Effect of Center of Pressure Modulation on Knee Adduction Moment in Medial Compartment Knee Osteoarthritis

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ABSTRACT: The knee adduction moment (KAM) provides a major contribution to the elevated load in the medial compartment of the knee. An abnormally high KAM has been linked with the progression of knee osteoarthritis (OA). Footwear-generated biomechanical manipulations reduce the magnitude of this moment by conveying a more laterally shifted trajectory of the foot's center of pressure (COP), reducing the distance between the ground reaction force and the center of the knee joint, thus lowering the magnitude of the torque. We sought to examine the outcome of a COP shift in a cohort of female patients suffering from medial knee OA. Twenty-two female patients suffering from medial compartment knee OA underwent successive gait analysis testing and direct pedobarographic examination of the COP trajectory with a foot-worn biomechanical device allowing controlled manipulation of the COP. Modulation of the COP coronal trajectory from medial to lateral offset resulted in a significant reduction of the KAM. This trend was demonstrated in subjects with mild-to-moderate OA and in patients suffering from severe stages of the disease. Our results indicate that controlled manipulation of knee coronal kinetics in individuals suffering from medial knee OA can be facilitated by customized COP modification. J Orthop Res 29:1668–1674, 2011

Keywords: center of pressure; footwear-generated biomechanical manipulations; gait analysis; knee adduction moment; knee medial compartment osteoarthritis

The knee is the most prevalent weight-bearing joint prone to the development of osteoarthritis (OA).[1] The medial compartment of the tibiofemoral joint is affected more often than the lateral compartment.[2,3] Various biomechanical factors have been implicated to account for this unequal distribution. Vast evidence suggests that repetitive articular cartilage overloading plays a key role in the development and progression of OA.[4] Loads transferred through the medial compartment are $\sim$2.5 times greater than those transferred through the lateral compartment.[5,6] The relatively high medial loads are due to the line of force during gait acting under the foot's center of pressure (COP) passing medial to the knee joint center.[7] This force generates an adduction moment about the knee proportional to the product of the magnitude of the ground reaction force (GRF) and the orthogonal distance between this force's line of action and the joint center.[8] The knee adduction moment (KAM) tends to adduct the tibiofemoral joint, providing a major contribution to the elevated medial compartment load. An abnormally high KAM is characteristic of gait in subjects with knee OA,[5,9] has been linked with progression of knee OA,[10] and is recognized as a marker of disease severity.[9]

Mundermann et al.[11] examined KAM in patients with knee OA and matched healthy controls. In patients with severe OA, both the first peak (during midstance; MS) and the second peak (during terminal stance; TS) of the KAM were elevated, while in patients early in the course of the disease, the second peak was lower. Thorp et al.[12] reported that in Kellgren–Lawrence (KL) grade II patients, the KAM and the knee adduction angular impulse were both significantly higher in symptomatic than in asymptomatic subjects. Several studies investigated the effect of footwear-generated biomechanical manipulations (e.g., wedge insoles and foot orthoses) to counter the effect of elevated KAM. These interventions are intended to convey a shift of the COP on the foot, thereby altering the orientation of the GRF vector and reducing the distance between the force and the center of the knee, hence reducing KAM.[13] Using computer modeling simulation, Shelburne et al.[14] reported that a 1 mm displacement of the COP can decrease KAM by 2%. In a recent study, an instrumented knee replacement was utilized to examine medial knee joint loading while walking with variable-stiffness shoes.[15] This intervention reduced loading on the medial compartment. Moreover, the reduction in medial compressive force correlated with the external KAM. A beneficial effect of wearing a laterally wedged insole was reported in knee OA patients; medial- and lateral-wedged insoles increased and decreased lateral thrust at the knee during walking, respectively.[16] Kakihana et al.[17] reported a reduction in the KAM with the application of lateral wedged insoles. Similarly, Kerrigan et al.[18] reported that the use of lateral wedged insoles reduced the KAM in patients with KL grades III and IV. On the other hand, Shimada et al.[19] reported that wearing a laterally wedged insole significantly reduced the KAM during gait in patients with KL grades I and II, but not III and IV. However, a methodical examination of the association between the

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exact COP location and the KAM in patients suffering from OA has yet to be performed.

