Effect of Footwear Type on Biomechanical Risk Factors for Knee Osteoarthritis

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Background: Regular walking in different types of footwear may increase the mediolateral shear force, knee adduction moment, or vertical ground-reaction forces that could increase the risk of early development of knee osteoarthritis (OA).

Purpose: To compare kinematic and kinetic parameters that could affect the development of knee OA in 3 footwear conditions.

Study Design: Controlled laboratory study.

Methods: A total of 40 asymptomatic participants performed walking trials in the laboratory at self-selected walking speeds under barefoot (BF), minimalistic (MF), and neutral (NF) footwear conditions. Knee joint parameters were described using discrete point values, and continuous curves were evaluated using statistical parametric mapping. A 3 × 1 repeated-measures analysis of variance was used to determine the main effect of footwear for both discrete and continuous data. To compare differences between footwear conditions, a post hoc paired *t* test was used.

Results: Discrete point analyses showed a significantly greater knee power in NF compared with MF and BF in the weight absorption phase ($P < .001$ for both). Statistical parametric mapping analysis indicated a significantly greater knee angle in the sagittal plane at the end of the propulsive phase in BF compared with NF and MF ($P = .043$). Knee joint moment was significantly greater in the propulsive phase for the sagittal ($P = .038$) and frontal planes ($P = .035$) in BF compared with NF and MF and in the absorption phase in the sagittal plane ($P = .034$) in BF compared with MF and NF. A significant main effect of footwear was found for anteroposterior (propulsion, ↑MF, NF, ↓BF [$P = .008$]; absorption, ↑BF, MF, ↓NF [$P = .001$]), mediolateral (propulsion, ↑MF, NF, ↓BF [$P = .005$]; absorption, ↑NF, MF, ↓BF [$P = .044$]), and vertical (propulsion, ↑NF, BF, ↓MF [$P = .001$]; absorption, ↑MF, BF, ↓NF [$P < .001$]) ground-reaction forces. Knee power showed a significant main effect of footwear (absorption, ↑NF, MF, ↓BF [$P = .015$]; propulsion, ↑MF, NF, ↓BF [$P = .039$]).

Conclusion: Walking in MF without sufficient accommodation affected kinetic and kinematic parameters and could increase the risk of early development of knee OA.

Keywords: walking; footwear; knee; osteoarthritis; minimalistic; barefoot; SPM

Osteoarthritis (OA) is one of the most common diseases that affect knee joint function in the middle-aged Western population.[24] An early stage of OA is manifested by marginal osteophytes, narrowing of the knee joint space, cartilage loss, pain, and functional deficits.[1,2,30,61] The development of OA is influenced by bone marrow lesions, age, physical activity, muscle atrophy, obesity, and the loss of knee cartilage that absorbs mechanical loading.[‖] Andriacchi et al[3] showed that an early stage of knee OA development in healthy people was associated with a change in mechanical loading. Additionally, pathological changes in the knee joint structures were reported to be caused by cyclic loading during walking.[25,47] Previous studies identified various kinematic parameters (a smaller range of motion at the knee, less knee flexion at heel strike, greater femoral anterior displacement relative to the tibia, and greater knee flexion in midstance) and kinetic parameters (greater adduction knee moment, greater mediolateral shear force, and greater knee flexion moment) associated with mechanical loading that increased the probability of early development of knee OA in young people.[4-6,18,38] However, most of these studies were cross-sectional, and thus, cause and effect cannot be determined. Only Lynn et al[38] used a longitudinal design and identified greater knee adduction moment and mediolateral shear force as risk parameters, which could increase the risk of early knee OA development. Even though the development of OA in the knee joint

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[‖] References 4, 14, 15, 19, 20, 36, 43, 44, 66.

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is not caused solely by loading, it has a great impact on OA development.[38]

Regular footwear affects foot function[22] and has an impact on shock absorption during loading[34]; thus, footwear choice may help prevent knee OA. A plethora of literature has been published on the differences between barefoot (BF) walking and use of neutral footwear[57] (NF) during walking.[34,55,58,59,71] Some studies reported that BF conditions resulted in significantly lower values for knee adduction moment, knee extension moment, knee range of motion, peak external knee adduction moment, first peak of vertical ground-reaction force (vGRF), propulsive vGRF, and absorption vGRF.[58,59] However, Keenan et al[34] reported greater knee flexion, propulsive vGRF, and knee flexion moment during the stance phase in BF conditions. All the above-mentioned parameters could increase the risk of early knee OA development.[4-6,18,38]

Even though BF walking is a natural human movement, it is impractical in the modern urban environment and has evolved into walking in closed aesthetic footwear.[33,41,62,63] Hence, footwear companies have started to produce different types of footwear with minimal soles and sufficient space for toe movement using the foot tripod function[8,40] (static "triangle of support," which consists of the center of heel, first metatarsal head, and fifth metatarsal head). This type of footwear is called *minimalistic barefoot technology footwear*.[16] Minimalistic footwear (MF) should theoretically combine the advantages of BF walking (increasing proprioception, balance, and movement control[46] and activating the smaller muscles of the foot and the larger muscles of the ankle joint[45]) with added foot protection and is regarded as an intermediate stage between walking in footwear and BF.[10]

