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Published in:
The Knee

DOI:
10.1016/j.knee.2021.01.010

Publication date:
2021

Document Version
Author accepted manuscript

The use of pedobarographic analysis to evaluate movement patterns in unstable total knee arthroplasty: a proof of concept study

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ABSTRACT

Background: Definition and clinical diagnosis of instability in TKA is challenging. Sensitive and objective biomechanical tools to aid diagnosis are currently lacking. This proof-of-concept study evaluates the use of pressure mat analyses to identify abnormal biomechanical loading patterns associated with TKA instability within an outpatient clinical setting.

Methods: Twenty participants were examined: 10 patients with suspected unilateral TKA instability and 10 healthy controls. Participants underwent bilateral stance and gait tests measuring time and limb loading pressure parameters. Gait was divided into three phases: heel strike, mid-foot and toe off. Pressure recordings are expressed relative to bodyweight. Between-limb loading discrepancies were calculated in TKA patients and controls, and these differences were then compared between groups. Statistical significance was accepted at $p < 0.05$.

Results: TKA patients consistently offloaded pressure away from the operated limb, whereas healthy controls exhibited more even limb loading throughout bilateral stance ($p < 0.05$). TKA patients exhibited greater discrepancy in overall step contact time between limbs (-0.09 s $\pm$ 0.16 s; p = 0.016) compared to controls (0.06 s $\pm$ 0.08 s; p = 0.04). Post-hoc tests showed significant between-group differences during midfoot (-0.04 s $\pm$ 0.07 s; p = 0.03) and toe-off (0.05 s $\pm$ 0.14 s; p = 0.013). Between-group differences in limb loading discrepancy were evident at heel strike (-9.24 % $\pm$ 2.11 %; p = 0.0166) and toe-off (-10.34 % $\pm$ 5.51 %; p = 0.0496).

Discussion: Pedobarographic measurements demonstrated differences in mechanical loading patterns in patients with TKA instability compared to healthy controls during functional tasks and warrants further investigation. This may prove to be a useful clinical diagnostic tool in identifying patients that would benefit from revision surgery or physical therapy.

KEY WORDS
Instability, total knee replacement, function, biomechanics

INTRODUCTION

Prior to undertaking revision total knee arthroplasty (TKA), it is imperative to identify the cause of TKA failure and to solve specific problems with appropriate treatments [1,2]. Instability is cited as a mode of failure contributing to approximately 20% of revision TKA cases. However, the definition of instability as a clinical diagnosis is broad, encompassing issues such as component wear/breakage, improper implant sizing, malpositioning, poor soft tissue balancing and loss of ligamentous integrity [3–6] .

There is, as yet no definitive 'test' to establish instability as a clinical diagnosis. Patients frequently complain of the knee 'giving way' and conformational clinical assessment is by consideration of the clinical history, manual joint examination, visual assessment of function and radiographic review [7]. Reported symptoms can cover a spectrum of dysfunction from a vague sense of instability to frank knee dislocation [8]. On physical examination, a varus or valgus thrust gait, or hyperextension locking during the stance phase can indicate more severe forms of instability. Varus-valgus laxity can be assessed with the knee in extension and in 30° flexion, with a view to differentiating flexion and extension instability [9,10]. However, evaluation of 'problematic knee replacements' remains somewhat subjective and dependent on clinical perception. The development of sensitive and objective biomechanical tests of functional tasks may offer enhanced understanding of movement insufficiencies which may in turn aid in clinical diagnosis and management.

Typically, kinematic analyses are carried out within gait laboratories and require specialist equipment such as force plates and 3-dimensional motion capture systems. Such systems can uncover detailed information about movement kinetics and kinematics [11] but are hugely expensive and difficult to access in routine orthopaedic clinical practice. Distinct mechanical patterns associated with knee replacement instability have been demonstrated using a simple loaded extension of the knee [12]. The leg extension equipment used in this evaluation was however bulky and not suitable for the everyday outpatient clinic environment.

