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The Effects of Common Footwear on Joint Loading in Osteoarthritis of the Knee

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Abstract

Objective—Elevated joint loads during walking have been associated with the severity and progression of osteoarthritis (OA) of the knee. Footwear may have the potential to alter these loads. This study compared the effects of several common shoe types on knee loading in subjects with OA of the knee.

Methods—31 subjects (10 men, 21 women) with radiographic and symptomatic knee OA underwent gait analyses using an optoelectronic camera system and multi-component force plate. In each case, gait was evaluated barefoot and while wearing 4 different shoes: 1) clogs (Dansko®), 2) stability shoes (Brooks Addiction®), 3) flat walking shoes (Puma H Street®), and 4) flip-flops. Peak knee loads were compared between the different footwear conditions.

Results—Overall, the clogs and stability shoes, resulted in a significantly higher peak knee adduction moment (3.1±0.7 and 3.0±0.7 %BW*ht, respectively, ~15% higher, $p<0.05$)) compared with that of flat walking shoes (2.8±0.7%BW*ht), flip-flops (2.7±0.8%BW*ht) and barefoot walking (2.7±0.7%BW*ht). There were no statistically significant differences in knee loads with the flat walking shoes and flip-flops compared to barefoot walking.

Conclusions—These data confirm that footwear may have significant effects on knee loads during walking in subjects with OA of the knee. Flexibility and heel height may be important differentiating characteristics of shoes which affect knee loads. In light of the strong relationship between knee loading and OA, the design and biomechanical effects of modern footwear should be more closely evaluated in terms of their effects on the disease.

Introduction

Traditionally, footwear has been engineered to provide maximum *foot* support and comfort, and little attention has been paid to the mechanical effects of shoes on the rest of the lower extremity. However, the entire lower extremity is known to be an interrelated functional and mechanical unit, and alterations at one aspect of the lower extremity (e.g., the foot) can have significant impact on distant areas such as the knee(1,2). Therefore, the design of footwear itself may substantially affect the loading patterns of the entire lower body, and these biomechanical effects may have important implications for conditions in which mechanical

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Conflict of interest statement

The authors have no conflicts of interest to declare in connection with this study.

factors are important to the pathogenesis and progression of disease, such as osteoarthritis (OA) of the knee. Nonetheless, the potential impact of footwear on knee OA has not been widely recognized or critically evaluated.

OA is the most common arthritic condition, and symptomatic OA of the knee is a significant source of disability and impaired quality of life(3–5). Despite this impact, OA management remains largely palliative and generally focuses on oral analgesics rather than on the aberrant biomechanical loading that underlies much of its progression. OA of the lower extremity is mediated, at least in part, through aberrant dynamic loads (loads during ambulation) transmitted across the joints. Quantification and assessment of these knee loads through gait analysis has demonstrated that in OA of the knee, elevated joint loads are directly associated with radiographic severity(6), disease progression(7), and pain(8–10), whereas in contrast, reduction of loading at the knee may yield significant symptomatic benefits(11,12).

Recent evidence suggests that modern shoes have a substantial influence on knee loading, particularly among people with symptomatic knee OA(13–15). This is particularly relevant because shoes are worn during most of the day, especially during ambulation, when the load on the lower extremity joints is significantly greater than at rest(16). We recently reported that the use of modern comfortable self-chosen walking shoes results in an approximately 14% increase in dynamic loading of the knees during ambulation, compared to barefoot walking, among individuals with knee OA(13). Another one of our studies suggested that flat, flexible footwear may have biomechanical advantages for the knee joint(15). In light of these findings, the purpose of the current investigation was to evaluate and differentiate the effects of common walking shoes, with the primary hypothesis being that shoes that were flat and flexible, would be associated with the lowest knee loads.

Patients and Methods

Subjects were recruited through ongoing studies and clinic patients in the Section of Rheumatology at Rush University Medical Center. This study was approved through the institution’s review board for studies involving human subjects, and written informed consent was obtained from all subjects. Inclusion criteria included the presence of *symptomatic* OA of the knee, which was defined by the American College of Rheumatology’s Clinical Criteria for Classification and Reporting of OA of the knee(17) and by the presence of at least 20 mm of pain (on a 100 mm scale) while walking (corresponding to question 1 of the visual analog format of the knee-directed Western Ontario and McMaster Universities Arthritis Index (WOMAC))(18). Although many subjects had bilateral knee OA, the most symptomatic knee on the day of the initial study visit was considered the “index” knee. OA of the index knee was documented by weight-bearing full extension anterior-posterior knee radiographs, of grade 2 or 3 out of 4 (moderate OA severity) as defined by the modified Kellgren-Lawrence (KL) grading scale(19). All subjects had medial compartment disease, defined as either qualitative joint space narrowing of greater than or equal to 1 or the presence of medial bone cyst, sclerosis, or osteophyte(20). Major exclusion criteria were 1) flexion contracture of greater than 15 degrees at either knee 2) clinical OA of either ankle or either hip 3) inability to ambulate without assistance and 4) significant intrinsic foot disease per a podiatric exam.