Little attention has been paid to the comparison of BF walking and MF.[65] The gait pattern in MF has been reported to be more similar to that of BF walking.[10,68,69] Only 2 studies have compared walking in MF versus BF.[29,70] One study found a significant effect on kinematic gait parameters (cadence, step length, foot progression angle, and center of pressure length) and kinetic gait parameters (vGRF) between both conditions.[29] The other study reported no significant differences in kinematic knee parameters (angles) and kinetic knee parameters (net joint moments) in any planes between MF and BF, but the investigators suggested that MF might be an optimal compromise for healthy adults, considering the gait symmetry parameters.[70] The results of the abovementioned studies are inconclusive when comparing both conditions to determine the appropriate footwear that reduces the risk factors for knee OA.

The aim of the current study was to assess participants walking in 3 footwear conditions and compare kinematic and kinetic parameters[4-6,18,38] that could increase the risk of early knee OA development. We hypothesized that (1) BF walking would show a significant reduction in selected parameters that could decrease the risk of early knee OA development compared with walking in neutral running footwear, (2) walking in MF would show a significant reduction in parameters that could decrease the risk of early knee OA development compared with walking in neutral running footwear, and (3) walking in MF would have a smaller effect on parameters that could increase the risk of early knee OA development compared with walking BF.

METHODS

Participants

We recruited for this study 40 young adults (20 men and 20 women; age, 28.7 ± 4.86 years; height, 174.27 ± 70.92 cm; mass, 87.80 ± 12.87 kg; body mass index, 23.24 ± 3.16 kg/m^2). Eligibility criteria required individuals to have no previous injury to the lumbar spine or lower extremities. The study protocol was approved by our institutional review board, and all participants were informed about the procedures and provided written consent for participation.

Experimental Setup

Kinematic data were acquired by a motion capture system using infrared cameras (Track Manager; Qualisys). Ten cameras (9 Oqus 700+ cameras and 1 Oqus 510+ camera; Qualisys) located at a height of 2.5 m around the laboratory were synchronized with 3 force plates (Kistler 9286AA, 9281CA, and 9287CCAQ02; Kistler Instruments) embedded in the ground to acquire kinetic data. Two photocells (P-2RB/1; EGMedical) positioned within 2 m between force plates were used to control walking speed. Kinematic and kinetic sampling frequencies were set to 240 and 2160 Hz, respectively.[32]

Experiment Protocol

During the first laboratory visit, participants underwent separate walking trials in 3 footwear conditions: BF, MF, and NF. First, retroreflective markers were bilaterally

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Ethical approval for this study was obtained from the University of Ostrava (No. OU-53107/45-2022).

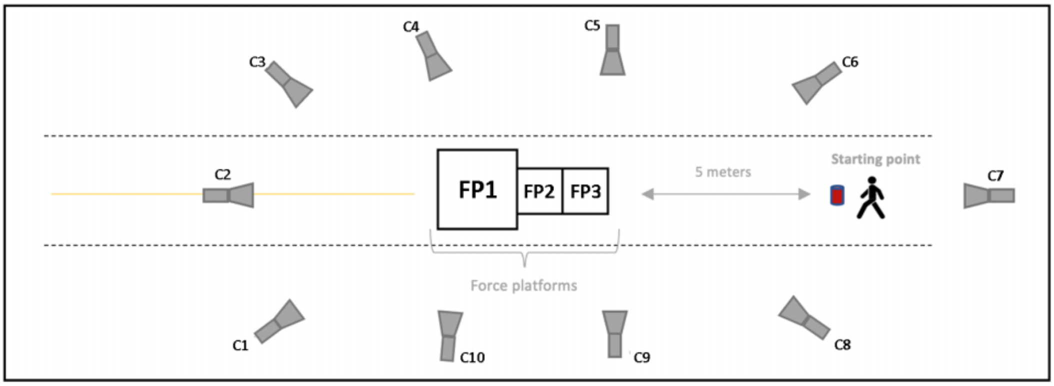

Figure 1. Measurement setup. C, camera; FP, force platform.

attached to participants by means of customized lower extremity and foot models.[39] Next, participants were given 2 minutes for accommodation to particular footwear conditions, such as walking with markers attached. The starting point was marked by a small red cone positioned 5 m before the first force plate. Participants were asked to pay close attention to the yellow line on the ground, which was approximately 5 m from the force plates on the other side of the walkway (Figure 1). Participants were encouraged to walk at a self-selected speed in the range of previously reported regular walking speed of 1.45 m/s (±5%).[35] The walking trial was successful when the participant contacted the first force plate with the right foot at the correct approach speed. A total of 8 successful trials were needed per footwear condition (MF, NF, and BF). The MF (minimalistic index, 96%) used was Primus Knit (Vivobarefoot) and the NF (minimalistic index, 28%) used was Brooks Launch 5 (Brooks Sport). The order of the footwear conditions was randomized by using a research randomizer.[64]

