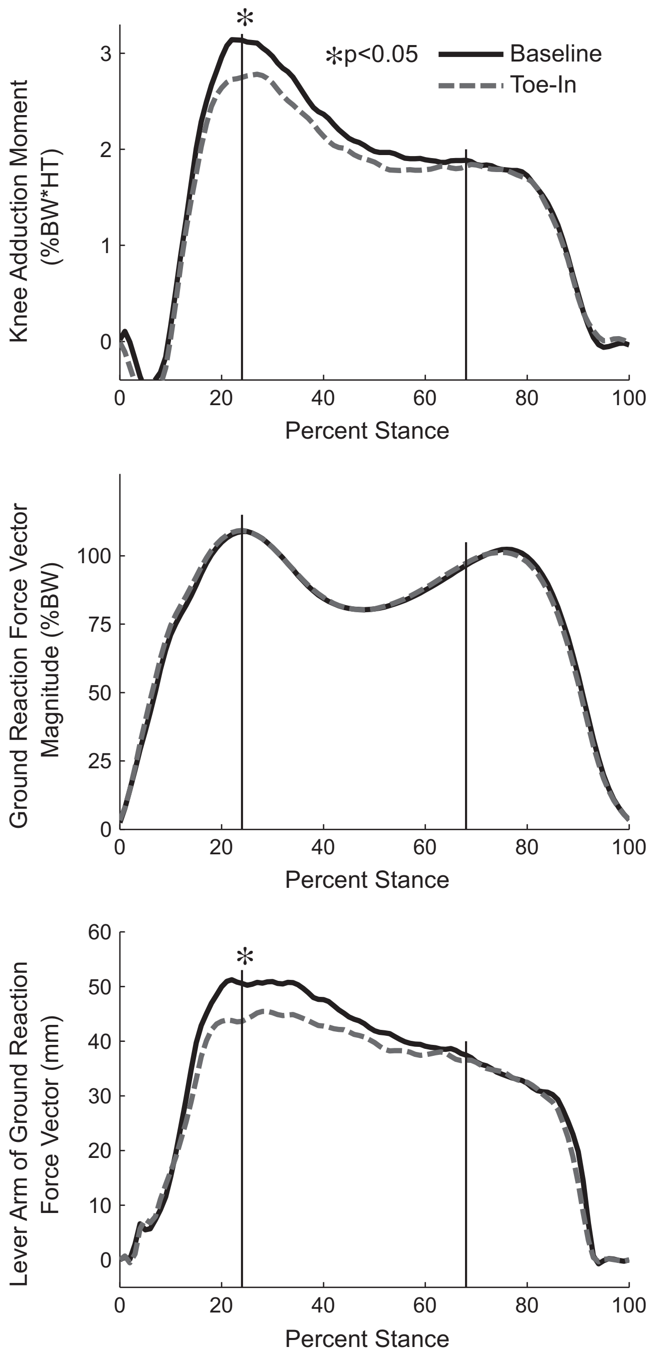

Fig. 2. Average (top) knee adduction moment, (middle) ground reaction force vector magnitude, and (bottom) lever arm of the ground reaction force vector for baseline and toe-in gait patterns. Vertical lines indicate the average location of the first and second peak knee adduction moment. The first peak knee adduction moment decreased due to a shorter lever arm, while no significant change in the ground reaction force magnitude was detected.

The 13% reduction in KAM achieved by toe-in gait is relevant for knee OA. Miyazaki et al. (2002) demonstrated that a one unit (%BW∗HT) increase in the KAM at baseline increases the risk of knee OA progression by more than six times. The KAM reduction from baseline due to toe-in gait in the current study was a little more than a third of a unit (%BW∗HT) (Table 2) which suggests there may be potential to use toe-in gait to reduce the risk of knee OA progression. The KAM reduction from toe-in gait is slightly greater than other non-surgical interventions such as lateral

