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Muscle force modification strategies are not consistent for gait retraining to reduce the knee adduction moment in individuals with knee osteoarthritis ☆

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ABSTRACT

While gait retraining paradigms that alter knee loads typically focus on modifying kinematics, the underlying muscle force modifications responsible for these kinematic changes remain largely unknown. As humans are generally thought to select uniform gait muscle patterns such as strategies based on fatigue cost functions or energy minimization, we hypothesized that a kinematic gait change known to reduce the knee adduction moment (i.e. toe-in gait) would be accompanied by a uniform muscle force modification strategy for individuals with symptomatic knee osteoarthritis. Ten subjects with self-reported knee pain and radiographic evidence of medial compartment knee osteoarthritis performed normal gait and toe-in gait modification walking trials. Two hundred muscle-actuated dynamic simulations (10 steps for normal gait and 10 steps from toe-in gait for each subject) were performed to determine muscle forces for each gait. Results showed that subjects internally rotated their feet during toe-in gait, which decreased the foot progression angle by 7° ($p < 0.01$) and reduced the first peak knee adduction moment by 20% ($p < 0.01$). While significant muscle force modifications were evidenced within individuals, there were no consistent muscle force modifications across all subjects. It may be that self-selected muscle pattern changes are not uniform for gait modification particularly for individuals with knee pain. Future studies focused on altering knee loads should not assume consistent muscle force modifications for a given kinematic gait change across subjects and should consider muscle forces in addition to kinematics in gait retraining paradigms.

1. Introduction

Knee osteoarthritis (OA) is a significant worldwide health concern characterized by joint pain and dysfunction and can lead to joint stiffness, muscle atrophy, and limb deformity (Buckwalter et al., 2004). In the United States, symptomatic knee OA affects 11% of women and 7% of men over age 60 (Felson et al., 1987) with similar incidence rates reported in China for men and even higher for Chinese women (Du et al., 2005; Zhang et al., 2001). Medications are often used to treat symptoms though disease progression generally leads to total knee replacement (Gabriel et al., 1997). Knee loading is believed to contribute to the degeneration of articular cartilage associated with OA progression (Andriacchi et al., 2004; Schipplein and Andriacchi, 1991). Thus conservative interventions often seek to reduce knee loading for early stage knee OA.

The knee adduction moment (KAM) is an important clinical measurement given the mechanical etiology of knee OA. In vivo instrumented knee replacement testing (D'Lima et al., 2006, 2005) has revealed a strong correlation between medial compartment loading and the KAM and shown that the KAM is a valid, reliable measure of the relative load distribution across the tibiofemoral knee joint (Zhao et al., 2007). It is thus often used as a surrogate measure of medial compartment loading though the estimate is not always guaranteed to be accurate (Walter et al., 2010). The first peak of the KAM has been linked with pain and the presence, severity, and progression of medial compartment knee OA (Hurwitz et al., 2002; Miyazaki et al., 2002; Sharma et al., 1998; Thorp et al., 2007) and the KAM impulse, i.e. the area under

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the KAM-time curve, has been shown to be predictive of cartilage loss over 12 months (Bennell et al., 2011).

Gait retraining is an effective method for reducing the KAM. Initial, proof-of-concept studies in healthy subjects showed that increased trunk sway, toe-in gait (internal foot rotation), reduced tibia angle, and medial thrust were all effective strategies for reducing the first peak KAM (Barrios et al., 2010; Hunt et al., 2011; Mündermann et al., 2008; Shull et al., 2011; Van den Noort et al., 2013), and gait retraining for individuals with knee osteoarthritis has confirmed these initial trends for toe-in gait and increased trunk sway (Shull et al., 2013a; Simic et al., 2012). Gait changes have also been shown to improve symptoms. Shull et al. (2013b) demonstrated that toe-in gait reduced the first peak KAM, reduced pain, and increased function for individuals with symptomatic knee OA after 6 weeks of gait retraining, and improvements in pain and function were approximately 75% larger than the expected placebo effect. Hunt and Takacs (2014) performed 10 weeks of gait retraining and showed that a toe-out gait modification reduced the second peak KAM, the KAM impulse, and knee pain, though it was unclear what portion of knee pain improvement was attributed solely to the placebo effect.