Data Analysis

The raw kinematic and kinetic data were processed with Track Manager and Visual3D software (C-Motion). A fourth-order Butterworth low-pass filter with a cut-off frequency of 40 Hz (kinetics) and 12 Hz (kinematics) was used to filter overground walking trials.[11,23,31,67] The values of dependent variables were determined from the first step of each successful trial for a particular footwear condition. All variables were calculated as a mean of the first (absorption) and the second (propulsion) 50% of the stance phase. Kinematic variables were obtained from 3-dimensional knee angles (sagittal plane: knee flexion; frontal plane: knee adduction; transverse plane: knee internal rotation). Kinetic variables were obtained from 3-dimensional knee net moments and selected loading characteristics (sagittal plane: flexion moment, anteroposterior force; frontal plane: adduction moment, mediolateral force; transverse plane: internal rotation moment, vGRF). In addition, the scalar power from all planes was calculated. All force data were normalized to body mass. All dependent variables curves were normalized into 101 points (0%-100% stance phase) for statistical parametric mapping (SPM) analysis.[48]

Statistical Analysis

The sample size of 36 to 39 participants was estimated using GPower 3.1 software[17] for an alpha level of .05 and a beta level of .95. Sample size calculations were based on differences between the different conditions in the propulsive vGRF phase from discrete data.[34,56] According to Robinson et al,[53] who predicted a large sample size for continuous analysis, 40 participants were included in the present study.

Means and standard deviations were determined to describe the study population characteristics and the kinematic and kinetic parameters. Continuous gait parameters were analyzed in Matlab (MathWorks) using 1-dimensional SPM.[48] All SPM analyses were conducted with a custom-made Matlab script using the open-source software spm1D 0.4 (www.spm1d.org). The comparison of discrete point data (eg, peaks, means, magnitudes) and continuous waveform showed several differences. Discrete point analyses are primarily dependent on prior knowledge, and thus, important information can be lost.[13] This can occur, for example, in a maximum that occurs at a different peak, such as a comparison of the anteroposterior ground-reaction force data, where the maximum peak occurred at a different time.

Several studies[9,12,13,27,54] recommended the use of continuous data to better understand movement patterns. Therefore, we decided to use both discrete and continuous data analysis to show the connection between these 2 approaches in data interpretation. The main effects of footwear were analyzed by repeated-measures analysis of variance (ANOVA) followed by post hoc paired t tests to compare differences between footwear conditions.[49] For repeated-measures ANOVA and post hoc paired t tests, the critical threshold for statistical significance in the initial analysis was set at $P = .05$. The means of the first 50% and second 50% of the stance phase were determined as propulsion and absorption phases, respectively. These discrete data were screened for normality by the Shapiro-Wilk test. Normally distributed data were analyzed by the parametric t test. Non-normally distributed data were analyzed by Wilcoxon signed-rank test.

TABLE 1
Discrete Point Values of Absorption and Propulsion Stance Phases[a]

Parameter	Footwear Condition			P Values		
	NF	BF	MF	NF vs BF	BF vs MF	NF vs MF
Anteroposterior force, N						
Absorption phase	16.52 ± 8.25	17.37 ± 7.22	16.61 ± 9.14	.260	.292	.875
Propulsion phase	18.14 ± 12.51	18.41 ± 11.71	18.10 ± 10.85	.722	.276	.946
Mediolateral force, N						
Absorption phase	68.07 ± 13.29	66.69 ± 13.28	66.46 ± 13.82	.287	.823	.065
Propulsion phase	–81.21 ± 15.30	–84.65 ± 14.67	–82.62 ± 14.66	**.001**	.070	.102
Vertical ground-reaction force, N						
Absorption phase	594.33 ± 100.21	595.24 ± 102.65	600.47 ± 103.42	.717	**.037**	**<.001**
Propulsion phase	568.61 ± 110.24	587.01 ± 111.54	573.91 ± 108.11	**<.001**	**<.001**	.056
Flexion angle, deg						
Absorption phase	–13.44 ± 5.03	–12.60 ± 4.93	–12.21 ± 5.23	**.001**	.121	**<.001**
Propulsion phase	–13.19 ± 3.82	–14.83 ± 3.74	–13.00 ± 3.63	**<.001**	**<.001**	.365
Adduction angle, deg						
Absorption phase	1.24 ± 3.09	1.27 ± 2.95	1.17 ± 3.06	.856	.472	.733
Propulsion phase	0.79 ± 3.10	0.84 ± 3.23	0.89 ± 3.23	.768	.715	.586
Internal rotation angle						
Absorption phase	–3.96 ± 4.03	–3.95 ± 4.58	–4.59 ± 4.67	.973	**.041**	.124
Propulsion phase	–1.66 ± 4.29	–1.52 ± 4.26	–2.59 ± 4.52	.698	**.002**	**.035**
Flexion moment, Nm/kg						
Absorption phase	0.08 ± 0.14	0.05 ± 0.14	0.08 ± 0.14	**<.001**	**.001**	.250
Propulsion phase	–0.21 ± 0.11	–0.22 ± 0.10	–0.19 ± 0.10	.439	**<.001**	**.001**
Adduction moment, Nm/kg						
Absorption phase	–0.19 ± 0.10	–0.20 ± 0.12	–0.20 ± 0.11	.476	.607	.444
Propulsion phase	–0.20 ± 0.10	–0.19 ± 0.11	–0.18 ± 0.11	.175	.441	.075
Internal rotation moment, Nm/kg						
Absorption phase	0.03 ± 0.02	0.04 ± 0.02	0.04 ± 0.03	**.018**	**.011**	**.010**
Propulsion phase	–0.08 ± 0.03	–0.09 ± 0.03	–0.09 ± 0.03	**<.001**	.153	**<.001**
Power, J						
Absorption phase	4.53 ± 6.24	0.59 ± 6.11	1.01 ± 5.50	**<.001**	.624	**<.001**
Propulsion phase	0.45 ± 12.70	1.62 ± 14.00	1.68 ± 13.78	.213	.934	.203