Footwear

Subjects had gait analyses performed while walking barefoot and while wearing the following four common shoe types. Shoe and barefoot runs were performed in random order for each subject. Subjects were allowed to acclimate to the various footwear conditions for several minutes between testing trials.

Clogs—Dansko® produces and distributes clogs that are particularly popular among healthcare professionals (Fig 1); these clogs are felt to provide cushioned foot "support" and comfort. The sole of the clog is stiff and the heel height is 50mm. Depending on the size, the weight of the shoe ranges from 182 to 363 grams. The clogs in this study were "slip-ons" and lacked back support.

Stability shoes—The Brooks Addiction® is a common "stability shoe" (Fig 2). Stability shoes are often prescribed for foot comfort and stability during walking. Like most stability shoes currently marketed, the shoe has cuts in the *outsole* to promote motion across the ball of the foot during propulsion, while leaving the rear foot without significant cuts, to promote stability. The heel height is 50mm for men and 40mm for women. The weight of the shoe ranges from 273 to 454 grams.

Flat walking shoes—The Puma H-Street® is a flat, flexible shoe allowing for significant foot mobility (Fig 3). It is similar to other popular modern-day walking shoes. The heel height is 10 to 15 mm depending on the shoe size (slightly increases with increasing shoe size). The weight of the shoe ranges from 91 grams to 182 grams.

Flip-flops—Flip flops are very common walking shoes (Fig 4). The flip flops in this investigation were made of flexible rubber. The heel height was 15 mm and the weight 91 grams for all sizes.

Gait Analyses

Gait assessment included collection of three-dimensional kinematics and ground reaction forces using four Qualisys (Innovision Systems, Inc., Columbiaville, MI) optoelectronic cameras with passive markers and a multi-component force plate with a sampling frequency of 120 Hz (Bertec, Columbus, OH). Passive markers were placed at the lateral most aspect of the superior iliac crest, the superior aspect of the greater trochanter, the lateral knee joint line, lateral malleolus, lateral calcaneus, and the head of the fifth metatarsal. For moment calculations, the joint centers of the hip, knee, and ankle were approximated following previously published methods(21,22). The joint center of the ankle was determined to be the midpoint of the distance from the medial to lateral malleolus. The joint center of the knee was determined to be the midpoint of the distance between the medial and lateral joint lines of the tibio-femoral joint. The joint center of the hip was determined to be 2.5 cm distal to the midpoint of the distance between the anterior superior iliac spine and the pubic tubercle.

Subjects were instructed to walk at a self-selected normal speed on a 2-inch thick wooden pressboard covered with linoleum. Kinetic components calculated using processing software developed by CFTC (Computerized Functional Testing Corporation, Chicago, IL) included frontal plane external joint moments at the knee(23). A minimum of two trials per shoe type were performed at the subject's normal walking speed.

These position and force data were then utilized to assess range of motion at the joints and to calculate three-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. The external moments are normalized to the subjects body weight (BW) multiplied by height (Ht) times 100 (%BW*Ht)(24). In order to compare footwear conditions, trials with minimal speed differences were chosen. This methodology, which has long been a standard approach, is intended to control for the confounding effect of variable gait speeds in assessing dynamic loading in OA subjects. Patients with OA significantly alter loading across the knees at different gait speeds(23); thus, the use of speed-matched gait run analyses may provide a closer estimate of the true effect of different interventions on knee loading by OA subjects, while avoiding artifactual heterogeneity introduced by testing at variable gait speeds.

Primary gait endpoints

The primary endpoint for the study was the peak external knee adduction moment (PAddM), a gait parameter that reflects the extent of medial compartment knee loading during walking. The magnitude of the PAddM has been shown to directly relate to the radiographic and clinical severity of medial knee OA(6), radiographic progression of knee OA(7), and to surgical outcomes in knee OA(22,25). The PAddM was defined as the external adduction moment of greatest magnitude during the stance phase of the gait cycle.