In a previous study,[20] we examined the outcome of COP manipulation on the KAM in healthy subjects, utilizing a novel foot-worn biomechanical device that allows controlled manipulation of the COP location. We found that the KAM magnitude was significantly associated with the coronal orientation of the COP. We devised the current study to examine the effect of COP location on the KAM during gait in woman suffering from medial compartment knee OA. We hypothesized that manipulation by the device via translation of elements in the coronal plane (i.e., from medial to lateral) would result in a shift of the COP trajectory. We further hypothesized that a medial and lateral parasagittal shift of the COP trajectory would result in an increase and decrease of the KAM during the stance phase.

METHODS

Participants

Twenty-two female patients (Table 1) with symptomatic bilateral medial compartment knee OA were recruited from cohorts of patients who were enrolled in a prospective clinical trial at the Department of Orthopedics at Ha'Emek Medical Center in Afula, Israel, investigating the effect of continuous biomechanical training on gait patterns (all data were collected prior to clinical trial initiation). All patients had symptomatic knee OA for $\geq$6 months, fulfilled the ACR criteria for knee OA,[21] had definite radiographic signs of OA in the medial compartment with KL grades from 1 to 4,[22] and had no signs of lateral compartment joint space narrowing. Pain was assessed by means of the WOMAC.[23] Additionally, participants completed the SF-36[24] health survey. Exclusion criteria included any other orthopedic musculoskeletal or neurological pathology, prior knee surgery (excluding arthroscopy), significant co morbidities affecting back, hip or foot, and other major systemic diseases. All patients were able to ambulate independently, without the use of a walking aid.

Subjects were instructed to refrain from using any analgesic medication for a 5-day period prior to gait analysis testing and clinical evaluation. Approval of the Ethics Sub-Committee was obtained, and informed consent was given by all participants. The study was registered in the NIH clinical trial registration system (No. NCT00724139). The purpose and methods of the study were explained to the subjects.

The Biomechanical System

The biomechanical device (APOS System, APOS-Medical and Sports Tech. Ltd., Herzliya, Israel) consists of 2 convex-shaped elements attached to each foot (Fig. 1), 1 located under the hindfoot and the other under the forefoot. The elements are attached using a platform shoe equipped with a specially designed sole that consists of two mounting rails to enable flexible positioning of each element under each region. Each element can be individually calibrated allowing specific manipulations in multiple planes. The devices used in the study were donated by the manufacturer.

Lower Limb Alignment

Knee alignment was measured on double-limb AP radiographs, with subjects standing barefoot with knees in full extension, bearing weight equally on both lower legs. The mechanical axis was formulated by the angle between an axis from the center of the femoral head to the center of the knee femoral intercondylar notch and an axis from the center of the tips of the tibial spines to the ankle talus.[25] Twelve patients had varus alignment and 10 had neutral or mild valgus alignment. Radiographs were assessed by a single trained investigator.

Experimental Protocol

Functional assessment was performed prior to testing by a single physician. Calibration of the biomechanical device was performed by a single trained physiotherapist. First, position of the elements for the "functional neutral sagittal axis" was determined and documented. The functional neutral axis was defined as the position in which the apparatus caused the least valgus or varus torque at the ankle. Medial and lateral axes were then defined as 0.8 cm medial and 1.5 cm lateral deviation of the biomechanical elements from the neutral sagittal axis, respectively (Fig. 2).

Successive testing, each with singular calibration of the apparatus, was conducted in four conditions: foot-worn platform with no elements attached (control condition, Fig. 2A); biomechanical elements placed at neutral axis (Fig. 2B); elements placed at lateral sagittal axis (Fig. 2C); and elements placed at medial sagittal axis (Fig. 2D). Subjects were asked to walk at a self-selected velocity that was then indicated by a metronome to ensure consistent cadence throughout the trial. Six trials of each condition were collected per subject. All conditions were tested in random order on the same day.