Pedobarography is technique that measures foot contact area and pressure via sensors embedded in shoe insoles or mats. This plantar pressure analysis offers a compact and relatively inexpensive method of objectively measuring functional loading patterns [13–15]. Such equipment is most familiar in the orthopaedic foot and ankle setting [16] though can be applied more widely throughout orthopaedics with notable examples in pediatrics [13]. In terms of arthroplasty, Güven et al. explored the use of pedobarography in evaluating gait related to tibial component alignment in total knee arthroplasty [14]. Though based on a small sample, hindfoot loading differences were suggested in varus deformities that were not evident in neutral or valgus knees. There are currently no reports however of using pedobarography as a tool with which to evaluate the unstable TKA.

This is a proof of concept study, which aims to evaluate the use of pedobarographic pressure mat analyses to identify abnormal biomechanical loading patterns associated with TKA instability within an outpatient clinical setting. Specifically, we evaluated whether differences would be evident in loading parameters between unstable TKA and controls during a prolonged stance task and then explored further between group differences in gait.

METHODS

Study approval was obtained from the South Central Hampshire B, NHS ethics board (ref: 18/SC/0251). Patients who were unhappy following primary TKA and reporting symptoms of instability in the operated knee were examined by consultant orthopaedic surgeons at a single high volume arthroplasty unit in the UK and invited to take part in the study assessments. A convenient sample of healthy controls without previous TKA were also recruited to take part. This group were screened for lower limb pathology to ensure a representative healthy sample.

All assessments took place in a typical outpatient clinic space. Peak pressure and time pedobarographic parameters were measured during two-minute bilateral stance and during level walking at a self-selected pace using a pressure mat (SB Mat, Tekscan Inc, Boston, MA, USA). Following a one-minute normalization period, side-to-side limb loading pressure distribution was calculated over sequential 10-second intervals during the second minute of a bilateral stance task on the pressure mat. Gait analyses involved walking three meters on a flat surface, with the mat centrally placed to allow multiple steps prior to and following pressure mat contact. A minimum of three foot strikes on each limb were recorded. The gait cycle was divided into three phases: heel strike, midfoot stance, and toe-off. Peak pressures and corresponding time parameters were collected during each phase of gait. Difference in limb loading was calculated as peak pressure in the non-operated limb minus operated limb. In healthy controls this was calculated as the dominant minus the non-dominant limb. These between-limb differences were then compared between groups. Between-group differences were calculated as side-to-side limb loading difference in healthy controls minus limb loading difference in TKA patients. Pressure recordings are expressed relative to bodyweight.

Statistical analyses were performed using Prism Version 8 (GraphPad Software Inc., San Diego, CA, USA). Data are described as percentage of bodyweight (%BW) or as mean/median with corresponding standard deviation/interquartile range as a measure of dispersion as appropriate. Primary analysis was of between group distribution of pressure on prolonged bilateral stance task. A two-way repeated measures ANOVA was applied to compare pressure distribution between groups over time with post-hoc Tukey HSD pairwise comparisons to investigate individual time points. Secondary analysis explored between-group gait parameters by evaluating between group differences in overall loading time through gait cycle, with post-hoc analysis of the individual gait phases, and further exploratory analysis of pressure parameters relating to the individual gait phases. Mann-Whitney U-tests were employed to compare time parameters. Statistical significance of the primary analysis was accepted at $p = 0.05$. Post-hoc and exploratory analyses should be interpreted as such.

RESULTS

Twenty participants were examined: 10 patients following primary total knee arthroplasty with suspected TKA instability (M = 6; age = 67.11 $\pm$ 12.08 years; weight = 79.73 $\pm$ 20.12 kg) and 10 healthy controls (M = 5; age = 44.6 $\pm$ 7.52 years; weight = 70.80 $\pm$ 14.65). All patients had undergone unilateral primary TKA. All healthy controls were free from lower limb injury and pathology (Table 1).

Table 1. Demographic summary (Values are means ± standard deviation).

Group	n	Sex	Age (years)	Weight (kg)
TKA	10	M = 6	67.11 ± 12.08	79.73 ± 20.12
Control	10	M = 5	44.6 ± 7.52	70.80 ± 14.65

Primary analysis - Bilateral stance pressure distribution

All 20 participants were examined in bilateral stance. The unstable TKA patients showed significant differences in limb loading discrepancy ($p < 0.001$) and on post-hoc pairwise analyses at each 10-second interval during the second minute of the timed bilateral stance ($p < 0.001$) compared to the controls (Figure 1). Results showed a consistent offloading of pressure away from the operated limb in TKA patients whereas healthy controls exhibited more even limb loading during prolonged stance.