Secondary gait endpoints

Other gait parameters were also measured and compared as secondary endpoints in the study. The major peak moments at the other lower extremity joints were evaluated, as were ground reaction forces (GRFs). Walking speed can affect peak joint loads and therefore, the various trials were matched for normal walking speed during the different footwear conditions. Stride refers to the length of steps during walking and cadence represents the number of steps per minute. Range of motion (ROM) at the lower extremity joints was evaluated as well. These measures were included to gain better insight into how overall gait was changing during walking with the various footwear designs.

Missing Data

Four subjects completed all but one walking trial with the various shoes. These included one who did not walk barefoot, one did not walk with the clog, and two that did not walk while wearing flip-flops. The barefoot trial was not completed due to lack of time during the study visit. The other trials were not completed because the appropriate shoe sizes were not available. Imputation of missing data was performed so that these subjects could be included in the analyses(26). Because these data are not normally distributed, a ‘Hot Deck’ method was used for imputing missing data. Hot Deck methods replace missing values in such a manner that the statistical moments of the distribution are maintained, as well as the shape of the distribution.

Statistical Analyses

Statistical analyses were performed using SPSS software. Descriptive data for all groups and variables was expressed as mean ± SD for continuous measures. Differences in gait parameters during the different footwear conditions and barefoot walking were measured using repeated measures analysis of variance. If an overall effect was detected, group differences were further evaluated for significance with Tukey’s HSD post-hoc pair-wise comparisons using paired-contrasts (27). Statistical significance was assumed if the $p < 0.05$ throughout these analyses. A power analysis was conducted using the effect sizes found for PAddM for the samples(28). We estimated Cohen’s ‘d’ for the median difference between each type of footwear and the barefoot condition. We estimated this effect ($d=0.29$) and with a sample of 31 per group, and assuming a one-tailed alpha of 0.05, we estimated the power of each pair-wise comparison to be 0.85. **Multiple** linear regression was used to evaluate the influence of gait parameters on peak knee loads. PAddM was used as the dependent variable and stride, cadence, knee ROM, and hip ROM as the dependent variables. Variables were entered individually as well as together in a combined model.

Results

Thirty-one subjects with knee OA underwent gait analyses; there were 21 females and 10 males, with a mean age(SD) of 57(10) years and a mean BMI of 29.3±4.8 kg/m^2. Of these subjects, 20 had KL grade 2 and 11 had KL grade 3 severity of radiographic knee OA.

Table 1 provides specific peak joint load values with the footwear compared to barefoot walking. The various shoe types were associated with significant differences in loading at the knees, as assessed by the PAddM, the primary outcome measure. The clogs and stability shoes were associated with the highest PAddMs during walking, 7 to 15% greater than the flat walking shoes, flip flops and barefoot walking ($p<0.05$ for all comparisons). In contrast, knee loading while wearing flip-flops was not different than barefoot walking, nor was there a statistically significant difference with the flat walking shoes compared to barefoot. In terms of peak joint loads, there were no significant differences in the knee flexion or hip adduction moments. The peak hip flexion moment varied up to 31% and was highest with flip flops and lowest with clogs. The ankle dorsiflexion moment varied up to 12% amongst footwear and was the lowest with clogs and the highest with stability shoes. Ankle inversion also varied up to 12%, and was the highest with flip flops and lowest with clogs. Finally ground reaction forces were lowest while barefoot and highest while wearing flip flops. Thus, the ground reaction forces did not mirror peak knee moments. They also did not appear to be higher with heavier weight shoes.

In addition to peak joint moments, assessment of other gait parameters is summarized in Table 2. There were no significant differences in walking speed among the different footwear conditions. Stride (length of steps) appeared to be lower while barefoot and cadence (steps per time) tended to be greater while barefoot and with flip flops. Range of motion at the knee and ankle during walking varied significantly with the different types of shoes and barefoot walking, however, no consistent pattern was identified

Regression analyses were used to evaluate the influence of stride, cadence, knee range of motion and ankle range of motion on the PAddM during the different footwear conditions. There were no significant relationships observed between PAddM with any of the parameters during the various footwear conditions ($r^2 = 0.019$ to 0.063, all p values greater than 0.1). Therefore, although these parameters varied among the various footwear trials, they did not account for the variations in PAddMs among the footwear.