Data Acquisition and Processing

3D motion analysis was performed using an 8-camera Vicon motion analysis system (Oxford Metrics Ltd., Oxford, UK) for kinematic data capture. The GRFs were recorded by two AMTI OR6-7-1000 force plates. Kinematic and kinetic data were collected simultaneously while subjects walked over a 10-m walkway. Passive reflective markers were fixed with tape to anatomical landmarks identified by an experienced physician. A standard marker set was used to define joint centers and axes of rotation.[26] A knee alignment device

Table 1. Participant Characteristics ($n = 22$)

Age (years)	Height (cm)	Weight (kg)	Kellgren–Lawrence Grade	SF36 Score	WOMAC Score	Coronal Knee Alignment (°)[a]
61.3 ± 6.1	159.4 ± 9.8	78.3 ± 5.75	2.7 ± 0.92	1838 ± 610	4.8 ± 2.1	2.5 ± 5.4

Values are the mean ± SD.
[a]Positive values corresponded to varus knee alignment.

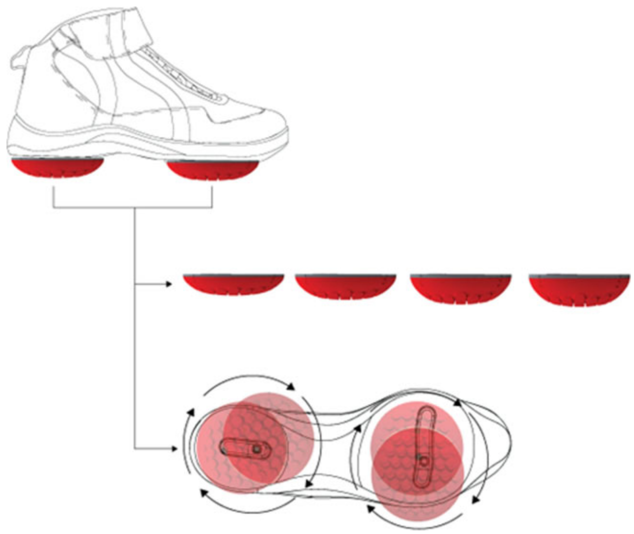

Figure 1. Biomechanical platform and mobile elements.

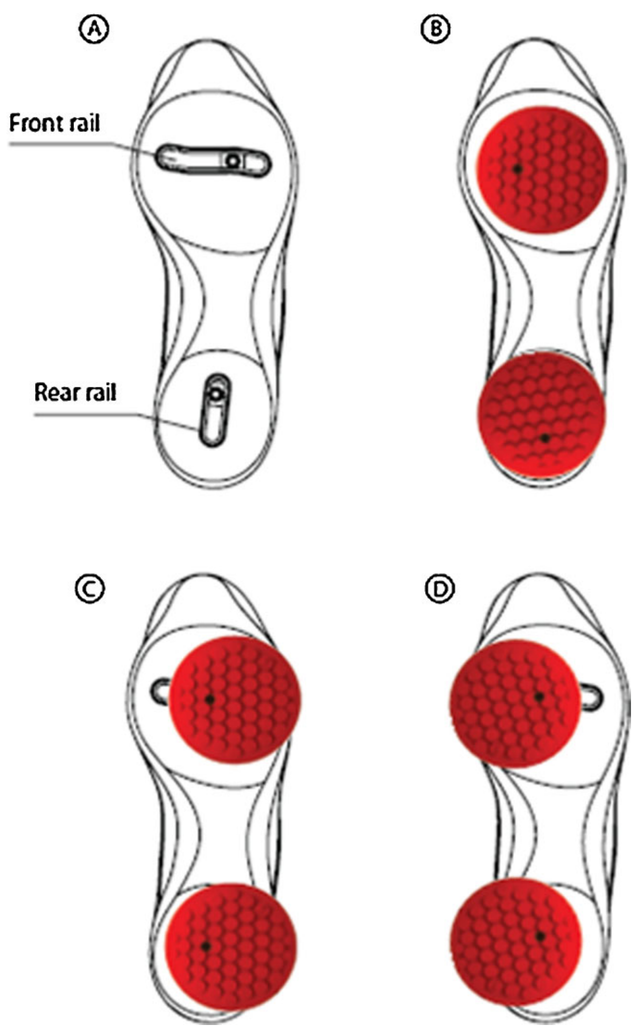

Figure 2. (A) Biomechanical device with no elements attached; (B) at neutral sagittal axis; (C): at lateral sagittal axis; and (D): at medial sagittal axis.