[a] Data are displayed as group mean ± SD. Boldface P values indicate statistically significant difference between groups ($P < .05$). BF, barefoot; MF, minimalistic footwear; NF, neutral running footwear.

RESULTS

The first set of analyses examined the effect of footwear. Discrete point values showed significant differences in knee power in the absorption phase ($P = .006$) (Table 1). The NF condition showed significantly greater values in the absorption phase in knee power compared with the BF condition. The post hoc analysis of knee power showed significant differences between NF and BF conditions (NF, 4.53 ± 6.24 J; BF, 0.59 ± 6.11 J; $P < .001$) and between NF and MF conditions (NF, 4.53 ± 6.24 J; MF, 1.01 ± 5.50 J; $P < .001$) in the absorption phase.

The post hoc t test revealed significant differences in knee flexion angle between NF and BF conditions in the absorption phase (NF, –13.44° ± 5.03°; BF, –12.60° ± 4.93°; $P = .001$). The propulsion phase in equal conditions showed significant differences in knee flexion angle (NF, –13.19° ± 3.82°; BF, –14.83° ± 3.74°; $P < .001$). Analysis of BF and MF conditions showed significant differences in absorption knee internal rotation angle (BF, –3.95° ± 4.58°; MF, –4.59° ± 4.67°; $P = .041$), propulsion knee flexion angle (BF, –14.83° ± 3.74°; MF, –13.00° ± 3.63°; $P < .001$), and propulsion knee internal rotation angle (BF, –1.52° ± 4.26°; MF, –2.59° ± 4.52°; $P = .002$). The comparison between NF and MF conditions showed significant differences in knee flexion angle (NF, –13.44° ± 5.03°; MF, –12.21° ± 5.23°; $P < .001$) in the absorption phase. The propulsion stance phase between NF and MF conditions showed significance in knee internal rotation angle (NF, –1.66° ± 4.29°; MF, –2.59° ± 4.52°; $P = .035$).

Kinetic variables showed significant post hoc differences between NF and BF conditions in the absorption phase in knee flexion moment (NF, 0.08 ± 0.14 Nm/kg; BF, 0.05 ± 0.14 Nm/kg; $P < .001$) and knee internal rotation moment (NF, 0.03 ± 0.02 Nm/kg; BF, 0.04 ± 0.02 Nm/kg; $P = .018$). The propulsion phase in equal conditions showed significant differences in mediolateral force (NF, –81.21 ± 15.30 N; BF, –84.65 ± 14.67 N; $P = .001$), vGRF (NF, 568.61 ± 110.24 N; BF, 587.01 ± 111.54 N; $P < .001$), and knee internal rotation moment (NF, –0.08 ± 0.03 Nm/kg; BF, –0.09 ± 0.03 Nm/kg; $P < .001$). Analysis of BF and MF conditions showed significant differences in absorption vGRF (BF, 595.24 ± 102.65 N; MF, 600.47 ± 103.42 N; $P = .037$), absorption knee flexion moment (BF, 0.05 ± 0.14 Nm/kg;

