■ KNEE

Gait comparison of unicompartmental and total knee arthroplasties with healthy controls

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Aims

To compare the gait of unicompartmental knee arthroplasty (UKA) and total knee arthroplasty (TKA) patients with healthy controls, using a machine-learning approach.

Patients and Methods

145 participants (121 healthy controls, 12 patients with cruciate-retaining TKA, and 12 with mobile-bearing medial UKA) were recruited. The TKA and UKA patients were a minimum of 12 months post-operative, and matched for pattern and severity of arthrosis, age, and body mass index.

Participants walked on an instrumented treadmill until their maximum walking speed was reached. Temporospatial gait parameters, and vertical ground reaction force data, were captured at each speed. Oxford knee scores (OKS) were also collected. An ensemble of trees algorithm was used to analyse the data: 27 gait variables were used to train classification trees for each speed, with a binary output prediction of whether these variables were derived from a UKA or TKA patient. Healthy control gait data was then tested by the decision trees at each speed and a final classification (UKA or TKA) reached for each subject in a majority voting manner over all gait cycles and speeds. Top walking speed was also recorded.

Results

92% of the healthy controls were classified by the decision tree as a UKA, 5% as a TKA, and 3% were unclassified. There was no significant difference in OKS between the UKA and TKA patients ($p = 0.077$). Top walking speed in TKA patients (1.6 m/s; 1.3 to 2.1) was significantly lower than that of both the UKA group (2.2 m/s; 1.8 to 2.7) and healthy controls (2.2 m/s; 1.5 to 2.7; $p < 0.001$).

Conclusion

UKA results in a more physiological gait compared with TKA, and a higher top walking speed. This difference in function was not detected by the OKS.

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Total knee arthroplasty (TKA) provides substantial improvements in quality of life for people with end-stage gonarthrosis.[1] However, only 75% of patients report satisfaction with the outcome,[2] a figure not improved by the use of newer implant designs.[3] The underlying premise of unicompartmental knee arthroplasty (UKA) is that the preservation of both cruciate ligaments, and of the remaining intact compartments of the knee, should result in more physiological knee kinematics, and hence better outcomes. However, large scale national joint registry (NJR) studies using patient reported outcome measures (PROMs) report only small differences between UKA and TKA.[4-6] Given that TKA continues to account for 90% of primary knee arthroplasties performed in the United Kingdom,[7] it is clear that the majority of surgeons are not persuaded by these small functional gains in the context of a higher reported rate of revision associated with UKA.[8]

PROMs may be unable to detect potential differences between UKA and TKA due to their inherent subjectivity and ceiling effect.[9] Gait analysis is an alternative, objective metric of arthroplasty performance, and previous studies have concluded that UKA patients exhibit a more normal gait pattern than TKA patients.[10-14] With the exception of one paper from our group,[15] these studies are limited by a reliance on self-selected walking speeds which make comparisons between participants unreliable.[16-18] Additionally, in common with most

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Table I. Subject demographics. Data are displayed as means (range)

	UKA	TKA	Healthy controls
Age (yrs)	65 (52 to 79)	68 (56 to 83)	32 (18 to 81)*
BMI (kg/m^2)	29 (24 to 34)	30 (24 to 39)	24 (17 to 35)*
Height (cm)	175 (167 to 184)	167 (151 to 186)	174 (153 to 198)
Ahlbäck Grade[1]	2 (1 to 3)	2 (1 to 3)	NA
Oxford Knee Score	44 (40 to 48)	43 (40 to 48)	NA

* Significant difference between the groups (p < 0.05)
BMI, body mass index; UKA, unicompartmental knee arthroplasty; TKA, total knee arthroplasty

gait studies, they rely on the extraction of specific gait parameters from the large volume of data collected, thereby excluding potentially valuable information.[19]

Decision trees are a method of machine-learning for approximating discrete-valued functions – they are well suited to gait analysis in that they are useful for identifying regularities in large databases, they are robust to 'noisy' data, and have the added advantage that the resulting trees can be represented as sets of rules which are easily understood.[20] We set out to train a decision tree to discriminate between the gait of matched UKA and TKA patients, using all recorded gait parameters, at multiple velocities up to their maximum walking speed. By testing this decision tree with gait data from healthy controls, we wished to test the hypothesis that due to the joint preserving nature of UKA, normal healthy controls would be more likely to be classified as UKAs than TKAs.

