

Walking Barefoot Decreases Loading on the Lower Extremity Joints in Knee Osteoarthritis

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Objective. To evaluate the effects that modern shoes have on gait and lower extremity joint loads in osteoarthritis (OA).

Methods. Gait analyses were performed on 75 subjects with knee OA while they were wearing their everyday walking shoes and while they were walking barefoot. The trials involved optoelectronic detection of external markers during ambulation over a multicomponent force plate, and were matched for speed. Comparisons were made of gait parameters and joint loading during trials in which the subjects walked while wearing shoes and while barefoot.

Results. Peak joint loads at the hips and knees significantly decreased during barefoot walking, with an 11.9% reduction noted in the knee adduction moment. Stride, cadence, and range of motion at the lower extremity joints also changed significantly, but these changes could not explain the reduction in the peak joint loads.

Conclusion. Shoes may detrimentally increase loads on the lower extremity joints. Once factors responsible for the differences in loads between with-shoe and barefoot walking are better delineated, modern shoes and walking practices may need to be reevaluated with regard to their effects on the prevalence and progression of OA in our society.

Osteoarthritis (OA) of the lower extremity is largely mediated by aberrant biomechanical forces. In knee OA, the most well-studied form, there is evidence

that patients with abnormally high dynamic loading of the knees are at greater risk of incident and progressive disease (1,2). Consequently, strategies that effectively reduce loads on the knee during gait would be of great interest.

One standard parameter assessed as a marker of knee loading is the external knee adduction moment, a varus torque on the knee that reflects the magnitude of medial compartment joint loading. The peak adduction moment has been shown to correlate with both the severity (1) and the progression of radiographic knee OA (2), as well as with the severity of pain (3). Hence, biomechanical interventions aimed at reducing medial compartment loading, such as lateral wedge shoe orthotics, are under evaluation as potential adjuncts to therapy (4,5). However, the observation that inserts in normal shoes may affect gait mechanics and knee loading suggests that modern shoes may influence loading patterns in the knees of patients with OA. Further, since the lower extremity joints are interrelated, alterations of mechanics of the foot may not only affect knee loads but may have consequences at the other lower extremity joints. Therefore, the primary aim of this investigation was to evaluate the impact of modern shoes on gait mechanics and joint loads in a controlled population of subjects with medial compartment knee OA, with the primary hypothesis being that these subjects would demonstrate significant differences in gait mechanics and joint loads when walking barefoot compared with when walking in their normal shoes.

SUBJECTS AND METHODS

Subjects in this study were participants in an ongoing double-blind randomized controlled trial of the efficacy of lateral wedge orthotics for the treatment of knee OA (NLM Identifier: NCT00078453, at www.clinicaltrials.gov). The study was approved by the Institutional Review Board, Rush Medical College, for studies involving human subjects, and informed consent was obtained from all subjects. Inclusion criteria included the presence of symptomatic OA of the knee, as

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defined by the American College of Rheumatology's (formerly, the American Rheumatism Association) criteria (6), and by the presence of a pain rating of at least 20 (on a 100-mm visual analog scale) while walking (corresponding to question 1 of the visual analog format of the knee-directed Western Ontario and McMaster Universities Osteoarthritis Index) (7).

Although all subjects had bilateral knee OA, the most symptomatic knee on the day of the initial study visit was considered the index knee. Subjects had OA of the index knee documented by weight-bearing full-extension anteroposterior knee radiographs showing grade 2 or 3 OA, as defined by the Kellgren/Lawrence (K/L) grading scale, as modified by Felson et al (8). The contralateral knee also had a radiographic OA of K/L grade 1–3. Subjects had medial compartment OA, defined as medial joint space narrowing (JSN) grade of ≥ 1 , as well as medial JSN greater than lateral JSN by a grade of ≥ 1 (9). Major exclusion criteria were flexion contracture of $>15^\circ$ at either knee, clinical OA in the ankle or the hip, significant intrinsic foot disease as determined by a podiatric examination, and a body mass index >35 .