Discussion

Currently, biomechanical interventions for the treatment of OA of the knee are an active area of investigation. Therapies, such as unloading knee braces and wedged orthotic shoe inserts have been reported to lower peak knee loads anywhere from 3 to 20%(1,11,12,29,30); hence, the 11 to 15% variation in loads induced by the various footwear in this study suggest that one clinically significant and practical approach to knee OA would be to carefully evaluate the shoes worn by patients. Recently, the Osteoarthritis Research Society International (OARSI) issued consensus guidelines for the treatment of knee OA that recommend that "every patient with hip or knee OA should receive advice concerning appropriate footwear"(31), but the statement concedes that this is based on expert opinion and that there is scant evidence that recommended footwear actually reduces impact loads(31). This study provides novel and important information that may serve to inform these recommendations.

Several aspects of footwear may uniquely affect joint loading. Conventional walking shoes vary in heel height. Previous studies have suggested that high-heeled and even moderate heeled shoes can increase knee loads in healthy women(32). Therefore, heel lifts and heel height in walking shoes may affect loading. In this study the greater heel height of the stability shoes and clogs, although not conventionally what a layperson may consider a “heel”, could have contributed to the higher knee loads experienced with these footwear. Another characteristic of footwear likely to affect joint loading is the “stiffness” imposed by shoe soles. We have previously shown(13), and others have confirmed(33), that barefoot walking is associated with lower peak knee loads compared to the use of conventional footwear. It may be that the flexible movement of a bare foot is biomechanically advantageous. The natural flexion of the foot upon contact with the ground may attenuate proximal joint impact, compared to artificial “stomping” movement created by a stiffed-sole shoe.

Previous studies have shown that lateral wedge orthotics can result in lower peak knee loads in subjects with medial compartment knee OA(1,30). The lateral wedge essentially alters the mechanical axis of the lower extremity by pronating the foot and thereby decreasing the lever arm and rotational torque on the knee joint(34)(1). Similarly, the bare foot pronates during normal walking(35), and this natural movement can be attenuated by the stiffness or medial arch support imposed by common conventional footwear. Franz et al. demonstrated that the addition of medial arch supports to control footwear in *healthy* subjects increased the PAddM by 4 to 6% during walking and running(36). The flat walking shoes and flip flops in this study lack medial arch support or stiffness and thereby allowed for this movement while the stability shoes and clogs provide a fair amount of medial arch support and stiffness. However, the relationship between lateral wedges and arch supports is more complicated since others have observed that addition of arch support to lateral wedged orthotics is actually associated with further reductions in the PAddM compared to a lateral wedge alone(37).

Finally, we believe additional advantages of barefoot or ‘lightweight” footwear may be related to increased sensory input from skin or a minimally insulated foot contacting the ground, relative to an insulated foot contacting the ground. The increased sensory input could initiate protective neuromuscular reflexes to help minimize proximal joint impact and load(38–40).

In our study, flip-flops and the walking shoe were flat, flexible, and lightweight and seemed to mimic barefoot mechanics. The clogs and stability shoes, in contrast, are considered “supportive and stable shoes”. Ironically, although these shoes have conventionally been considered advantageous in providing appropriate “cushioning” and support, their effects on proximal joint loads during ambulation had not previously been well studied. Counterintuitive to conventional philosophies, these “cushioned and supportive,” shoes appear to be associated with increased joint loading at the knee as opposed to shoes with less “support”, flatter heels, and more flexibility.

Evaluation of other lower extremity peak moments and gait parameters in this study suggests that there is quite a bit of variability, both in some peak moments at the hip and ankle as well as in stride, cadence and range of motion at the lower extremity joints. However, the variations were not particularly consistent and since we do not have much data suggesting the significance of peak moments at the other lower extremity joints, it is difficult to make substantial conclusions from these results. Furthermore, stride, cadence, and range of motion did not demonstrate significant relationships with peak knee loads. When evaluating chronic use of footwear, it would be useful to continue to monitor these parameters for any clinical or pathological significance.

It should be noted that heel heights were assessed in this study, and the stability shoes and clogs had higher heel heights than the “flexible” shoes. Thus, one possible limitation in this study is that the different heel heights across the shoes may have acted as a confounder of joint loading independent from the effects of flexibility. However, we recently compared peak knee loads during gait in a Puma flat walking shoe versus the same shoe with a modified sole to increase shoe flexibility, and found that the modifications alone conferred significantly ($p<0.05$) lower joint loads at the knee-suggesting that when heel heights are equal, flexibility of footwear independently affects joint loading(41).

