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Original Article

Comparison of gait biomechanics in patients with and without knee osteoarthritis during different phases of gait
比較有和沒有膝關節骨性關節炎的受試者在不同步態階段的步行生物力學

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ABSTRACT

Background: This study aimed to characterise knee adduction angles (KAA) and knee adduction moments (KAM) and compare this with foot centre of pressure (COP) in volunteers with and without knee osteoarthritis (OA).
Methods: A total of 108 participants were recruited; 84 had no known pathology, 18 had medial knee OA, and six had lateral knee OA. Linear regression was used to determine correlations between the normalised COP, KAM, and KAA during each phase of gait for all participants.
Results: The first phase of gait demonstrated significant differences between groups for all measures: KAA in all phases, COP in phases one and two, and KAM in phase one only.
Conclusion: The largest mechanical changes are seen in the first phase of gait in osteoarthritic patients. Although COP is an easy to measure tool, it is not as sensitive as KAA and did not demonstrate a significant difference between healthy and medial OA patients.

中 文 摘 要

背景: 本研究旨在表徵膝關節內收角（KAA）和膝關節內收力矩（KAM），並將其與有和沒有膝關節骨性關節炎（OA）的志願者的腳部壓力中心（COP）進行比較。
方法: 招收108名受試者; 84例未見病理、18例有內側膝關節骨性關節炎、6例有外側膝關節骨性關節炎。 使用線性回歸來確定所有受試者的每個步態階段標準化的COP、KAM和KAA之間的相關性。
結果: 步態的第一階段顯示了不同組別之間在所有測量參數具有顯著差異：所有階段的KAA，第一階段和第二階段的COP和第一階段的KAM。
結論: 膝關節骨性關節炎患者步態第一階段發生最大的機械變化。 雖然COP是一個易於測量的工具，但它並不像KAA那樣敏感，並沒有顯示健康和內側OA患者之間的顯著差異。

Introduction

It has previously been shown that overloading of the cartilage plays an important role in the development of osteoarthritis (OA).[1] The medial knee condyles carry most of the load applied at the knee joint,[2] which can increase further in patients with the medial OA.[3] As such, the medial compartment is more commonly affected compared with the lateral compartment.[4] The development and progression of OA can be attributed, at least in part, to various biomechanical factors leading to these kinematic adaptations during gait.[5] As a result, gait analysis has the potential for disease diagnosis and monitoring as well as treatment and planning of surgeries.[6]

Such biomechanical factors include the knee adduction angle (KAA), which is associated with both progression and development of knee OA,[7] where varus deformity can increase the forces acting on the medial side while valgus deformity can increase the forces on the lateral knee compartment.[7] The external knee adduction moment (KAM), a surrogate measure for the tibio-femoral contact

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force reflecting the load on the knee condyles,[8] has been reported to be higher in patients with medial OA comparedwith controls[9,10] with a high KAM correlating with increased OA severity and OA progression.[11] Yet, to measure KAM, costly motion-capturing equipment is required, and the procedure is time consuming, requiring considerable expertise.

Centre of pressure (COP) can be defined as the centre of all the external forces acting on the plantar surface of the foot. Recent studies have demonstrated a relationship between KAM and COP in medial OA patients during gait. COP has been shown to be laterally shifted in patients with medial knee OA,[12] and by modifying the COP medially a decrease in peak KAM can be achieved by shortening the lever arm for adduction moment.[13,14] Another study found that interventions to adapt COP can lead to reduced pain and increased function at the knee joint.[15] The usefulness of COP in comparison with KAA and KAM in identifying OA patients from healthy patients has not been well defined nor has the relationship of these gait factors within the different phases of gait. By determining an association between COP position, KAM, and KAA during different phases of the gait cycle, it may be possible to determine if COP position can be used as an alternative or in conjunction with peak KAM and KAA, through instrumented footwear or treadmills. This information could be used as a clinical marker to evaluate the success of interventions, thereby avoiding the reliance on expensive and time-consuming motion capturing systems, and to design patient-specific foot orthoses to customise COP modifications to alter knee coronal kinetics during gait.

Therefore, the major aim of this preliminary research was to:

(1). characterise and compare the COP positions, KAA, and peak KAM during barefoot gait between OA patients and healthy patients
(2). determine in which phases of gait osteoarthritic patients show the most measurable mechanical adaptations
(3). determine the usefulness of COP positions in differentiating healthy and OA patients compared with KAA and KAM.