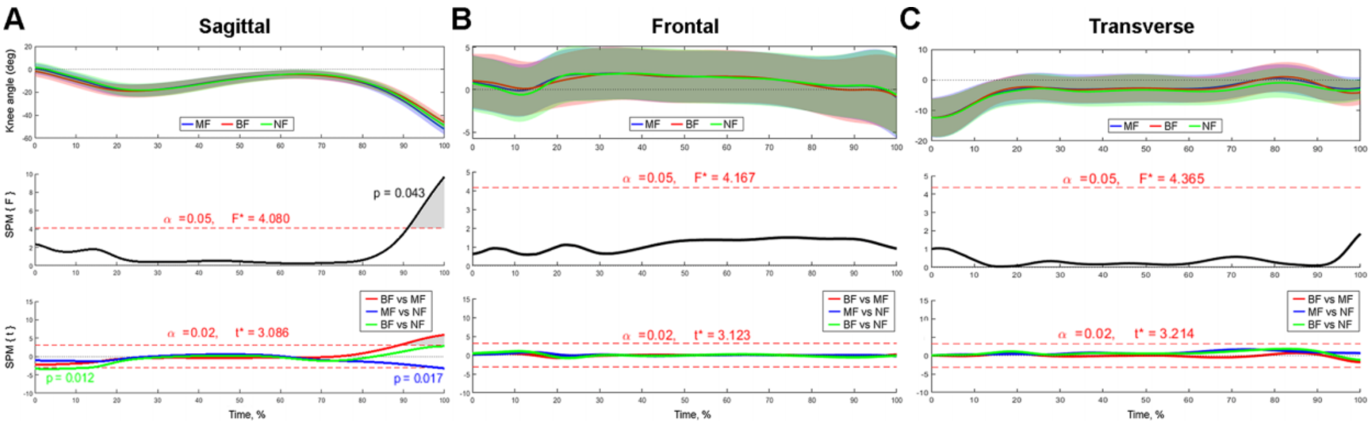

Figure 2. Knee angles during the stance phase in the (A) sagittal plane, (B) frontal plane, and (C) transverse plane. For each plane, curves in the top part show the mean and standard deviation of the stance phase for all 3 footwear conditions, curves in the middle part show the main effect of all 3 footwear conditions (SPM{*F*}), and curves in the lower part show the results of the post hoc *t* test between 2 of the 3 conditions separately (SPM{*t*}). The critical threshold was set to $\alpha \leq .05$ (dashed red line). BF, barefoot; MF, minimalistic footwear; NF, neutral running footwear; SPM, statistical parameter mapping.

MF, 0.08 ± 0.14 Nm/kg; $P = .001$), absorption knee internal rotation moment (BF, 0.04 ± 0.02 Nm/kg; MF, 0.04 ± 0.03 Nm/kg; $P = .011$), propulsion vGRF (BF, 587.01 ± 111.54 N; MF, 573.91 ± 108.11 N; $P < .001$), and propulsion knee flexion moment (BF, –0.22 ± 0.10 Nm/kg; MF, –0.19 ± 0.10 Nm/kg; $P < .001$). Comparison between NF and MF conditions showed significant differences in vGRF (NF, 594.33 ± 100.21 N; MF, 600.47 ± 103.42 N; $P < .001$) and knee internal rotation moment (NF, 0.03 ± 0.02 Nm/kg; MF, 0.04 ± 0.03 Nm/kg; $P = .010$) at the absorption phase. The propulsion stance phase between NF and MF conditions showed significance in knee flexion moment (NF, –0.21 ± 0.11 Nm/kg; MF, –0.19 ± 0.10 Nm/kg; $P = .001$) and knee internal rotation moment (NF, –0.08 ± 0.03 Nm/kg; MF, –0.09 ± 0.03 Nm/kg; $P < .001$).

Figure 2 presents an SPM analysis of knee kinematics in the stance phase with repeated-measures ANOVA. At the end of the stance phase, the BF condition showed significantly greater values of knee angle in the sagittal plane compared with the other conditions (SPM{*F*} in Figure 2A). No other differences were appreciated as a function of the stance phase.

Knee moments are presented as a main effect of footwear and post hoc analyses in Figure 3. This analysis revealed significant differences in the main effect of footwear in both the absorption and propulsion phases in the sagittal plane (SPM{*F*} in Figure 3A) and the propulsion phase in the frontal plane (SPM{*F*} in Figure 3B). At the end of the stance phase, the BF condition showed the greatest values of knee moment in the sagittal and frontal planes (SPM{*t*} in Figure 3, A and B). The absorption phase in knee moment during the stance phase showed the lowest values in the MF condition in the first peak, and the next phase of the BF condition showed the greatest value in the sagittal plane (SPM{*t*} in Figure 3A). No other differences were appreciated as a function of the stance phase in the transverse plane.

Results for ground-reaction force (SPM{*F*} in Figure 4) showed significant differences in the main effect of footwear during the stance phase in all 3 planes in the absorption and propulsion phases. The lowest value of anteroposterior forces was detected in the NF condition in the absorption stance phase and in the BF condition at the end of the stance phase (SPM{*t*} in Figure 4A). In the absorption phase, the NF condition showed the lowest value in mediolateral force; however, the differences were caused due to the time shift of the first minimum of ground-reaction force. At the end of the propulsion phase, the BF condition showed the lowest mediolateral force (SPM{*t*} in Figure 4B). The vGRF showed the lowest value in the NF condition in the initial contact of the stance phase. Propulsion vGRF showed the lowest value in the MF condition (SPM{*t*} in Figure 4C).

The last set of analyses of knee joint power showed significant differences in absorption and propulsion phases in the main effect of footwear (SPM{*F*} in Figure 5). In the absorption stance phase, the MF condition showed the greatest value of knee power generation in the first peak. The BF condition showed a greater value of knee power absorption in the first peak in the absorption phase. At the end of the stance phase, the BF condition showed the greatest value of knee power absorption (SPM{*t*} in Figure 5).