Patients and Methods

A total of 145 participants were included in the study, which consisted of 121 healthy controls with no history of any disorder affecting their gait, 12 patients who had undergone TKA, and 12 who had undergone medial UKA. All arthroplasty patients had undergone their procedures for isolated radiographic medial tibiofemoral compartment arthrosis, and had completed at least 12 months of post-operative follow-up. TKA patients were matched to UKA patients for age, height, body mass index (BMI), and disease severity (assessed by two authors using Ahlbäck's classification,[1] Table I).[21] The UKAs were performed by one consultant surgeon (JPC), and the TKAs by another (RKS) – both surgeons perform more than 70 of these respective procedures each year. The implants used were the Oxford Phase III UKA (Zimmer Biomet, Bridgend, United Kingdom), performed using a minimally-invasive approach, and the Genesis II cruciate-retaining TKA (Smith & Nephew, London, United Kingdom). Post-operative component alignment was measured according to established methods, using digital short-knee radiographs.[22] A standardised post-operative rehabilitation regime was followed for all arthroplasty patients. All participants gave written informed consent, and ethical approval for the project was granted by the National Research Ethics Service (London-Camberwell St. Giles, REC Reference: 10/H0807/101) and Imperial College Healthcare NHS Trust (R&D Reference: 11/NE/0383).

Gait analysis was performed according to an established protocol, using a treadmill instrumented with force plates (Kistler Gaitway, Kistler Instrument Coporation, Amherst, New York).[15] After the patients familiarised themselves with the treadmill by walking at a comfortable speed for six minutes, this was increased in increments of 0.5 km/h until a maximum walking speed was reached (defined as the point at which the patient feels unsafe or would need to run if the speed was further increased).[23] Temporospatial gait parameters and vertical ground reaction force data were captured for 10s at each speed, with a sampling frequency of 100 Hz. All data were adjusted for body size using the methodology described by Hof.[24] Assessors were blinded to the type of operation performed. Oxford Knee Scores (OKS) were collected at the same time as gait analysis.[25]

A programme written in Matlab (Mathworks, Natick, Massachusetts) was used to implement an ensemble of trees (also known as a committee of trees) algorithm.[26] The gait data from UKA and TKA patients were used to train classification trees for each speed (4 km/h to 7.5 km/h); a total of eight trees comprised the ensemble. The following variables were considered: speed (m/s), incline (°), maximum force time (s), maximum force (N), first and second peak time (s), first and second peak force (N), mid-support time (s), mid-support force (N), peak ratio, active force time (s), active force (N), impulse (N*s), weight acceptance rate (N/s), push-off rate (N/s), contact time (s), gait cycle time (s), cadence (1/s), step time (s), double-support time (s), single limb stance time (s), base of support (cm), mean anteroposterior centre of pressure (cm), average mediolateral centre of pressure (cm), step length (cm), and stride length (cm).

The output of the decision tree was a binary prediction of whether these variables were derived from a patient that has undergone UKA or TKA (a representative tree can be seen in Figure 1). Gait data from healthy controls were then tested by the decision tree at each speed to predict whether they were most similar to a patient with a UKA or a TKA. The final decision was reached in a majority voting manner over all gait cycles and speeds.

Statistical analysis. This was performed with SPSS v.22 (IBM Inc., Armonk, New York). A paired *t*-test or one-way analysis of variance with Tukey *post hoc* analysis was used as appropriate. Kendall's W was used to determine reliability of Ahlbäck grading. Statistical significance was set at a p < 0.05. Results are reported as means (range).