Materials and methods

This study had ethical approval from the South West London Research Ethics Committee with all patients providing written informed consent. A total of 108 participants were recruited and analysed, of which 84 had no known pathology, 18 had medial OA, and six had lateral OA (Table 1). Participants were volunteers who agreed to take part in the advertised study. For healthy patients, results from both left and right legs are included in the data set and for OA patients only the affected legs are included. OA diagnosis was based on clinical and radiographic evidence from the individuals' medical records. Exclusion criteria were predefined as follows: neurological or musculoskeletal conditions other than knee OA, rheumatoid or other systemic inflammatory arthritis, morbid obesity [body mass index (BMI) >35 kg/m^2], or previous surgical treatment for knee OA. All participants completed the Knee Osteoarthritis Outcome Scores (KOOSs) questionnaire.[16] Participant's height, weight, foot length, and foot width were measured. Because of the small numbers, severity of disease was not considered.

Motion Capture Protocol

Twenty reflective markers were positioned on the patient's pelvis and lower limbs and four marker clusters were positioned on the patient's left and right thigh and calf segments.[17] A static trial was initially captured. Two Kistler portable force plates (Kistler Type 9286B, Kistler Instrumente AG, Winterthur, Switzerland) were embedded into a 6-m walkway, and a 10-camera Vicon motion capture system was used (Vicon Motion Systems Ltd, Oxford, UK). Patients were asked to walk at a comfortable speed along the 6-m walkway five times, or until three clean foot strikes had been recorded from each force plate. The results were averaged across three trials for each patient.

Data analysis

The gait cycle was normalised to 100% with respect to time. The stance phase was divided into the following three phases using force plate data: (1) early-stance [initial contact (ground reaction force {GRF} $\geq$ 40N) until the first peak GRF], (2) mid-stance (first peak GRF to second peak GRF), and (3) late-stance [second peak GRF until toe off (GRF $\leq$ 40N)].

Kinematic and kinetic parameters at the ankle, knee, and hip were determined using a custom-made cluster model (ClussBB), as described previously by Duffell et al in 2014.[17] This model uses the Horsman method to define hip joint centres.[18] and knee and ankle joint centres were defined as the central points between medial and lateral femoral epicondyles and malleoli, respectively. Local reference frames were constructed from the bilateral thigh and shank clusters. Transformation between the cluster frames and the anatomical frames for each segment was obtained from the static trial. The clusters were tracked during dynamic trials and the transformations obtained were used to derive the anatomical frames at each instant. Using Euler angles, kinematics were calculated for each joint (in the sequence X–Y–Z). Moments were calculated using dynamics and anthropometric properties.

KAA and KAM were averaged for each phase, KAM was normalised to the patient's bodyweight $\times$ height. COP trajectory in the global frame was transformed to the local frame at the foot (where X and Y axes represented medio-lateral and antero-posterior directions, respectively). The COP trace in X and Y directions was then normalised with respect to the known width and length of each patient's foot, respectively. This was plotted on the footprint and comparisons were made between healthy and OA patients. Linear regression was used to determine correlations between COP and KAM and KAM and KAA for all patients.

Significant differences between group's height, weight, and BMI and significant differences of KAM, KAA, and COP between groups at each stance phase of gait were determined using a one-way analysis of variance. Significant results were analysed with a

Table 1
Demographics of patients analysed in this study.

Number of knees	KOOS pain score	Height (cm)	Weight (kg)	BMI (kg/m^2)	Age (yr)	Male/Female
A—Healthy (n = 168)	95 (8)	170 (10)	68 (12)	23.4 (3)	45 (17)	36/48
B—Medial OA (n = 18)	59 (12)	173 (12)	82 (20)	26.9 (3.8)	57 (12)	11/7
C—Lateral OA (n = 6)	57 (22)	169 (11)	71 (10)	24.8 (2.8)	46 (15)	2/4

Standard deviations are shown in brackets.
BMI = body mass index; KOOS = Knee Osteoarthritis Outcome Score; OA = osteoarthritis.

post-hoc Bonferroni test correcting for the three groups at each gait phase. All statistics were analysed with Statistical Package for Social Sciences 20 (SPSS 20, Chicago, IL, USA), with statistical significance designated as $p < 0.05$.