DISCUSSION

The purpose of this study was to compare kinematic and kinetic risk factors that could increase the risk of early knee OA development when walking in 3 different footwear conditions. Discrete point analyses showed a significantly greater knee power in the NF condition compared with the MF ($P < .001$) and BF ($P < .001$) conditions in the absorption phase. The SPM analysis showed a significantly greater knee angle in the sagittal plane at the end of the propulsive phase in the BF condition compared with the NF and MF conditions ($P = .043$). The knee joint moment was significantly greater in the propulsive phase for the sagittal ($P = .038$) and frontal ($P = .035$) planes in the BF condition compared with the NF and MF conditions and in the

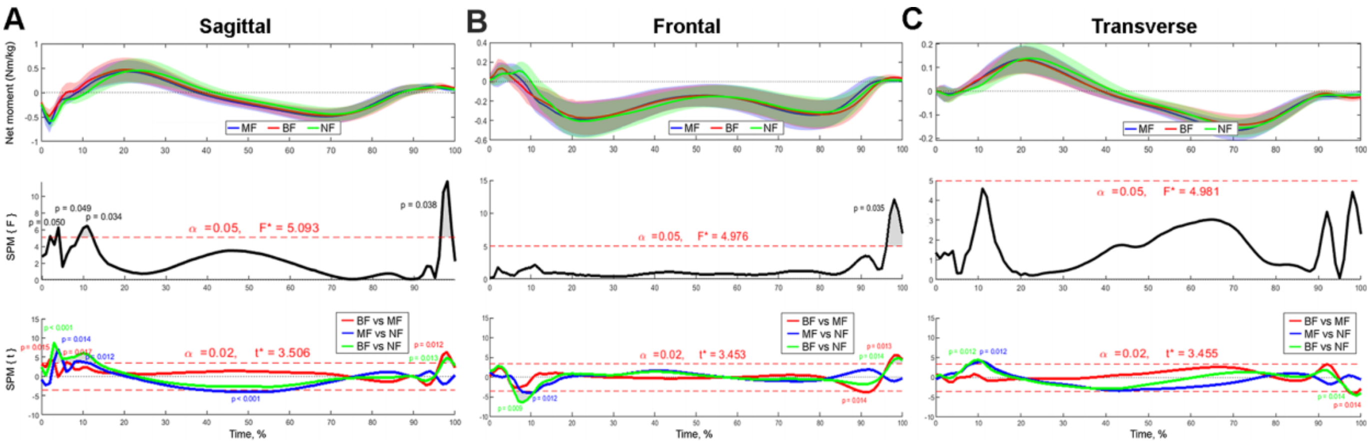

Figure 3. Knee moment during the stance phase in the (A) sagittal plane, (B) frontal plane, and (C) transverse plane. For each plane, curves in the top part show the mean and standard deviation of the stance phase for all 3 footwear conditions, curves in the middle part show the main effect of all 3 footwear conditions (SPM{*F*}), and curves in the lower part show the results of the post hoc *t* test between 2 of the 3 conditions separately (SPM{*t*}). The critical threshold was set to $\alpha \leq .05$ (dashed red line). BF, barefoot; MF, minimalistic footwear; NF, neutral running footwear; SPM, statistical parameter mapping.

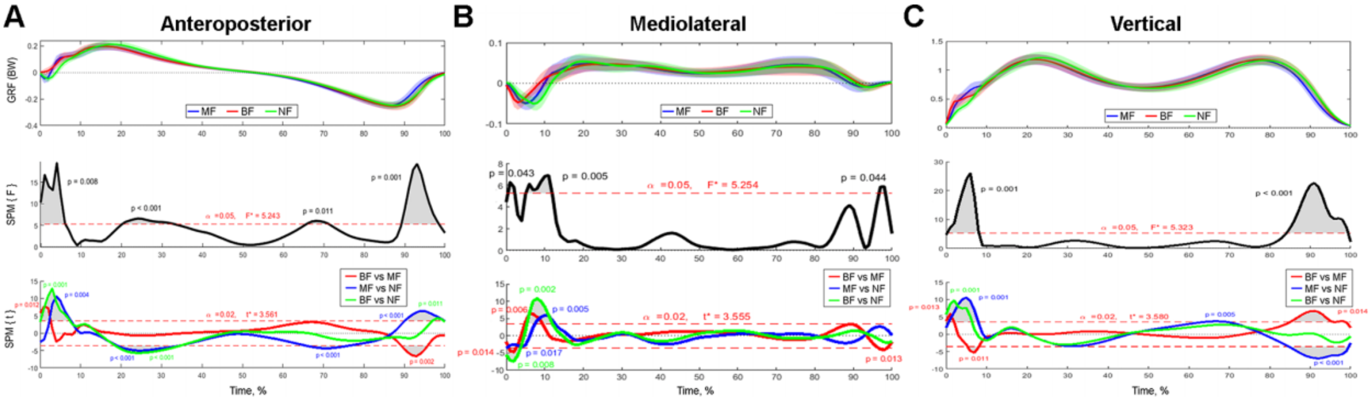

Figure 4. (A) Anteroposterior, (B) mediolateral, and (C) vertical ground-reaction forces. For each ground-reaction force, curves in the top part show the mean and standard deviation of the stance phase for all 3 footwear conditions, curves in the middle part show the main effect of all 3 footwear conditions (SPM{*F*}), and curves in the lower part show the results of the post hoc *t* test between 2 of the 3 conditions separately (SPM{*t*}). The critical threshold was set to $\alpha \leq .05$ (dashed red line). BF, barefoot; MF, minimalistic footwear; NF, neutral running footwear; SPM, statistical parameter mapping.

absorption phase in the sagittal plane ($P = .034$) in BF compared with MF and NF. Additionally, a significant main effect of footwear was found in anteroposterior (propulsion, $P = .008$; absorption, $P = .001$), mediolateral (propulsion, $P = .005$; absorption, $P = .044$), and vertical (propulsion, $P = .001$; absorption, $P < .001$) ground-reaction force. Knee power showed a significant main effect of footwear (absorption, $P = .015$; propulsion $P = .039$).