Gait retraining paradigms have thus far focused primarily on the relationship between altered gait kinematics and KAM while neglecting the potentially crucial role that muscle forces might play in intervention. For example, internal muscle forces may lead to higher knee joint compartment loading that is not captured by the KAM (Walter et al., 2010). In addition, uniform kinematic gait modifications shown to reduce knee loads for a population on average can actually be ineffective for individuals within that population (Erhart et al., 2008; Hunt and Takacs, 2014), which has led some to propose subject-specific modifications (Fregly et al., 2007; Gerbrands et al., 2014; Shull et al., 2011). Muscle force modification strategies may thus be crucial to the efficacy of gait retraining.

Although there are many potential muscle force combinations that produce stable gait, humans are generally thought to select uniform muscle patterns while walking such as strategies based on fatigue cost functions or energy minimization (Ackermann and van den Bogert, 2010; Bianchi et al., 1998; Sparrow and Newell, 1998). Thus, we performed this study to test the hypothesis that a kinematic gait change known to reduce the KAM (i.e. toe-in gait) would be accompanied by a uniform muscle force modification strategy for individuals with symptomatic medial compartment knee OA. We further sought to determine the relative degree of force change across individual muscles for the gait modification. Identifying the combinations of muscle force modifications adopted by individuals with symptomatic knee OA provides an objective tool to study and potentially improve gait retraining.

2. Methods

2.1. Subjects

Ten subjects with symptomatic, medial-compartment knee OA participated in this study (Table 1). To be included, subjects were required to have radiographic evidence of medial compartment knee OA defined as Kellgren and 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, to be between 18 and 80 years, and to be able to walk unaided for at least 25 consecutive minutes. Exclusion criteria included: body mass index greater than 35; inability to adopt a new gait due to previous injury or surgery on back or lower extremities; use of a shoe insert or hinged knee brace; or corticosteroid injection within the previous six weeks. Gait retraining was focused on the limb with greatest self-reported knee pain (4 right legs, 6 left legs). All subjects gave informed, written consent prior to participation.

2.2. Experimental data collection

Subjects performed weekly gait retraining sessions over six weeks to adopt a toe-in gait pattern (Fig. 1) and each session was experimentally recorded in a motion analysis laboratory. At the beginning of each testing session, a static standing 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

Table 1
Subject characteristics.

	Mean (SD)
Age (yr)	60(13)
BMI (kg/m^2)	26.6(4.7)
Gender	F:4, M:6
Kellgren and lawrence grade	II:3, III:6, IV:1
Foot progression angle (deg)	
Normal gait	2.1(4.0)
Toe-in gait	−5.1(5.1)*
Knee adduction moment (%BW*HT)	
Normal gait	3.11(1.40)
Toe-in gait	2.61(1.47)*
Visual analog pain score	
Normal gait	3.20(2.30)
Toe-in gait	1.35(0.88)*

* Represents a significant difference compared with normal gait at the $p < 0.01$ significance level.

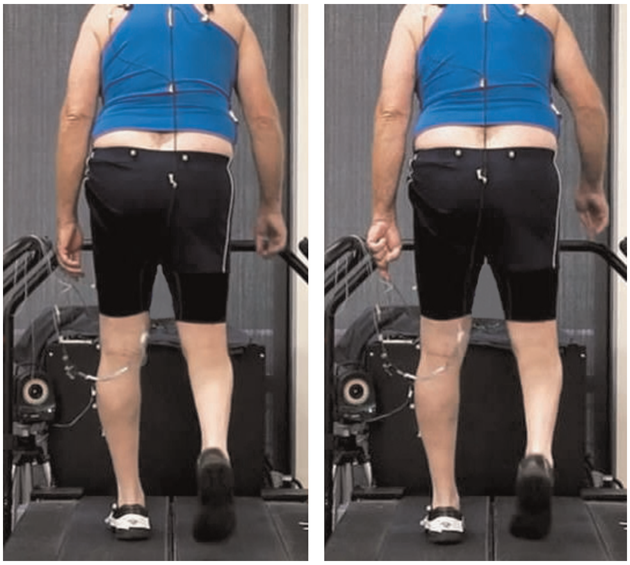

Fig. 1. A representative subject walking with (left) normal gait and (right) toe-in gait. The subject internally rotated the foot by 6° which reduced the first peak knee adduction moment by 20%.

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