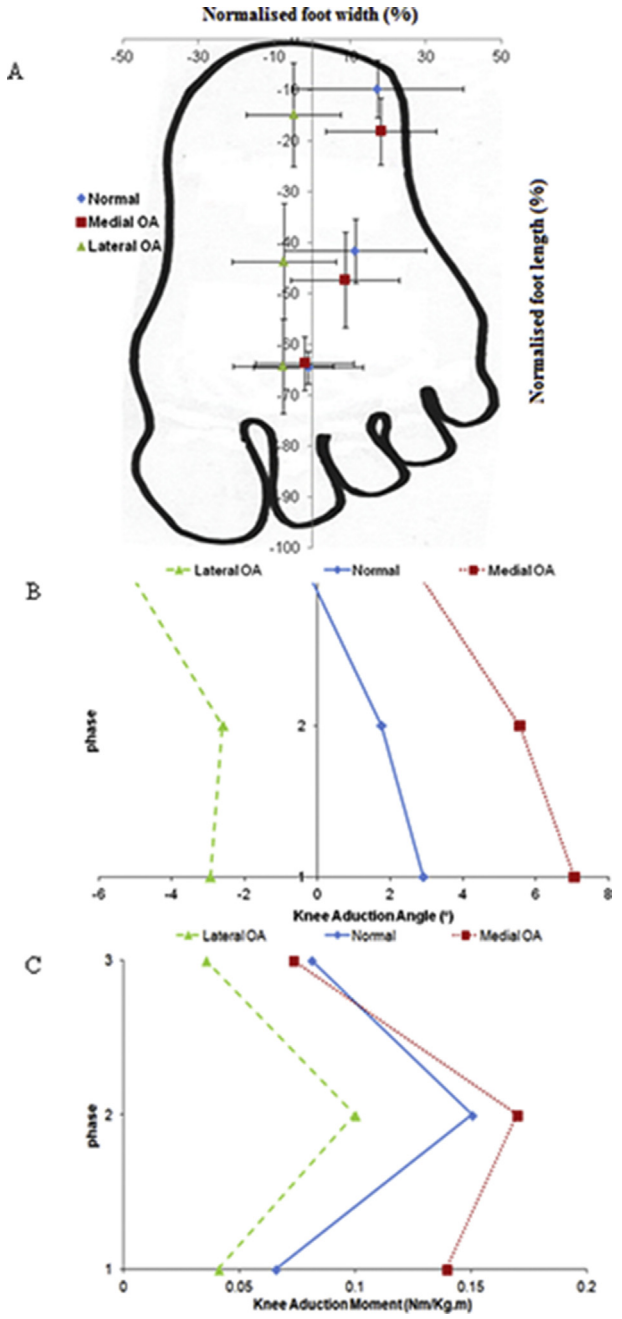

Figure 1. (A) Position of centre of pressure, (B) knee adduction angle, and (C) knee adduction moment for healthy, medial OA, and lateral OA groups during early, mid, and late stance (phases one to three, respectively). OA = osteoarthritis.

Results

Table 1 reports the demographics of the study population. There was no significant difference between group's height, weight, or BMI. All OA patients had unilateral deformity.

The transformed COP is shown in Figure 1A for all participant groups. Healthy patients showed a large variation in COP patterns in the medio-lateral direction [17 (22), 11 (19), and −1 (14) mm for phases one to three, respectively]. In the antero-posterior direction, healthy patients showed less variability in COP positions for all three phases [10 (6), 42 (6), and 65 (3) mm for phases one to three, respectively]. The COP for patients with medial OA was similar to healthy patients [18 (15), 9 (14) and −2 (13) mm for phases one to three, respectively] in the medio-lateral direction. Patients with lateral OA showed a substantial medial shift in their COP toward the centre of the foot for all three phases, comparedwith healthy and medial OA groups [−5 (13), −7 (14), and −8 (10) mm for phases one to three, respectively]. In the antero-posterior direction, the average COP, particularly for the first phase and also the second phase of gait, was shifted anteriorly and was more variable in the medial and lateral OA groups compared with the healthy patients. The medial OA group had a mean COP position of 18 (7), 47 (9), and 64 (9) mm, whereas for the lateral OA group this was 15 (10), 44 (9), and 64 (9) mm. The results from the KAA and KAM, averaged for each phase, are shown in Figure 1B and C and Table 2.

Healthy patients had KAAs that were closest to zero (average of 1.5°), whereas medial OA patients had the largest varus (5.1°) and lateral OA patients had a valgus deformity (−3.5°). The medial OA group also showed the largest adduction moment [average of three phases 0.13 (0.11) Nm/kg m] in comparison with the healthy patients [0.10 (0.09) Nm/kg m] and the lowest was found in patients with lateral OA [0.06 (0.05) Nm/kg m]. No relationship was found between KAM and KAA ($R^2 = 0.15$), nor between COP in the medio-lateral direction and KAM ($R^2 = 0.02$, 0.08, and 0.06 for phases one to three, respectively) for all patients. Large variability was observed between the medial OA groups' KAA and KAM in comparison with that of the healthy patients for most measures, as shown in Table 2.

