Journal of Biomechanics 41 (2008) 2989–2994

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Predicting changes in knee adduction moment due to load-altering interventions from pressure distribution at the foot in healthy subjects

Jennifer C. Erhart [a,b,*], Annegret Mündermann [b,d], Lars Mündermann [b], Thomas P. Andriacchi [a,b,c]

[a] Bone and Joint Center, Palo Alto VA, Palo Alto, CA, USA
[b] Department of Mechanical Engineering, Stanford University, Durand Building 061, Stanford, CA 94305-4308, USA
[c] Department of Orthopedic Surgery, Stanford University Medical Center, Stanford, CA, USA
[d] School of Physiotherapy, University of Otago, Dunedin, New Zealand

ARTICLE INFO

Article history:
Accepted 24 July 2008

Keywords:
Walking gait
Knee biomechanics
Osteoarthritis
Load-altering intervention
Pressure distribution
Lateral wedges

ABSTRACT

The purpose of this pilot study of healthy subjects was to determine if changes in foot pressure patterns associated with a lateral wedge can predict the changes in the knee adduction moment. We tested two hypotheses: (1) *increases or decreases* in the knee adduction moment and ankle eversion moment due to load-altering footwear interventions can be predicted from foot pressure distribution and (2) changes in *magnitude* of the knee adduction moment and ankle eversion moment due to lateral wedges can be predicted from pressure distribution at the foot during walking. Fifteen healthy adults performed walking trials in three shoes: 0°, 4°, and 8° laterally wedged. Maximum heel pressure ratio, first peak knee adduction moment, and peak ankle eversion moment were assessed using a pressure mat, motion capture system, and force plate. *Increases or decreases* in the knee adduction moment and ankle eversion moment were predicted well from foot pressure distribution. However, the *magnitude* of the pressure change did not predict the magnitude of the peak knee adduction moment change or peak ankle eversion moment change. Factors such as limb alignment or trunk motion may affect the knee adduction moment and override a direct relationship between the pressure distribution at the shoe–ground interface and the load distribution at the knee. However, *changes* (increases or decreases) in the peak knee adduction moment due to load-altering footwear interventions predicted from pressure distribution during walking can be important when evaluating these types of interventions from a clinical perspective.

Published by Elsevier Ltd.

1. Introduction

Osteoarthritis of the knee is one of the most common musculoskeletal disorders, affecting an estimated 20–40% of individuals over the age of 65 (Felson, 1990). In particular, the medial compartment of the knee is involved in osteoarthritis, approximately 10 times more frequently than the lateral compartment (Ahlback, 1968). This increased involvement is theorized to be a result of greater loads seen on the medial compartment articular cartilage (Andrews et al., 1996; Andriacchi, 1994; Morrison, 1970; Schipplein and Andriacchi, 1991). A high maximum adduction moment at the knee during walking has been associated with the severity, rate of progression, and treatment outcome of medial compartment knee osteoarthritis (Baliunas et al., 2002; Miyazaki et al., 2002; Mündermann et al., 2004; Prodromos et al., 1985; Sharma et al., 1998). Consequently, many mechanical interventions for knee osteoarthritis, including bracing, taping, wedging, orthoses, and shoe sole density modifications, have been aimed at reducing the maximum knee adduction moment during walking.

Controlling foot placement and ankle motion by using laterally wedged insoles and laterally wedged shoes has been frequently studied as a load-modifying intervention for patients with knee osteoarthritis (Crenshaw et al., 2000; Fisher et al., 2007; Kerrigan et al., 2002; Sasaki and Yasuda, 1987). While several studies (Andrews et al., 1996; Wang et al., 1990) have suggested a relationship between foot placement and the adduction moment at the knee, a precise mechanism that relates foot mechanics to knee loading has not been identified. It is not known whether the changes in foot pressure patterns associated with the lateral wedge are sufficient to predict the reported changes in the joint moment.

It is suggested that the pressure distribution at the shoe–ground interface is a good descriptor of foot mechanics as it describes the load distribution between the medial and lateral

* Corresponding author at: Department of Mechanical Engineering, Stanford University, Durand Building 061, Stanford, CA 94305-4308, USA.
Tel.: +1 650 723 5793; fax: +1 650 725 1587.
E-mail address: jerhart@stanford.edu (J.C. Erhart).