(KAD; Motion Lab Systems Inc, Baton Rouge, LA) was used to estimate the 3D alignment of the flexion axis during the static trial. Knee joint moments in the coronal plane were calculated using inverse dynamic analyses from the kinematic data and force platform measures using "PlugInGait" (Oxford Metrics Ltd., Oxford, UK). All analyses were performed for the more symptomatic knee, as selected by the patient. Joint moments were normalized for body mass and reported in SI units (Nm/kg).

A MATLAB program was used to examine the relationship between the different interventions on the outcome measures. KAM values (1st peak and 2nd peak) and the knee adduction impulse were calculated for each trial, and the average determined across trials for each subject. The Pedar-X Mobile insole pressure-measurement system (Novel Electronics, St. Paul, MN) was used to obtain the COP trajectory in the 4 walking conditions. Time corresponding coordinates of the COP throughout the stance phase were extracted in conjunction with gait analysis. Average values were calculated in association with a specific stage of gait: load response (LR) 0–10%; MS 10–30%; TS 30–50%; and pre-swing (PS) 50–60%. The relative COP offset was assessed by examining the difference in COP–foot axes in respect to the neutral and control configurations. Total COP offset was calculated by averaging the instantaneous values throughout the stance phase. Medial and lateral offsets of the COP were defined as positive and negative values, respectively.

Statistical Analysis

Nonparametric Friedman tests were used for comparison of spatio-temporal (cadence, step length, step width, gait velocity), kinetic (1st and 2nd acceleration peaks and knee adduction impulse) values, and COP offset parameters in the neutral medial–lateral configurations of the apparatus. Wilcoxon signed rank test was used to compare each pair from the three groups. $p < 0.05$ was considered significant. All analyses were performed by an independent biostatistician using SPSS (version 17.0).

RESULTS

Mean values (with SD) of spatial and temporal parameters are listed in Table 2. No significant difference was found for the different walking configurations tested. Figure 3 shows a representative scatter plot analysis of the COP trajectory during stance phase in the neutral, lateral, and medial sagittal axis configurations. Inter-subject analysis for the groups' means and standard deviations of COP displacement with medial and lateral configurations relative to the neutral and control configuration are shown in Table 3 (the average distance was calculated separately for each stance phase stage). COP offset was significantly altered with medial and lateral translation of the biomechanical elements from the neutral axis and from the control setting. Figure 4 shows an example of a time-normalized KAM plot with the neutral, lateral, and medial at sagittal axis configurations. Evidently, the KAM was reduced with the lateral sagittal axis configuration and increased with the medial sagittal axis configuration.

Group values for the knee adduction impulse and 1st and 2nd peaks during stance phase are presented

Table 2. Spatiotemporal Parameters, Group Values ($n = 22$)

Parameters	Control	Neutral Axis	Lateral Axis	Medial Axis	p-Value
Cadence (steps/min)	101.3 ± 7.1	101.9 ± 7.7	101.5 ± 7.5	100.2 ± 6.6	0.558
Step length (m)	0.57 ± 0.05	0.57 ± 0.05	0.58 ± 0.05	0.60 ± 0.04	0.968
Step width (m)	0.14 ± 0.02	0.16 ± 0.03	0.15 ± 0.03	0.13 ± 0.03	0.001
Walking Speed (m/s)	0.96 ± 0.11	0.97 ± 0.12	0.98 ± 0.12	1.01 ± 0.11	0.758