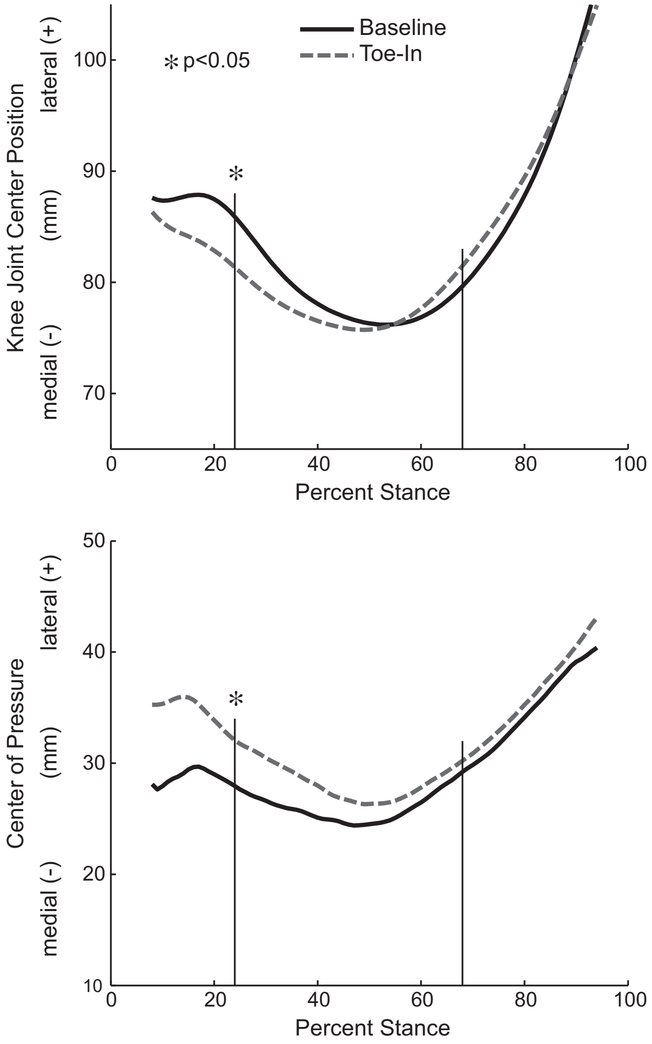

Fig. 3. Average (top) knee joint center position and (bottom) center of pressure; both values were relative to the pelvis. Vertical lines indicate the average location of the first and second peak knee adduction moment. Toe-in gait was accompanied by a medially-shifted knee joint center position and a laterally-shifted center of pressure in early stance.

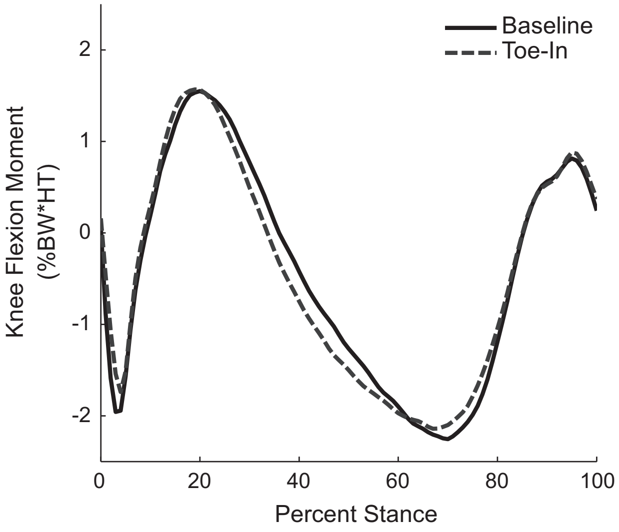

Fig. 4. Average external knee flexion moment. There was no significant difference in peak knee flexion moment between baseline and toe-in gait ($p = 0.85$).

Table 3
Standard deviations of the last ten steps (averaged across all subjects) for baseline and toe-in gait walking trials. Bold *p*-values denote 5% significance levels.

Measurement	**Standard deviation**		
	Baseline	Toe-In	*p*-val
Foot progression angle (deg)			
At KAM 1st peak	1.3 (0.5)	2.3 (1.2)	< **0.01**
At KAM 2nd peak	1.3 (0.5)	2.3 (1.1)	< **0.01**
Tibia angle (deg)			
At KAM 1st peak	0.8 (0.3)	1.0 (0.4)	0.09
At KAM 2nd peak	0.7 (0.2)	0.9 (0.3)	0.08
Lateral trunk sway angle (deg)			
At peak	1.0 (0.7)	1.3 (0.6)	0.15
At KAM 1st peak	1.0 (0.6)	1.3 (0.7)	0.15
At KAM 2nd peak	1.1 (0.8)	1.3 (0.8)	0.34

wedge insoles (Butler et al., 2007), valgus knee braces (Draganich et al., 2006), or variable stiffness shoes (Erhart et al., 2008), though less than surgical intervention such as high tibial osteotomy (Wada et al., 1998).

Subjectively, subjects in this study appeared to walk naturally with toe-in gait (Fig. 1). This is in contrast with other proposed altered gait patterns such as increased trunk sway, which involves noticeably larger kinematic changes (e.g. Mündermann et al., 2008—Fig. 1; Shull et al., 2011—Fig. 3; and Hunt et al., 2011—Fig. 1). Gait patterns that seek to medialize the knee can appear natural to outside observers but may feel somewhat unnatural to the subject due to the requirement to keep a constant foot progression angle, although some of the unnatural feeling decreases over time (Barrios et al., 2010). Though this study did not seek to quantify user preference for toe-in gait or other altered gait patterns, both the feeling of walking naturally and the appearance to others in social situations of walking naturally may be important factors for long-term compliance of an altered gait pattern.

It is important that individuals with symptomatic knee OA be able to learn and adopt altered gait patterns. While the intent of this study was not to quantify learning patterns, it was evident that subjects easily adopted toe-in gait within the two minute walking session, an important prerequisite for long-term retention. This approximate time for learning a new gait aligns with similar gait retraining protocols for young, healthy subjects (Shull et al., 2011; Wheeler et al., 2011). The standard deviation of foot progression angle over the last ten steps of the toe-in gait trial was larger than baseline (Table 3), which could be an indication that subjects were not yet as comfortable walking with toe-in gait as with their normal walking pattern.

One limitation of this study is that subjects performed toe-in gait during a single training session. Although subjects quickly learned to adopt toe-in gait, it is unlikely that they would be able to fully retain the new walking pattern after a single session. Though this study was an important first step in demonstrating the potential of toe-in gait for individuals with knee OA, an effective future strategy to help subjects internalize the new gait pattern could be for subjects to perform multiple gait retraining sessions at a spaced interval (Barrios et al., 2010) or to provide subjects with a portable retraining system that combines wearable sensing (Dowling and Favre, 2011, 2012) and wearable feedback (Shull et al., 2011) that could be used while walking outside of a laboratory setting. If subjects are able to retain this gait pattern, toe-in gait offers potential as an effective non-surgical treatment for medial compartment knee OA patients.

Conflict of interest statement

None of the authors had any conflict of interest regarding this manuscript.

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