0021-9290/$ - see front matter Published by Elsevier Ltd.
doi:10.1016/j.jbiomech.2008.07.021

aspect of the shoe. The current gold standard to assess treatments for knee osteoarthritis involves the use of a gait laboratory, which is not always available for clinical use. Use of a gait laboratory in a clinical setting is most hampered by the length of time and costs required for performing a study and interpreting it (Simon, 2004). A pressure mat, however, may be a simple, objective way to investigate the effect of load-modifying footwear interventions, without the need for costly equipment.

Pressure measurement systems include both pressure mats, measuring pressure between the shoe and ground, and in-shoe systems, measuring the pressure between the insole and plantar surface of the foot (De Wit et al., 2000; Randolph et al., 1999). While in-shoe pressure measurements allow information to be gathered between the sole of the foot and the shoe interface, pressure-sensitive insoles can be affected by the environment of the inside of the shoe, including the temperature, shoe contour, and dampness (Cavanaugh et al., 1992). Pressure measurement on a flat walking surface is technically less demanding and thus possibly easier to perform quickly in a clinical setting compared to in-shoe pressure systems.

The overall goal of this pilot study was to determine if the changes in foot pressure patterns associated with a lateral wedge can predict changes in the knee adduction moment and ankle eversion moment by studying 15 healthy subjects walking with 4° and 8° laterally wedged shoes and testing the following hypotheses: (1) *increases or decreases* in the knee adduction moment and ankle eversion moment due to load-altering footwear interventions can be predicted from pressure distribution of the foot; (2) changes in *magnitude* of the knee adduction moment and ankle eversion moment due to load-altering footwear interventions can be predicted from pressure distribution at the foot during walking.

2. Methods

Fifteen physically active adults (6 male, 9 female; age: 28.6 ± 4.0 yr, height: 1.67 ± 0.10 m, mass: 62.8 ± 9.8 kg) without pain or previous injury in their lower extremity participated in this study. After giving written consent in accordance with the Institutional Review Board, the subjects performed three walking trials at self-selected slow, normal, and fast speeds in each of the three shoes with identical uppers: 0° laterally wedged shoe (control shoe), 4° laterally wedged shoe, and 8° laterally wedged shoe, for a total of 27 walking trials per subject. Before testing, subjects had the opportunity to practice their self-selected slow, normal, and fast speeds. The shoes were tested in a random order, and manufactured by Nike Inc. (Beaverton, OR). The 0°, 4°, and 8° laterally wedged shoes were uniform stiffness walking shoes with Asker C durometer values for the sole of 55 ± 2. The shoes were manufactured in women's US size 7 and men's US size 9, with masses of 9.9–10.4 and 11.9–12.5 oz, respectively. The 4° walking shoes (Fig. 1A) had a 4° valgus shoe sole angle, making the lateral thickness slightly greater than the medial thickness.

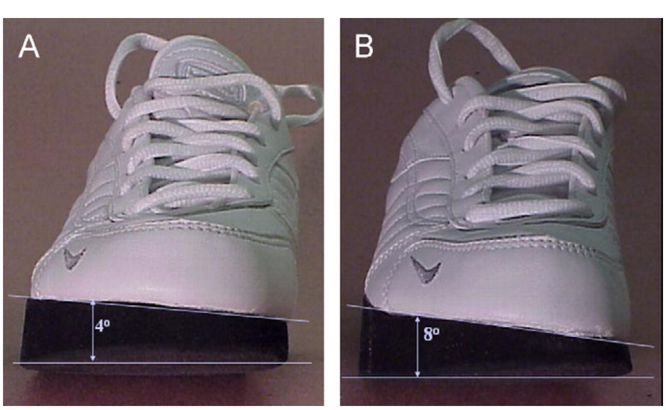

Fig. 1. Intervention shoes used in this study: (A) is the 4° laterally wedged shoe and (B) is the 8° laterally wedged shoe. The shoes were wedged along the entire length of the sole.

The 8° walking shoes (Fig. 1B) had an 8° valgus shoe sole angle, making the lateral thickness much greater than the medial thickness. The designs for the shoes were previously shown to reduce the adduction moment at the knee in healthy subjects (Fisher et al., 2007).