Gait analysis. All subjects underwent baseline gait analysis (before the use of orthotics). Motion during gait was measured by a multicamera optoelectronic system (Computerized Functional Testing Corporation, Chicago, IL), and force was measured by a multicomponent force plate (Bertec, Columbus, OH) (10). The walking surface consisted of a 2-inch-thick wooden pressboard covered with linoleum. Reflective markers were placed on the lower extremity, including the iliac crest, greater trochanter, lateral joint line of the knee, lateral malleolus, calcaneus, and the base of the fifth metatarsal bone, and joint centers were estimated on the basis of anatomic measurements of each subject. Subjects were instructed to walk at a range of speeds from slow to fast, and data on 6 stride lengths on each side were collected.

These position and force data were then used to assess range of motion (ROM) at the joints and to calculate 3-dimensional external moments, using inverse dynamics. The external moments that act on a joint during gait are, according to Newton's second law, equal and opposite to the net internal moments produced primarily by the muscles, soft tissues, and joint contact forces. To allow for comparisons between subjects, the external moments were normalized to the subject's body weight multiplied by height ($100 \times [\text{weight} \times \text{height}]$) (11).

Analyses of with-shoe and barefoot walking. All subjects were asked to wear their own comfortable walking shoes. Gait analyses were performed when the subjects were wearing these shoes. The shoes were then removed. Subjects walked for several minutes on the gait analysis platform while barefoot, and after the subjects felt comfortable, gait analyses were repeated when barefoot. Subjects were instructed to walk at their normal walking speed during the barefoot analyses. With-shoe and barefoot trials were chosen for comparison of the index knee limb and similarly for the contralateral limb. Normal-speed barefoot walking trials were matched for speed with normal-speed with-shoe walking trials for analysis.

Statistical analysis. Student's paired *t*-tests were used to compare moments and gait parameters between with-shoe and barefoot walking. Relationships between differences in gait parameters and differences in joint moments during with-shoe and barefoot walking were evaluated using linear

Table 1. Demographic data on the study subjects

Age, mean $\pm$ SD (range) years	59 $\pm$ 10 (35–83)
Sex, no. men/no. women	16/59
Weight, mean $\pm$ SD kg	78.9 $\pm$ 14.4
Height, mean $\pm$ SD meters	1.7 $\pm$ 0.1
Body mass index, mean $\pm$ SD kg/m ²	28.4 $\pm$ 4.1

regression. All analyses were performed using SPSS software (SPSS, Chicago, IL). *P* values less than 0.05 were considered significant.

RESULTS

Eighty-six subjects met the eligibility criteria and underwent gait analyses while walking barefoot and in shoes. Eleven were excluded because their data could not be appropriately matched for speed, leaving 75 subjects for whom speed-matched gait data were available on the index knee. Of these, 40 subjects also had gait data (with and without shoes) available on the contralateral knee. Table 1 summarizes the demographics of the study population. The distribution of radiographic severity of OA was as follows: in index knees, 57 K/L grade 2 and 18 K/L grade 3; in contralateral knees, 2 K/L grade 1, 35 K/L grade 2, and 3 K/L grade 3.

Gait parameters. Walking speed did not change between the trials in which the subjects walked while wearing shoes and while barefoot (Table 2); however, stride length significantly decreased during barefoot walking. Meanwhile, cadence significantly increased during barefoot walking, suggesting that although subjects were taking shorter steps, they were taking more steps per unit of time. ROM at the major lower extremity joints, as well as the toeout angle, were significantly reduced during barefoot walking.

Dynamic loads. Barefoot walking significantly decreased dynamic loads at the knees (Table 3). There was an 11.9% reduction in the peak knee adduction

Table 2. Gait parameters during with-shoe and barefoot walking analyses

	With shoes	Barefoot
Speed, mean $\pm$ SD meters/second	1.17 $\pm$ 0.21	1.16 $\pm$ 0.21
Stride, mean $\pm$ SD meters/height	0.78 $\pm$ 0.08	0.73 $\pm$ 0.07*
Cadence, mean $\pm$ SD steps/minute	107 $\pm$ 9	114 $\pm$ 11*
Range of motion, mean $\pm$ SD degrees		
Knee	63 $\pm$ 5	57 $\pm$ 5*
Hip	30 $\pm$ 5	29 $\pm$ 5*
Ankle	30 $\pm$ 5	26 $\pm$ 5*
Toeout angle, mean $\pm$ SD degrees	18 $\pm$ 6	15 $\pm$ 7*

* *P* < 0.05 versus with shoes, by paired *t*-test.