The first study hypothesis was that BF walking would show a significant reduction in ground-reaction forces, knee joint moments, and angles that could decrease the risk of early knee OA development compared with walking in neutral running footwear. This hypothesis was not supported by the discrete point analyses, where we found greater mediolateral shear force in the BF condition in the propulsion phase. Our results are in line with those of Lynn et al,[38] who found a strong correlation between the development of medial knee OA and greater knee mediolateral shear force and knee adduction moment force, which could increase the risk of early knee OA development (visit one after 5 years [$r = -0.834$, $p < 0.01$; visit two after 11 years $r = -0.763$, $p < 0.01$]. If the authors remove the two subject due to the knee OA, the correlations were weakened but were still significant [visit 1, $r = -0.790$, $p < 0.01$; visit 2, $r = -0.673$, $p < 0.01$]).

Second, we hypothesized that walking in MF would show a significant reduction in ground-reaction forces, knee joint moments, and angles that could decrease the risk of early knee OA development compared with walking in neutral running footwear. The knee adduction moment and mediolateral shear force did not show significant differences between MF and NF. From this perspective, we do not consider the second hypothesis to be supported.

Third, we hypothesized that walking in MF would have a smaller effect on reducing parameters that could increase

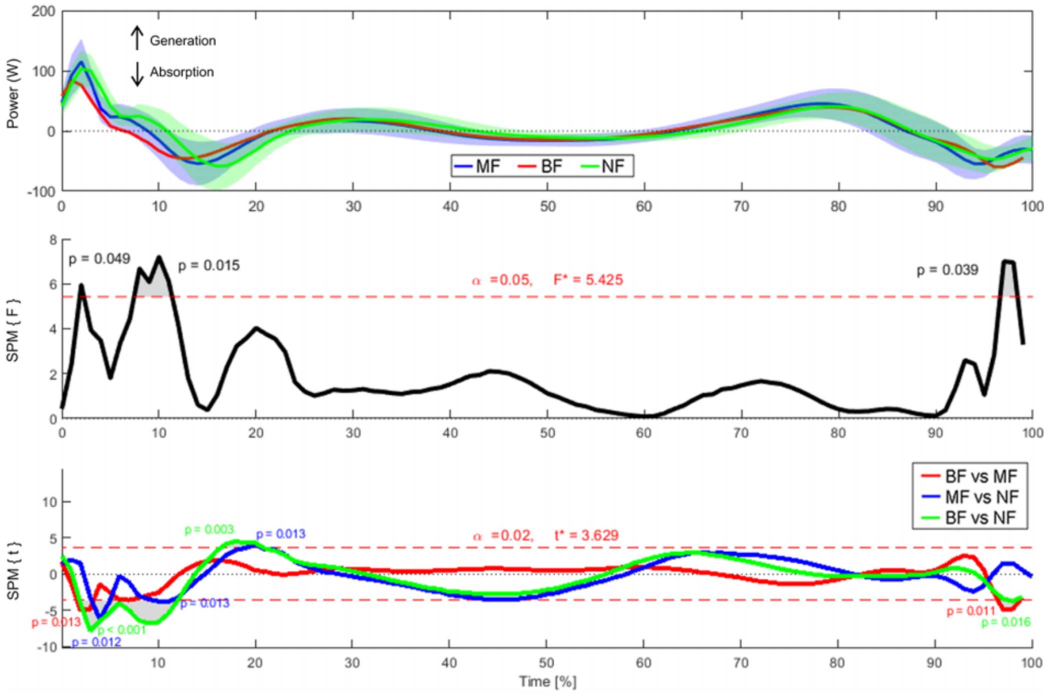

Figure 5. Knee power during the stance phase. Curves in the top part show the mean and standard deviation of the stance phase for all 3 footwear conditions, curves in the middle part show the main effect of all 3 footwear conditions (SPM{*F*}), and curves in the lower part show the results of the post hoc *t* test between 2 of the 3 conditions separately (SPM{*t*}). The critical threshold was set to $\alpha \leq .05$ (dashed red line). BF, barefoot; MF, minimalistic footwear; NF, neutral running footwear; SPM, statistical parameter mapping.

the risk of early OA development compared with walking BF. Discrete point values of walking in MF did not show significant differences in knee adduction moment and mediolateral shear force. MF showed significantly greater vGRF, knee internal rotation angle, knee flexion moment, and knee internal rotation moment in the absorption phase compared with BF. In contrast, during the propulsion phase, MF showed significantly lower vGRF, knee flexion angle, knee flexion moment, and greater knee internal rotation angle. According to these results, the third hypothesis was not supported.