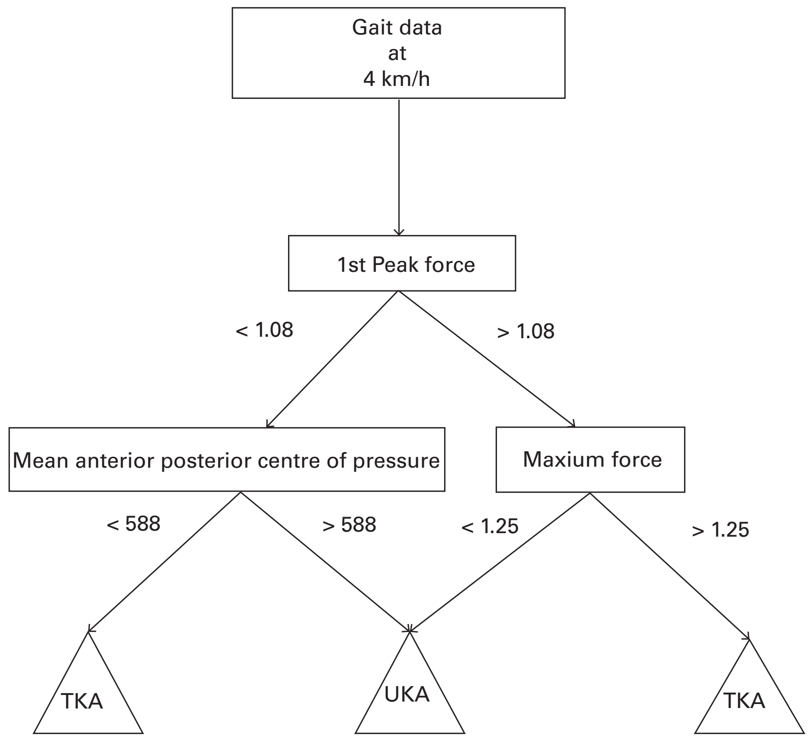

Fig. 1

Decision tree at 4 km/h trained with unicompartmental and total knee arthroplasty (UKA and TKA) data to classify gait in a binary fashion. First peak force and maximum force (normalised, therefore dimensionless), and mean anteroposterior centre of pressure (cm) values were selected by the algorithm. Gait data from each healthy control at 4 km/h was then processed by this decision tree, and classified as either a UKA or TKA. This was repeated at all eight walking speeds.

Results

There was no significant difference between the TKA and UKA groups for age ($p = 0.509$), weight ($p = 0.507$), height ($p = 0.08$), BMI ($p = 0.749$), OKS ($p = 0.077$) or Ahlbäck grade ($p = 0.474$). There was significant intra- ($W < 0.001$, $p = 1.0$) and inter-observer ($W = 0.125$, $p = 0.083$) agreement on Ahlbäck grading. The healthy control group was significantly younger ($p < 0.001$), and had a significantly lower BMI than both the arthroplasty groups ($p < 0.001$).

All components were well aligned radiographically:[22,27] mean femoral component alignment in the TKA group was 5° (2° to 7°) in the coronal plane, and 2° (0° to 5°) in the sagittal plane, with mean tibial component alignment 89° (87° to 90°) in the coronal plane, and 6° (3° to 8°) in the sagittal plane. In the UKA group, mean femoral component alignment was 3° (1° to 6°) in the coronal plane, and 2° (-2° to 5°) in the sagittal plane, with mean tibial component alignment 88° (86° to 90°) and 5° (3° to 7°) in the coronal and sagittal planes, respectively.

Of the 121 healthy controls, 111 (92%) were classified by the decision tree as a UKA, six (5%) as a TKA, and four (3%) were inconclusive.

First peak force (the maximum force measured during heel strike), weight acceptance rate (the slope of the force time curve during the loading phase, measured between a point at 10% of first peak force and a point at 90% of first peak force), and maximum force time (time from initial heel contact to the time of the absolute maximum force for an individual foot strike) were commonly selected by the decision tree to discern between the two arthroplasty groups. The force time curve in Figure 2 illustrates these differences.

Top walking speed was 1.6 m/s (1.3 to 2.1) in patients who had received TKA, which was significantly lower than the 2.2 m/s (1.8 to 2.7) achieved by patients with UKA ($p < 0.001$), and the 2.2 m/s (1.5 to 2.7) achieved by the healthy controls ($p < 0.001$, Fig. 3).

Discussion

In total, 92% of healthy controls were classified by the decision tree as a medial UKA, supporting the theory that preservation of both cruciate ligaments and the unaffected lateral tibiofemoral and patellofemoral compartments of the knee results in a more physiological gait compared with TKA. Inspection of the decision trees revealed that factors relating to initial heel strike were often used to discriminate between the two groups, with UKA patients having a faster weight acceptance rate and higher first peak force, similar to healthy controls. OKS in the UKA group were, on average, one point higher than those in the TKA group, but this difference was not statistically significant.