Table 3. Peak dynamic joint loads (moments) during with-shoe and barefoot walking analyses*

	With shoes	Barefoot	Change, %†	<i>P</i>
Knee				
Adduction	2.94 ± 0.77	2.59 ± 0.75	-11.9	<0.001
Abduction	0.66 ± 0.34	0.69 ± 0.30	4.5	0.356
Flexion	1.83 ± 1.22	1.77 ± 1.14	-3.3	0.435
Extension	3.51 ± 0.93	3.25 ± 0.87	-7.4	0.006
Hip				
Adduction	4.00 ± 0.84	3.83 ± 0.86	-4.3	0.001
Abduction	1.91 ± 0.93	1.92 ± 0.84	0.5	0.930
Flexion	6.08 ± 1.90	6.22 ± 1.85	2.3	0.472
Extension	2.34 ± 1.00	2.26 ± 0.99	-3.4	0.395
Internal rotation	0.63 ± 0.23	0.56 ± 0.20	-11.1	<0.001
External rotation	0.59 ± 0.28	0.53 ± 0.24	-10.2	0.001

* Moments are the mean ± SD weight × height (× 100).

† Percentage change in load when walking barefoot as compared with when walking in shoes.

moment while walking barefoot compared with walking in shoes ($P < 0.001$). There was also a significant decrease in the peak knee extension moment ($P = 0.006$), while the peak knee flexion moment did not significantly change ($P = 0.435$) between the with-shoe and barefoot walking trials.

Similar reductions in dynamic loads were observed at the hips during barefoot walking (Table 3). The peak hip adduction moment decreased by 4.3% ($P = 0.001$). The peak hip internal and external rotation moments decreased by 11.1% and 10.2%, respectively ($P = 0.001$).

Evaluation of gait parameters and peak moments among the contralateral knees yielded comparable results. There were notable reductions in stride length, increases in cadence, and reductions in hip, knee, and ankle ROM during barefoot walking ($P < 0.05$). There were also significant reductions in peak knee adduction moment, knee extension, hip internal rotation, and hip external rotation moments during barefoot walking ($P < 0.05$). The only differences in the results for the contralateral knee were that the toeout angle and hip adduction moment did not significantly change.

To assess whether the reduced loading at the knees and hips while barefoot could be explained by gait alterations alone, stepwise linear regression was used to evaluate the influence of the change in cadence, stride, toeout angle, and hip, knee, and ankle ROM (independent variables) on the reduction in peak joint moments during barefoot walking (dependent variables). There were no significant relationships noted among any of these variables singly or collectively. This was further confirmed using backward linear regression, in which all

the independent variables were eliminated as having a significant influence on the change in peak moments. Therefore, although the character of the gait was somewhat altered, none of these measurable aspects of gait could explain the significant reductions in peak joint moments during barefoot walking trials.

DISCUSSION

It has long been appreciated that excessive loading of the lower extremities is associated with the onset and progression of knee OA; however, no attention has been given to the role that modern shoes may play in potentiating these aberrant loads. In the present study, we formally evaluated the differences in gait and joint loads that occur when patients with knee OA walk barefoot compared with when they walk in shoes. This study demonstrated that such patients undergo a significant reduction in their joint loads at both the knees and the hips while walking barefoot compared with when walking in their normal shoes. Moreover, whereas significant changes in several gait parameters were observed during barefoot walking, including changes in stride, cadence, joint ROM, and toeout angle, these changes in gait could not explain the significant reduction in loads at the joints. This suggests that the design of modern shoes may intrinsically predispose such patients to excessive loading of their lower extremities.