in Figures 5, 6, and 7, respectively. Table 4 lists the mean values and standard deviations of KAM values for the study cohort. Translation of the biomechanical elements from neutral to lateral position and from neutral to medial position significantly decreased and increased, respectively, the KAM 1st and 2nd peak and the knee adduction impulse. On average, translation of the elements from the neutral to the lateral configuration reduced 1st and 2nd peaks by 0.1 and 0.07 mN-m/kg, a reduction of 10% ($p < 0.001$) and 14% ($p < 0.001$), respectively, and reduced the knee adduction impulse by 0.54 N-m/kg/s, a reduction of 14% ($p < 0.001$). Translation of the elements from neutral to medial increased the 1st and 2nd peaks by 0.06 mN-m/kg ($p = 0.001$) and 0.04 mN-m/kg ($p = 0.06$), an increase of 8.4% and 8%, respectively, and increased the knee adduction impulse by 0.41 N-m/kg/sec, an increase of 10.8% ($p = 0.001$). Subgroup analysis of KAM values are presented in Table 5. A similar association between COP location and KAM values was demonstrated for both mild to moderate and severe OA subgroups.

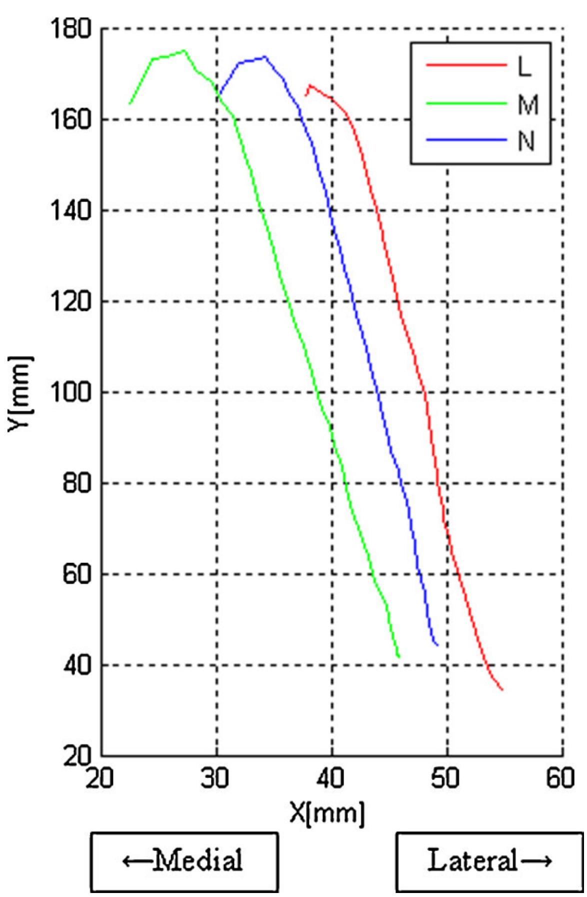

Figure 3. Representative subject's scatter plot of COP at the medial (M), neutral (N), and lateral (L) sagittal axis-configurations. [Color figure can be seen in the online version of this article, available at http://wileyonlinelibrary.com/journal/jor]

DISCUSSION

Our results support the hypothesis of an association between the KAM and the location of the COP trajectory in the coronal plane in patients with medial compartment knee OA. Previous studies that examined the capability of lateral wedged insoles to decrease KAM in this population were inconsistent. In our study, a novel biomechanical apparatus was used, allowing controlled manipulation of the COP. Furthermore, to our knowledge, this is the first study to implement direct examination of the COP trajectory via an in-shoe dynamic pressure measuring system in conjunction with 3D kinetic gait analysis. The study data indicate that the KAM was significantly associated with the coronal orientation of the biomechanical elements; translation of the elements from medial to neutral and from neutral to lateral significantly reduced the magnitude of the 1st and 2nd peaks of the KAM. Shimada et al.[19] tested the outcome of lateral wedge insoles application in knee OA patients with various stages of disease severity, and advocated the use of lateral wedged insoles for early and mild knee OA, but not for severe OA. Subgroup analysis of our study population revealed that the effect on the KAM with translation of the COP from medial to lateral position was more profound for the K/L II subgroups (27% and 23% reduction of the 1st and 2nd peaks, respectively) than for the K/L III–IV subgroups (21% and 15% reduction of the 1st and 2nd peaks, respectively). However, as the number of patients in each sub-group is small, we could not show significant differences. Nevertheless, our results suggest that a favorable effect can be attained, even in progressive stages of the disease.