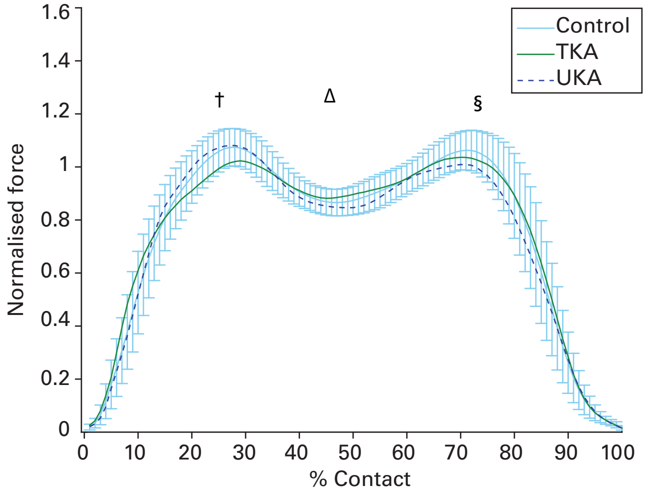

Fig. 2

Graph showing mean force time curve for unicompartmental and total knee arthroplasty (UKA and TKA) and healthy controls at 4 km/h. Healthy control data are displayed with 95% confidence intervals. † represents heel strike, Δ represents mid-stance, and § represents toe-off.

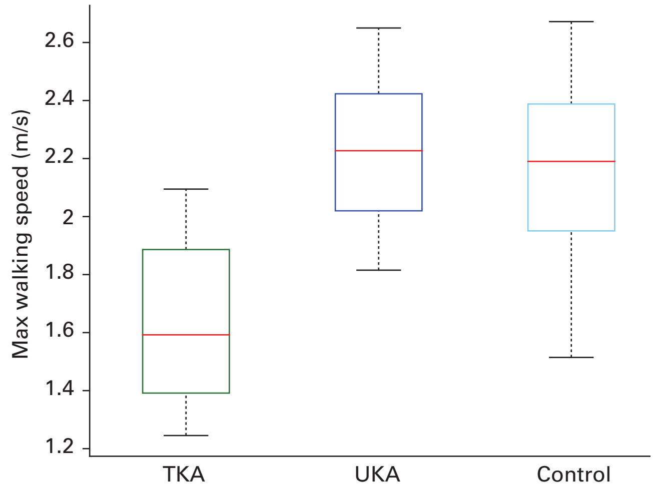

Fig. 3

Box-plots of top walking speeds showing median (red line), upper and lower quartiles (box), minimum and maximum values (whiskers). *Total knee arthroplasty (TKA) patients were significantly slower than unicompartmental knee arthroplasty (UKA) patients, and healthy controls ($p < 0.001$)

The strengths of this study include the use of an objective machine-learning algorithm to analyse the large volume of gait data acquired, avoiding the reporting bias normally introduced by extraction of specific gait variables for statistical testing. In reality, walking speed varies depending on the task at hand, and the use of a treadmill with integrated force-plates permits reproducible and comparable analysis of patients' gait at different speeds,[16] with gait data comparable with over-ground walking.[23] The UKA and TKA patients used to train the decision trees were well matched for pattern of arthrosis, radiological disease severity, age, height and BMI, thus reducing potential selection bias.

Limitations include the lack of randomisation, although the absence of clinical equipoise in the opinion of both surgeons made this impossible. Pre-operative gait data were not collected, and would have been useful to confirm that the UKA and TKA groups walked with a similar gait prior to operative intervention. The healthy controls were significantly younger, and had a lower BMI, than the arthroplasty patients, which may have affected their categorisation by the decision tree. The results of this study only apply to the two designs of prosthesis tested. In particular, the use of a cruciate-retaining TKA may affect the gait data obtained; fluoroscopic studies have demonstrated that cruciate-retaining TKAs have a paradoxical anterior movement of the femur on the tibia during flexion, which is improved in cruciate-substituting and medial pivot designs.[28-30] It is also uncertain whether an improved gait equates to higher patient satisfaction.