Previous studies of the effects of shoes on joint loading have been restricted to normal subjects without OA, and have demonstrated that even shoes with moderately high heels increase peak knee torques (12). In addition, results of one study suggested that shoes may result in elevations of knee loads in normal individuals, but these effects were attributed to differences in walking speeds while wearing shoes (13); in our study, comparisons were made using matched normal walking speed trials. Interestingly, Bergmann et al (14) evaluated hip loads in a patient who had an instrumented prosthesis that functioned as a force transducer inserted at the time of joint replacement for hip OA. By obtaining direct force measurements from the transducer, the investigators were able to demonstrate that there were no differences in hip loads among nearly 15 different types of shoes, but the hip loads were lower when the subject was barefoot than when wearing any of the shoes (14). These results are consistent with our data; however, they represent only a single case report of hip loads in a subject who had undergone joint replacement.

Although the effects of shoes on OA onset or exacerbation have not been carefully studied, there is

substantial precedent for the concept that subtle alterations at the foot may have effects on loading of the knees. For example, it is well established that the insertion of lateral wedge orthotics into regular shoes can induce significant decreases in knee torques (by up to 5–7%) in subjects with medial compartment knee OA, and such inserts have been evaluated for potential therapeutic effects in knee OA (4,5). It is of interest that in our study, we observed relative load reductions of nearly 12% at the knee and 4–11% at the hip merely by walking barefoot, which appears to be substantially greater than the previous experience with lateral wedge inserts.

It has yet to be determined what factors or biomechanical alterations are responsible for the significant reduction in joint loads during barefoot walking. Indeed, walking speed has been shown to affect loads at the joints (15). Subjects in this study maintained equal speeds during both the with-shoe and barefoot walking trials. Although stride, cadence, and ROM at the joints changed, these factors could not explain the observed reduction in joint loads. There may be several other differences between with-shoe and barefoot walking that could account for the noted differences. For example, previous investigators have suggested that heels on shoes can increase peak knee torques (12). Most commercial walking shoes have a partial lift at the heel; thus, the complete lack of a “heel” during barefoot walking may be effective at reducing peak torques at the knee.

Another factor is the stiffness imposed by the sole of most shoes; for example, in examining several different types of shoes in a single subject, Bergmann et al suggested that hard soles may disadvantageously affect loads at the hip (14). Thus, it is possible that soles of modern shoes may increase joint torques compared with the flexible movement of a bare foot. A final explanation of the biomechanical advantages of barefoot walking may be attributed to increased proprioceptive input from skin contact with the ground compared with an insulated foot contacting the ground. Each of these possibilities warrants further investigation.

Although the findings in this study are intriguing, there are limitations that should be recognized. First, the reductions in joint loads were observed soon after removing the shoes. Although an attempt was made to ensure that the subjects had accommodated to the barefoot conditions and that their gait parameters had equilibrated prior to the gait analyses, it is possible that the observed load reductions might not be fully maintained after extended periods of barefoot walking. Similarly, this study does not account for cultural popula-

tions that may be used to long-term barefoot walking. Second, it is possible that in OA, disease-specific characteristics, such as greater baseline knee torques, anatomic alterations of the lower extremity (mechanical axis), or the presence of knee pain, may contribute to greater sensitivity for the joint loads to be influenced by walking in shoes. Thus, it is not clear that the loading changes observed in this population would apply universally to normal subjects. Finally, the potential clinical significance of the observed reductions in joint loads, such as improvement in pain and function with barefoot walking, would need to be evaluated in a formal intervention trial. Conversely, the contributions, if any, of modern shoes to OA progression will need to be confirmed prospectively.

In summary, this study identified substantial differences in gait biomechanics and joint loads during barefoot walking and walking in shoes in a group of subjects with symptomatic knee OA. It appears that patients with medial knee OA undergo significant reductions in joint loads at their knees and hips when walking barefoot compared with when walking in their normal shoes. Since knee OA is mediated in part by aberrant loading, and since excess loading has been shown to be associated with pain and disease progression, these data suggest that modern shoes may exacerbate the abnormal biomechanics of lower extremity OA. Although further investigation is necessary to delineate the biomechanical factors responsible for the notable reductions in joint loads during barefoot walking, this study suggests that modern shoes, and perhaps our daily walking practices, may need to be reevaluated with regard to their effects on the prevalence and progression of OA.

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