Previous studies that examined the outcome of footwear-generated manipulations on KAM in healthy and arthritic subjects speculated that these interventions convey a more laterally shifted location of the COP, thus reducing the distance between the GRF and the

Table 3. Comparison of Average COP Coronal Trajectory Offset ($n = 22$)

Device Configurations	Medial Versus Neutral	Lateral Versus Neutral	Medial Versus Control	Lateral Versus Control	P 1–2	P 1–3	P 1–4	P 2–3	P 2–4	P 3–4
Stance phase stage										
Load response	−3.0 ± 2.1	2.9 ± 1.2	−3.8 ± 2.4	2.0 ± 2.0	<0.01	0.99	<0.01	<0.01	0.99	<0.01
Mid stance	−4.2 ± 2.5	4.0 ± 1.9	−5.9 ± 3.0	2.4 ± 2.8	<0.01	0.83	<0.01	<0.01	0.83	<0.01
Terminal stance	−4.6 ± 2.5	5.7 ± 3.1	−4.9 ± 3.4	5.4 ± 4.0	<0.01	0.99	<0.01	<0.01	0.99	<0.01
Terminal contact	−4.9 ± 3.0	4.5 ± 4.1	−3.3 ± 4.1	6.1 ± 5.2	<0.01	0.99	<0.01	<0.01	0.99	<0.01
Stance phase overall	−4.2 ± 2.5	4.3 ± 2.6	−4.5 ± 3.3	4.0 ± 3.5	<0.01	0.99	<0.01	<0.01	0.99	<0.01

All values are reported in mm. Values represent mean (SD) of orthogonal distance between COP locations with medial and lateral configurations in respect to the neutral and control setting. Negative and positive values indicate lateral and medial offset, respectively.

center of the knee joint and thus the moment.[13,17] In our study, successive testing of the COP trajectory and the KAM with different walking conditions was done in the same experimental setting. COP trajectory analysis confirmed this theory and established a clear association between manipulation of the biomechanical elements in the coronal plane, the COP location, and the KAM (Fig. 6).

The magnitude of the terminal stance phase (2nd) peak of the KAM was significantly altered by COP translation. In a previous study conducted with similar methodology in young healthy adults, no significant association could be established between the terminal stance peak of the KAM and COP orientation.[20] With disease development, the second KAM peak increases.[11] Elevated values of this parameter in the current study group may have rendered it more susceptible to influence by COP manipulation.

Our results offer significant clinical implications in subjects with medial compartment OA. Elevated KAM is a key factor contributing to excessive medial compartment loads in this population.[5] Repetitive micro trauma leads to damage to the hyaline cartilage and diminished compliance of the subchondral bone. With disease progression, "pseudo-laxity" occurs, which results from reduced tension in the joint capsule and ligaments, medial compartment narrowing, and proprioceptive decline.[27] Alignment is shifted in a varus direction, exacerbating KAM and disease development. Previous studies confirmed the effectiveness of unloading the diseased articular surface in knee OA patients.[28–31] Our results verify that KAM can be