Kinematic and kinetic data were collected using an approach described previously (Andriacchi et al., 1997). A reflective six-marker joint link system was used to model the subjects, with markers placed unilaterally (side randomly selected). Markers were placed on the anterior superior iliac spine, greater trochanter, lateral tibial plateau, lateral malleolus, lateral aspect of the calcaneus, and lateral head of the fifth metatarsal. An eight-camera optoelectronic system for three-dimensional motion analysis (Qualisys Medical AB; Gothenburg, Sweden) was used to collect marker data for 5 s for each trial. Ground reaction force data were collected using a multi-component force plate placed in the center of the walkway (Bertec Corporation; Columbus, OH). All data were collected at a frequency of 120 Hz. To calculate external moments at each joint center, each limb segment (foot, shank, thigh) was idealized to be a rigid body. Inertial properties of the segments were taken from the literature (Dempster and Gaughran, 1967). External moments including the knee adduction moment and ankle eversion moment for each trial were calculated from marker, force plate, and inertial segment data (Andriacchi et al., 1997). Moments were normalized to body weight and height (%Bw $\times$ Ht) to allow for comparison between subjects. The first peak knee adduction moment was calculated as the maximum knee adduction moment in the first half of stance. The peak ankle eversion moment was calculated as the maximum ankle eversion moment during stance. Average moment values for each shoe, speed, and subject combination for the three trials were calculated. The change in joint moments were calculated as the percent difference between the joint moment for the 4° and the 8° shoe and the joint moment for the control shoe for each subject and speed, respectively. Differences in walking speed and toe-out angle between the shoes were also assessed, as both speed and toe-out angle may affect the knee adduction moment (Andrews et al., 1996; Mündermann et al., 2004). Walking speed was calculated as the average speed of progression of the anterior superior iliac spine marker during stance. Toe-out angle was calculated as the angle between a line connecting the fifth metatarsal and calcaneus marker and the x-axis of the global coordinate system. Positive (negative) values indicated toe-out (toe-in) or foot abduction (adduction).

Pressure distribution data were collected synchronously using a $50 \times 40\,cm^2$ Footscan® pressure mat with $5 \times 7\,mm^2$ sensors (RSscan International; Belgium) placed on the force plate level with the walkway. To assess load distribution at the foot, the heel zone was calculated from the pressure region of the foot taken from the pressure mat data. The heel was defined as the rear 30% of the footprint. The heel was divided into an additional two zones, the medial and lateral heel, using an in-house algorithm written in Matlab (MathWorks Inc, Natick, MA) (Fig. 2). In brief, to determine the medial and lateral regions of the foot, we divided each row of sensors in the footprint output in half. If the number of sensors in the row was odd, the center sensor was disregarded. To calculate the maximum heel pressure ratio for each trial, the ratio of the maximum medial heel pressure to the maximum lateral heel pressure was calculated. From the three trials, the average maximum heel pressure ratio for each shoe, speed, and subject combination was then calculated. Heel pressure ratio was chosen because the first peak knee adduction moment and peak ankle eversion moment typically occur during the first half of stance phase (Mündermann et al., 2005). The changes in maximum heel pressure ratio were calculated as the percent difference between the heel pressure ratio for the 4° and the 8° shoe and the heel pressure ratio for the control shoe for each subject and speed, respectively.

Differences in maximum heel pressure ratio, first peak knee adduction moment, peak ankle eversion moment, speed, and toe-out angle for the 4° and 8° laterally wedged shoes versus the 0° control shoe were detected using repeated measures analysis of variance (ANOVA) with significance level adjusted to account for multiple comparisons ($\alpha = 0.01$). Upon significant result of the ANOVA, Bonferroni adjusted t-tests were used for post-hoc analyses.

The performance of the pressure mat to determine the success rate in predicting increases or decreases in the first peak knee adduction moment and peak ankle eversion moment with the 4° and 8° shoes versus control from maximum medial-to-lateral heel pressure ratio was quantified in truth table form. For the knee adduction moment the following terms were defined (Table 1): true positive—increase in medial-to-lateral heel pressure ratio with a decrease in knee adduction moment, true negative—decrease in medial-to-lateral heel pressure ratio with an increase in knee adduction moment, false positive—increase in medial-to-lateral heel pressure ratio with an increase in knee adduction moment, false negative—decrease in medial-to-lateral heel pressure ratio with a decrease in knee adduction moment. For the ankle eversion moment similar definitions were made (Table 1): true positive—increase in medial-to-lateral heel pressure ratio with an increase in ankle eversion moment, true negative—decrease in medial-to-lateral heel pressure ratio with a decrease in ankle eversion moment, false positive—increase in medial-to-lateral heel pressure ratio with a decrease in ankle eversion moment, false negative—decrease in medial-to-lateral heel pressure ratio with an increase in ankle eversion moment. Successful prediction of a change in knee adduction moment or ankle eversion moment included a true positive or a true negative. Linear regression analyses ($\alpha = 0.05$) were performed within subjects to detect a relationship between maximum heel pressure ratio with the