Significant differences were found between groups for the KAA at all stages of gait, KAM at phase one of gait, and centre of pressure in the medio-lateral direction (COPX) at phases one and two of gait, as shown in Table 3.

A post-hoc Bonferroni analysis for KAA demonstrated that these significant differences were between all groups at the first phase of gait and all groups in the second and third phases except when comparing the medial OA and healthy groups, as shown in Table 4. For KAM, differences were significant when comparing the healthy and medial OA groups only in phase one, as shown in Table 4. For COPX in phases one and two, significant differences were found when comparing all groups except the medial OA and healthy groups.

Discussion

Measuring biomechanical factors in osteoarthritic patients is useful in monitoring disease and evaluating surgical and non-surgical interventions. COP is a simple patient-friendly method of

Table 2
Knee adduction angle (in degrees) and adduction moment (Nm/kg m) for three groups at gait phases one to three.

Groups	KAA1	KAA2	KAA3	KAM1	KAM2	KAM3
A—Healthy	2.9 ± 4	1.8 ± 4	−0.2 ± 4	0.07 ± 0.13	0.15 ± 0.08	0.08 ± 0.08
B—Medial OA	7.1 ± 12	5.6 ± 14	2.8 ± 15	0.14 ± 0.05	0.17 ± 0.19	0.07 ± 0.10
C—Lateral OA	−2.9 ± 6	−2.6 ± 6	−5.1 ± 4	0.04 ± 0.06	0.10 ± 0.07	0.04 ± 0.04

KAA = knee adduction angle; KAM = knee adduction moment; OA = osteoarthritis.

Table 3
p-Values of analysis of variance tests comparing the three groups' knee adduction moment, knee adduction angle, and centre of pressure in the medio-lateral direction at each phase of gait.

	KAA1	KAA2	KAA3	KAM1	KAM2	KAM3	COPX1	COPX2	COPX3
p-Value	0.0005*	0.006*	0.0033*	0.011*	0.237	0.332	0.036*	0.0478*	0.484

COPX = centre of pressure in the medio-lateral direction; KAA = knee adduction angle; KAM = knee adduction moment.
* Indicates significant result.

such evaluation; however, its pattern in comparison with KAA and KAM has not been fully characterised in healthy and OA patients. This preliminary study investigated the pattern of normalised COP position, KAA, and KAM of a large group of healthy patients and compared this with patients with medial and lateral knee OA. We also determined within which phase of gait the greatest mechanical adaptations in OA patients are observed.

The small number of osteoarthritic study participants is a limitation to the study. However, osteoarthritic patients did not demonstrate as much inter-subject variability in comparison with healthy patients, for which a larger number of results enabled good representation of healthy patient gait trends. In addition, anatomical differences such as a shorter or anteverted femoral neck may have contributed to variability, which would affect the loading applied at the knee joint.[19] Further work is therefore needed to correlate COP and KAM with individual patients' bony morphology and knee alignment as well as disease severity.

In this study, the pathological subjects appeared to have COP positions reflecting the KAM acting on the knee joint. The medial shift in COP position for the lateral OA group could represent an increased loading on the pathological side of the knee joint resulting in a lower KAM. It is not possible to determine whether this is secondary to lateral OA or a compensatory response. Medial OA patients had a lateral COP, not significantly different to healthy patients. This opposes the previous study that found COP to be more lateral in patients with medial knee OA compared with controls.[12] This may be an attempt from some OA patients to modify their gait by shifting the COP medially during gait to reduce loading on the medial compartment. This may explain the variability seen in the OA patient's results because of individual OA patients modifying their gait by varying amounts depending on various factors such as severity. This may also explain why correlations between groups COP and KAM and KAA and KAM were weak while individual gait cycle COP measurements have showed strong correlations with KAM in the past.[8]

Table 4
Post-hoc Bonferroni tests comparing knee adduction moment, knee adduction angle, and centre of pressure in the medio-lateral direction at phases of gait which had a significant difference between groups A (healthy), B (medial OA) and C (lateral OA).