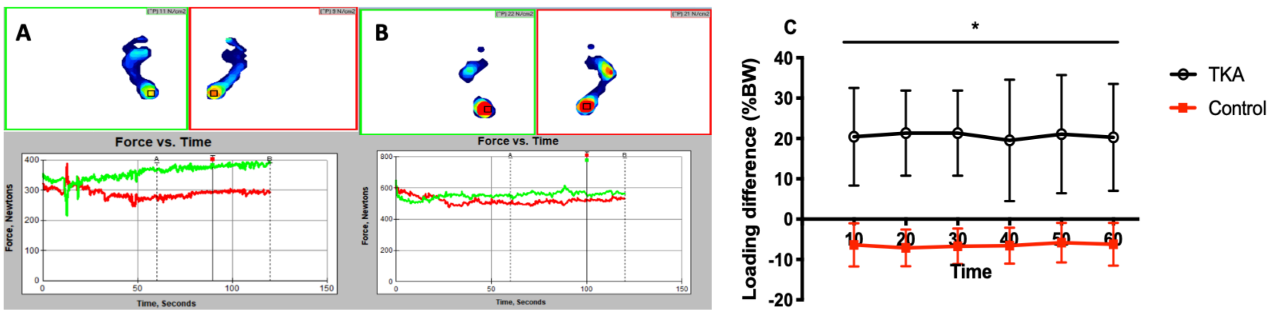

***Figure 1**. Sample plantar pressure map and corresponding pressure loading graph during bilateral stance in a TKA patient (A) and healthy control (B). The green box and trace show loading through the left side, and red box and trace through right side. The operated knee in the TKA patient was the right knee (red trace). (C) Differences in side-to-side limb loading distribution in patients with TKA instability versus healthy controls (where 0 = perfectly even loading). * = p < 0.001.*

Secondary analysis – Walking gait

Seventeen participants underwent pedobarographic gait analyses (TKA = 7; control = 10). Seven of the ten unstable TKA patients were able to complete the walking task. The pressure mat employs a left and right tile and requires participants to walk across the mat, placing a single foot into each tile per walking trial. If more than one-foot contact is made in the same tile during a single trial, the data is skewed. Three of the ten unstable TKA patients examined were unable to do this as their stride length was too short and multiple foot contacts were made in each tile.

Overall foot-mat contact time through the gait cycle was significantly different between groups (0.03 s ± 0.08 s; $p = 0.0001$) with unstable TKA group demonstrating longer overall step contact time than the healthy control group. TKA patients also showed greater discrepancy in contact time between limbs (-0.09 s ± 0.16 s; $p = 0.016$) compared to controls (0.06 s ± 0.08 s; $p = 0.04$) (Figure 2).

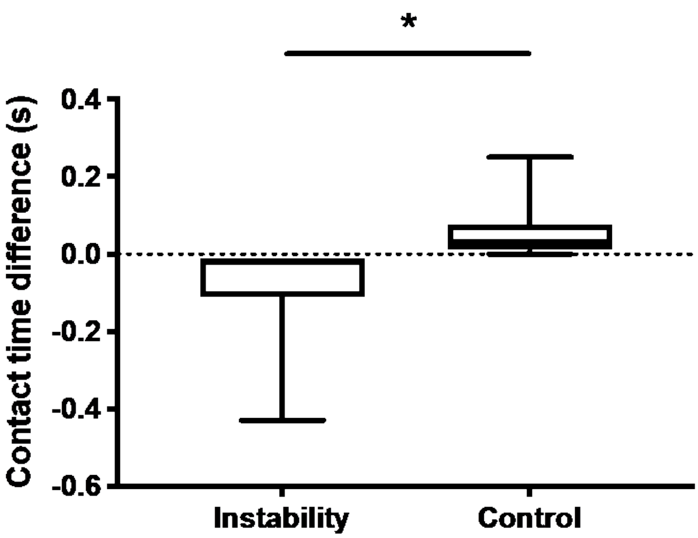

Figure 2. Difference in overall foot contact time during walking gait (seconds). * = p < 0.05.