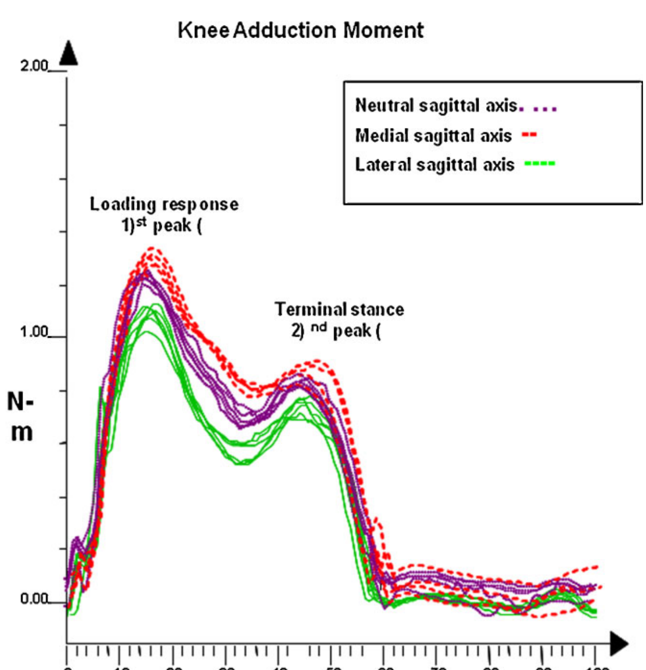

Figure 4. Representative KAM in the neutral, lateral, and medial sagittal axis configurations (multiple drills are presented for each configuration). The Y-axis represents the moment's magnitude (Nm), and the X-axis represents 100% of a single gait cycle. [Color figure can be seen in the online version of this article, available at http://wileyonlinelibrary.com/journal/jor]

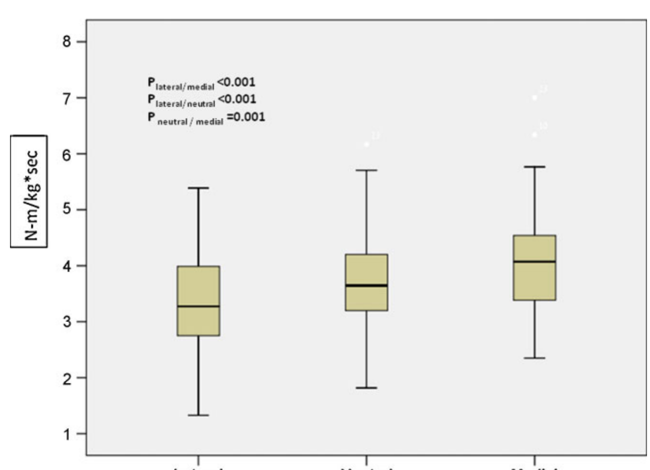

Figure 5. Values of knee adduction impulse with lateral, neutral, and medial translation biomechanical elements. Data presented as box-plots—the line in center of the box represents the median, the box represents the inter-quartile range, and the whiskers represent the range.

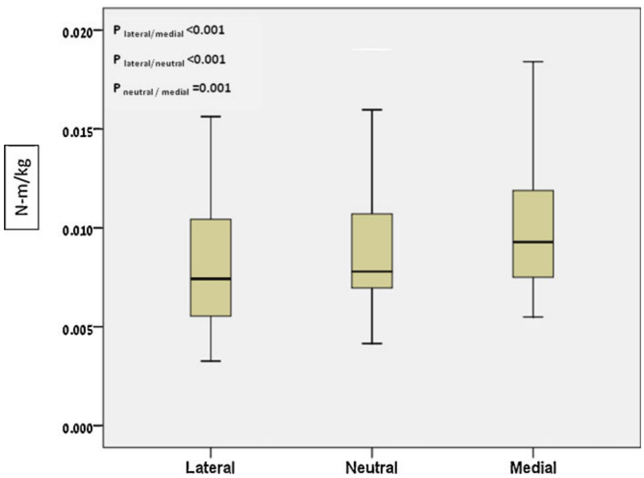

Figure 6. KAM values at loading response peak (1st peak) with lateral, neutral, and medial translation biomechanical elements. Data presented as box-plots—the line in center of the box represents the median, the box represents the inter-quartile range, and the whiskers represent the range.

effectively influenced by foot-generated COP manipulations in various stages of the disease.

Several limitations arising from the current study should be noted. Firstly, testing was performed shortly after the device was first used by the participants; continuous usage may lead to substantial gait adaptations and may change the outcome. An additional limitation was the employment of the apparatus with no elements attached as a control. This setting was chosen to ensure uniformity of the kinematic model (biomechanical elements were attached and modulated without repositioning of the retro reflective markers). With this setting, the flat bottom of the apparatus resembles a normal shoe. However, the sole of the device is more rigid than normal shoes, and this may cause changes in the subjects' gait patterns. To limit this potential bias, the neutral configuration was used as a reference and a secondary control for evaluation of the medial and lateral configurations. Finally, we focused on a unique group (females with medial compartment OA); therefore, our results are applicable only for subjects with characteristics similar to those of the study cohort.