We used a novel machine-learning approach to analyse all recorded gait parameters, with a binary classification outcome that is easy to understand. Similar to data from NJR studies, there was only a small, one point, mean difference in OKS between the UKA and TKA groups.[4-6] This is in marked contrast to the gait analysis outcome, which was overwhelmingly (93%) in favour of UKA, and which reinforces the concern that current PROMs are unable to capture the true benefits of joint preserving procedures; objective gait data may be a superior measure.

Previous gait studies comparing TKA with healthy controls[11,31] consistently report loss of the normal biphasic flexion/extension moments around the knee, with an associated quadriceps avoidance gait – this is observed much less frequently in UKA.[10,14] These abnormal gait features have been attributed to the anteroposterior (AP) instability induced by anterior cruciate ligament (ACL) removal.[10] We found that altered loading during heel strike was often used as a discriminator between TKA and UKA, with a lower weight acceptance rate and a delayed, smaller first peak force, which mirrors the change in flexion/extension moments seen in both TKA and ACL-deficient patients (Fig. 4).[31,32]

We have previously found that UKA patients walk faster than TKA patients,[15] which is important because life expectancy significantly improves with every 0.1 m/s increase in top walking speed.[33] The decision tree approach used in the present study did not consider top speed as a variable when discriminating between implants (spatiotemporal and kinetic gait parameters were considered at each speed separately). However, analysis of the present data set confirms that the UKA patients walked significantly faster than their TKA counterparts (Fig. 3). The paradoxical AP movement seen during flexion following TKA[28,29] may account for this observation by limitation of mid-swing flexion, which impacts on stride length, and hence, walking speed.[34]

Compared with traditional 3D motion capture, an instrumented treadmill is a low-cost, quick and easy method of gait analysis. The results offer an objective

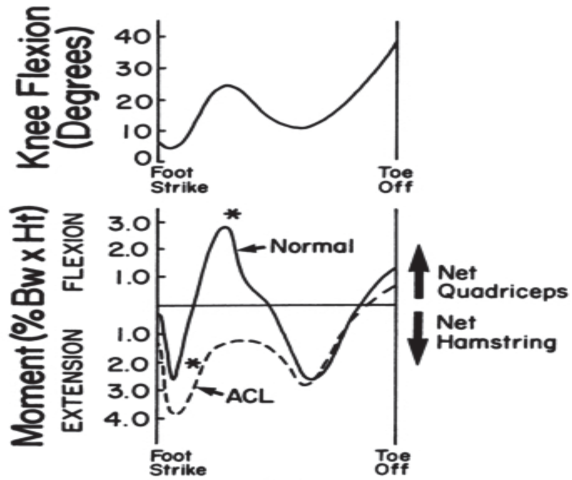

Fig. 4

During level walking by patients who had anterior cruciate (ACL) deficiency, an external extension moment about the knee persisted throughout most of the stance phase. In the presence of this moment, there is no need for activity of the quadriceps while the knee is near full extension. Normally, the necessary extension moment is produced by the quadriceps and is resisted by the anterior cruciate ligament. The asterisks identify the time during stance phase when the moments about knee of the control subjects and the patients were significantly different. Please see the original for the definitions of net quadriceps and net hamstring moments used in this study (reproduced from Berchuck et al[32] with permission).

assessment of function which is not captured using the PROMs collected by NJRs. A machine-learning approach to analysis of gait data is objective and simplifies data interpretation for clinicians. Of patients presenting with symptomatic knee arthrosis, 50% are suitable candidates for UKA.[35] The current study objectively demonstrates that for the two implants tested, UKA enables patients to have more normal gait compared with TKA, and patients should be aware of this when discussing their treatment options. Future studies will use the same approach to compare functional results between different implant designs.

Take home message:

Objective gait data is a valuable metric of function post-arthroplasty. When discussing UKA *versus* TKA, patients should be aware that UKA results in a more normal gait.

Author contributions:
G. G. Jones: Study design, Data analysis, Writing the paper.
M. Kotti: Study design, Data analysis, Writing the paper.
A. V. Wiik: Study design, Data collection, Writing the paper.
R. Collins: Data collection, Writing the paper.
M. J. Brevadt: Data collection, Writing the paper.
R. K. Strachan: Performed surgeries, Writing the paper.
J. P. Cobb: Performed surgeries, Writing the paper.

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