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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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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