In conclusion, our study indicates that controlled manipulation of knee coronal kinetics in individuals suffering from medial knee OA can be facilitated by customized COP modification. The results confirm the hypothesis that modification of the coronal trajectory of the COP can influence KAM. These findings expand the understanding of lower limb biomechanics in knee OA and have implications in the field of device design and practice. Implementation of these principles in the treatment of patients suffering from knee OA may help to stop disease progression and bring functional improvement. However, further studies are needed to examine the effect of long-term usage of such noninvasive interventions.

Table 4. Comparison of Mean KAM Values ($n = 22$)

Group Values	Loading Response (1st) Peak (N-m/kg)	Terminal Stance (2nd) Peak (N-m/kg)	Knee Adduction Impulse (N-m/kg/s)
Medial	0.77 ± 0.20	0.54 ± 0.16	4.20 ± 1.13
Neutral	0.71 ± 0.23	0.50 ± 0.15	3.79 ± 1.14
Lateral	0.61 ± 0.19	0.43 ± 0.14	3.25 ± 1.12
Control	0.69 ± 0.19	0.49 ± 0.14	3.78 ± 1.17
P-Value	<0.001	<0.001	<0.001

Values represent mean (SD) KAM values with control, neutral, medial, and lateral sagittal axis configurations.

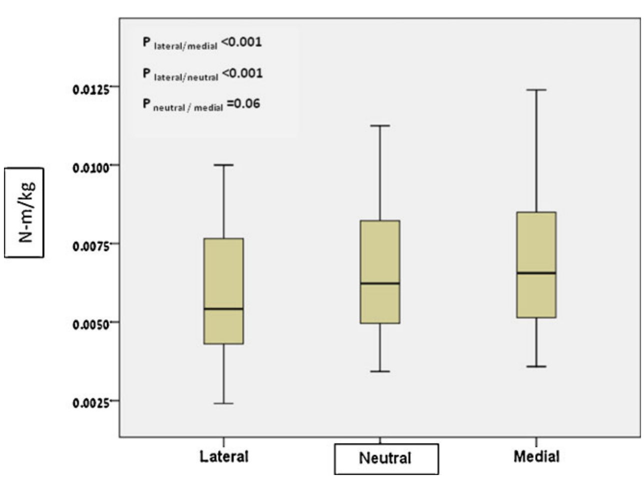

Figure 7. KAM values at terminal stance peak (2nd peak) with lateral, neutral, and medial translation biomechanical elements. Data presented as box-plots—the line in center of the box represents the median, the box represents the inter-quartile range, and the whiskers represent the range.

Table 5. Comparison of Mean KAM Values (Sub-Group Analysis)

	Loading Response (1st) Peak (N-m/kg)	Terminal Stance (2nd) Peak (N-m/kg)	Knee Adduction Impulse (N-m/kg/s)
KL 1–2 sub-group			
Medial	0.73 ± 0.24	0.47 ± 0.13	4.16 ± 1.18
Neutral	0.70 ± 0.29	0.44 ± 0.09	3.52 ± 1.23
Lateral	0.58 ± 0.27	0.36 ± 0.10	3.00 ± 1.18
Control	0.69 ± 0.25	0.44 ± 0.07	3.55 ± 1.19
p-Value	0.002	0.002	0.001
KL 3–4 sub-group			
Medial	0.80 ± 0.18	0.57 ± 0.17	4.24 ± 1.15
Neutral	0.71 ± 0.20	0.54 ± 0.16	3.94 ± 1.10
Lateral	0.63 ± 0.15	0.48 ± 0.15	3.39 ± 1.10
Control	0.69 ± 0.15	0.52 ± 0.16	3.91 ± 1.18
p-Value	0.000	0.002	0.000

Values represent mean (SD).

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