Other limitations to this study deserve consideration. First, this study only evaluated the short-term variations in joint loads with different types of footwear, and did not assess prolonged use of the footwear. It is possible that subjects walked differently in shoes, or with more caution, in those to which they were not accustomed and this could have had an effect on the results. Second, although load reduction presumably has clinical benefits in OA, the magnitude of any long term symptomatic palliation or delay in structural disease progression provided by these shoes will need to be determined in a prospective study.

Finally, additional considerations beside knee loading need to be factored in to any clinical recommendations based on this study; for example, in elderly or infirm individuals, flip-flops may be unsafe and may contribute to falls due to their loose fitting design. Also balancing foot mechanics and associated podiatric problems along with knee joint mechanics need to be taken into account and thus, recommendations for a particular shoe need to be personalized.

In summary, we report that flat, flexible footwear are associated with significant reductions in dynamic knee loads during ambulation, compared to supportive, stable shoes with less flexible soles. In light of the pathophysiological role of mechanical loading in the progression of knee OA, these findings suggest that footwear may have a substantial impact on the overall disease process in knee OA and may represent a novel therapeutic target for the treatment of knee OA. The types of shoes worn by patients with knee OA should be evaluated more closely in terms of their contribution to the disease, and long-term intervention trials to evaluate the clinical effects of shoe design on pain and disease progression in OA should be considered.

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Figure 1.
The clog (Dansko®)

Figure 2.
The stability shoe (Brookes®)

Figure 3.
The flat walking shoe (Puma®)

Figure 4.
Flip flops

Table 1

Peak joint moments during walking.

	Barefoot	Clog	Stability shoe	Flat walking shoe	Flip-flop
Knee adduction	2.7±0.7[bc]	3.1± 0.7[ade]	3.0± 0.7[ade]	2.8± 0.7[bc]	2.7± 0.8[bc]
Knee flexion	1.2± 1.0	1.3± 1.0	1.3± 1.1	1.4± 1.1	1.2± 1.2
Hip adduction	3.0± 1.2	3.2± 1.0	3.2± 1.2	3.2± 1.1	3.0± 1.1
Hip flexion	6.1± 2.0[b]	5.2± 1.3[ade]	5.7± 1.5[e]	6.0± 1.7[be]	6.8± 1.6[bcde]
Ankle dorsiflexion	8.5±0.8[bc]	8.0±1.1[acde]	9.0±1.1[abe]	8.7±0.9[b]	8.5±0.9[bc]
Ankle inversion	1.8±0.6[b]	1.6±0.5[ace]	1.8±0.6[b]	1.7±0.5	1.9±0.5[bd]
Ground Reaction Force (%BW)	103± 10[be]	108±8[a]	106±9	106±8	108±9[a]

All values are reported as mean (standard deviation). Peak moment values are %BW*ht.

$p<0.05$ with following pair-wise comparisons:

[a] compared to barefoot walking

[b] compared to clogs

[c] compared to stability shoes

[d] compared to flat walking shoe

[e] compared to flip flops

Table 2

Gait parameters during walking.

	Barefoot	Clog	Stability shoe	Flat walking shoe	Flip-Flop
Speed (meters/second)	1.10± 0.17	1.08± 0.17	1.12± 0.18	1.12± 0.17	1.10± 0.17
Stride (meters/height)	0.71± 0.07^{bcd}	0.75± 0.06^{a}	0.77± 0.07^{ae}	0.75± 0.06	0.73± 0.07
Cadence (steps/minute)	110± 12^{bc}	105± 9^{ae}	105± 10^{ae}	108± 9	109± 10^{bc}
Knee ROM (degrees)	58± 6^{cde}	58± 6^{cde}	63± 6^{ab}	65± 6^{abe}	62± 6^{abd}
Hip ROM (degrees)	26± 7	27± 6	28± 6	27± 5	27± 6
Ankle ROM (degrees)	27± 6^{bcd}	23± 4 ^{acde}	30± 4 ^{abe}	30± 5^{abe}	27± 6^{bcd}

All values are reported as mean (standard deviation); ROM: range of motion

$p<0.05$ with following pair-wise comparisons:

[a] compared to barefoot walking

[b] compared to clogs

[c] compared to stability shoes

[d] compared to flat walking shoe

[e] compared to flip flops