	Group 1	Group 2	*p*-Value
KAA1	A	B	0.001*
	A	C	0.008*
	B	C	0.003*
KAA2	A	B	0.0503
	A	C	0.01*
	B	C	0.026*
KAA3	A	B	0.13
	A	C	0.002*
	B	C	0.025*
KAM1	A	B	0.016*
	A	C	0.054
	B	C	0.631
COPX1	A	B	0.484
	A	C	0.018*
	B	C	0.001*
COPX2	A	B	0.824
	A	C	0.017*
	B	C	0.008*

COPX = centre of pressure in the medio-lateral direction; KAA = knee adduction angle; KAM = knee adduction moment; OA = osteoarthritis.
* Indicates significant result.

It has previously been shown that knee malalignment has a substantial influence on the progression of OA.[11] Patients with varus alignment have been shown to have the largest stresses on the medial compartment of the knee compared with patients with healthy knees and patients with valgus alignment.[3] Healthy patients had a positive KAM and a mostly positive KAA, which was higher still in medial OA patients. This may explain why medial knee OA is more common[19] compared with a prevalence of only 10% of lateral OA.[4] In the antero-posterior direction, COP moved from the posterior foot at heel-strike to the anterior foot at toe-off, as expected. Healthy patients showed less variability in the antero-posterior direction with an average standard deviation of 5% for all three phases, compared with the standard deviation in the medio-lateral direction, which was 19%. Compared with healthy patients, the pathological group showed less variability in the medio-lateral direction, but higher variability in the antero-posterior direction. This indicates that patients with pathological knees may have larger trunk tilt during the gait cycle, possibly with a slower gait speed causing less variation in the medio-lateral direction. Although trunk lean over the stance limb during gait has been linked to a reduction in the KAM,[20] a study comparing OA patients and healthy patients found increased trunk lean in the OA group only detectable by principal component analysis.[21] As gait speed and trunk lean were not quantified in this study, further work needs to be performed to assess its effect on gait measures.

When comparing the data of OA patients with healthy controls, the largest differences were observed in phase one. All three biomechanical measures showed significant differences between groups in this first phase of gait, whereas only COP position and KAA showed differences in phase two and only KAA showed a significant difference in phase three. In the first phase, patients with medial OA had a laterally positioned COP, similar to healthy patients, whereas lateral OA patients had a COP located slightly medial to the midline of the foot. This was also the only phase that significant differences in KAM were noted between normal and medial OA groups. In addition, KAA showed a significant difference between all three groups during phase one. Early stance is where patients tend to have the highest GRFs and, as a result, highest peak KAM.[10] As such, the effects of KAM as well as COP and KAA are particularly important in this phase. The first phase of gait was the most sensitive in detecting significant differences in gait measures between OA and healthy patients.

KAA appeared to be the most sensitive factor when comparing groups with significant differences found between all groups in phase one of gait. In comparison, KAM only demonstrated a difference between the normal and medial OA groups and COP only demonstrated a difference between the normal and lateral OA groups and the lateral OA and medial OA groups. KAM appeared to be the least sensitive, not demonstrating any other significant differences between groups at any other phase of gait. Although COP measures did demonstrate some differences between lateral OA and healthy patients during gait, it does not appear to be sensitive enough marker to be used alone when differentiating OA and healthy patient gait patterns. Instead, it may be useful in addition to other gait measures when assessing OA patients, such as the KAA.

Overall, healthy patients and medial OA patients tend to place their COP on the lateral side and lateral OA patients on the medial sides of their feet. Most observable differences occurred in the first phase of gait, with KAA being the most sensitive parameter throughout all phases. OA individuals most likely adapt their gait and hence COP, particularly in the first phase of gait, to apply the least force on the pathological knee condyle. Haim et al[13] looked at the effect of COP on KAM in patients with medial OA, with a focus on footwear. They reported that footwear can cause a reduction in KAM by medialising the foot COP further for patients with medial OA. This reduces the peak KAM in phase one, to delay progression of medial OA. However, further work with larger numbers of pathological subjects is required to further evaluate COP as a useful discriminator of medial OA and healthy patients.

Conclusion

Gait is a complex pattern of movement involving numerous biomechanical factors. We sought to characterise COP, KAA, and KAM measurements in different phases of gait in osteoarthritic and healthy patients. Most observable differences occurred in the first phase of gait, with KAA being the most sensitive parameter throughout. Although COP demonstrated differences between lateral OA and healthy patients, COP was not useful in discriminating medial OA and healthy patients. These findings expand current knowledge of lower limb biomechanics as potential cost-effective methods of evaluating OA patient's gait are sought. Further studies are needed to examine the effects of long-term gait modifications and assessments to bring functional improvement in OA patients.

Conflicts of interest

None.

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