The results from the discrete point analysis of BF versus NF were not supported by SPM analyses and indicated our first hypothesis was not confirmed. SPM analyses showed significantly lower knee adduction moment, lower anteroposterior force, and lower knee flexion moment in the absorption phase during BF walking. The propulsion phase showed significantly greater knee adduction moment and greater anteroposterior force during BF walking, which could potentially increase the risk of early knee OA development. Surprisingly, results showed no significant differences in ground-reaction forces in discrete point values, whereas the continuous data showed significantly greater values in all 3 planes in the absorption phase during BF walking, indicating that continuous data can discern more specific changes than discrete point values.[51] These results contradict the results of previous studies reporting lower values in propulsive vGRF[55,71] and absorption vGRF[34,55] in BF walking. However, our findings are consistent with those of Shakoor and Block,[58] who found significantly lower peak dynamic joint moments in BF conditions, and those of Keenan et al,[34] who showed greater propulsive vGRF and knee flexion moment in BF conditions versus NF. A possible explanation for these results may be that the participants did not have a sufficient accommodation phase for the altered walking (BF) conditions. Thus, during the measurements, they used the same gait pattern as when walking in NF, providing additional shock absorption through the insole and midsole.[21]

The results of discrete point analysis, which did not support our second hypothesis assessing MF versus NF, were analyzed by SPM. These results revealed significant differences in the first 15% of the absorption phase in greater vGRF, greater knee internal rotation moment, lower knee anteroposterior force, and lower knee mediolateral knee force in MF. In contradiction to the discrete point analysis, the results of the SPM analyses supported our second hypothesis. Previous cross-sectional studies also found that vGRF and internal rotation moment were important factors that could increase the risk of knee OA.[4-6,18,38] In contrast, the results of SPM analyses did not show significant differences in knee flexion angle in the absorption phase but showed a lower range of motion in knee flexion angle in the propulsive phase in MF. These parameters are also considered a potential factor associated with the development of knee OA. These results are consistent with the results of a recent study[26] that reported greater vGRF in MF compared with NF. The investigators in that study suggested that footwear companies should use caution in promoting the advantages of MF.[26] The human walking gait consists of cyclic loading phases, which could increase the possibility of a negative impact on knee joint loading due to the absence of a midsole, particularly with the lack of experience in novel users of MF.[22] Together, these results indicate that an acute transition to MF is not sufficient to avoid the changes in kinematic and kinetic parameters that potentially decrease the risk of early knee OA development resulting from walking in NF.

Our discrete point analysis showed significantly greater values of vGRF, knee internal rotation angle, knee flexion moment, and knee internal rotation moment during the absorption phase in MF compared with BF walking, which could increase the risk of early knee OA onset.[4-6,18,38] In the propulsion phase, MF showed lower knee flexion angles, higher knee internal rotation angles, lower knee flexion moments, and higher knee internal rotation moments. The SPM *t* test supported the results of the discrete point analysis, showing significantly greater values in the first 15% of the absorption phase in knee vGRF and knee flexion moment in MF. Contrary to the discrete point analysis, the SPM analysis showed a significantly greater value in the first 15% of the mediolateral force in BF walking; however, this difference was caused by a time shift in initial contact in mediolateral forces. Our findings are in line with those of Wallace et al,[65] who showed greater ground-reaction forces in MF compared with BF walking among indigenous subsistence farmers, the Tarahumara of Mexico, who habitually wear minimal sandals, as well as among urban Americans wearing commercially available minimal sandals. Previous studies showed that MF positively affects musculoskeletal structures of the body by strengthening the arch of the foot,[7,28,37,42] enlarging intrinsic foot muscles,[7,42] and improving overall gait stability.[50] However, the results of previous studies[4-6,18,38] indicate that greater vGRF could also increase the risk of early onset of knee OA. Our study results point out that an acute effect of using MF for walking in adults is similar to the effect of walking in NF. Considering the absence of damping features in MF, this may pose a greater risk of knee OA development in the adult population. Therefore, to benefit from lowering risk factors by using MF, people should follow a slow transition by gradually increasing step amounts.[52,60]

Limitations

This study has some limitations, and the results need to be interpreted with caution. First, the cross-sectional design of our study did not allow us to determine a causal relationship between particular footwear and risk factors for knee OA. A longitudinal study focusing not only on biomechanical parameters but also on magnetic resonance imaging of knee cartilage after constant walking loading would better identify the potential risk factors for knee OA in particular footwear conditions. Second, the participants in our study did not have sufficient time for familiarization with the footwear, and therefore, our results can be interpreted only as an acute effect. Future studies are needed to help us understand footwear and gait mechanics as risk factors in the development of knee OA.

CONCLUSION

The results of this study showed that ground-reaction forces, knee joint moments, and angles were significantly different in MF compared with NF and BF walking. Walking in MF without sufficient accommodation affects kinetic and kinematic parameters that could potentially increase the risk of early development of knee OA. To decrease the potential risks of greater knee joint loading during MF walking, people should follow a slow transition with gradually increasing step amounts.

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