Post-hoc analyses of individual components of the gait cycle similarly revealed longer phase contact time and greater discrepancy between limbs as well as increased variation in the unstable TKA group compared to healthy controls. There were no statistical differences between groups at heel strike (0.09 s ± 0.13 s; p = 0.11) but significant differences were found during mid-foot stance (-0.04 s ± 0.07 s; p = 0.03) and toe-off (0.05 s ± 0.14 s; p = 0.013) (Figure 3).

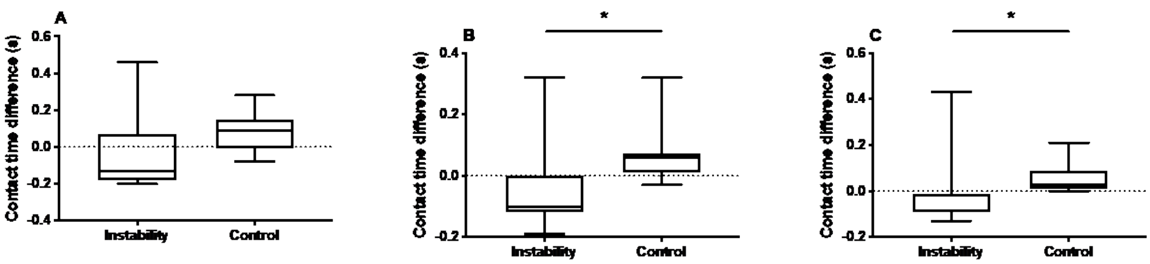

Figure 3. Between-group differences in foot contact time (s) during individual phases of gait: (A) heel strike, (B) mid-foot stance, (C) toe-off. * = p < 0.05.

Differences in pressure (reported as a proportion of bodyweight) were evaluated as further post-hoc exploratory analyses. In the TKA group approximately equal pressure in both limbs was evident during heel strike (-0.86 % ± 7.58 %; p = 0.938), but there was increased loading discrepancy in mid-foot (7.0 % ± 6.27 %; p = 0.047) and toe-off phases (12.86 % ± 12.81 %; p = 0.038), favouring the non-operated limb and reducing pressure on the operated side. This pattern contrasted to the healthy controls where a reduced pressure was evident in the dominant limb during heel strike (-10.10 % ± 5.47 %; p = 0.002), but pressure loading was more even during mid- foot (4.10 % ± 5.04 %; p = 0.030) and toe-off phases (3.2 % ± 7.30 %; p = 0.197) (Figure 4).

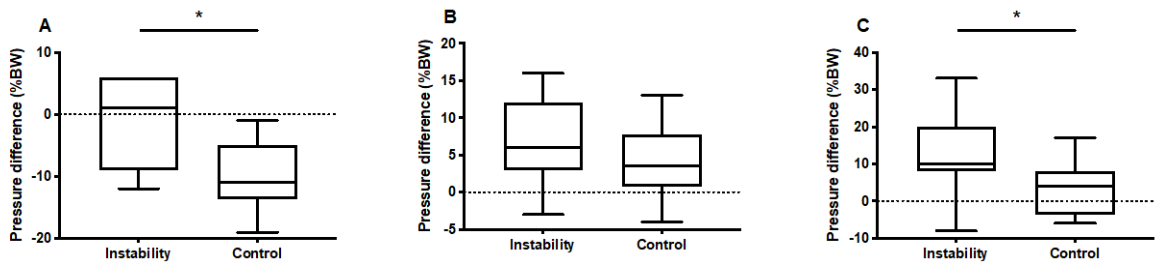

Figure 4. Between-group difference in limb loading (%BW) during individual phases of gait: (A) heel strike, (B) mid-foot stance, (C) toe-off. * = $p < 0.05$.

DISCUSSION

This study evaluates the use of pedobarographic pressure mat analyses to describe lower limb loading patterns in patients reporting instability following total knee replacement. We report differences in both prolonged stance and gait between patients reporting instability and healthy controls.

As this is a broadly explorative analysis, we interpret the data cautiously. Overall, TKA patients reporting instability exhibited greater variation in movement patterns relating to time and pressure during the standing and walking tasks examined in this study compared to controls, generally shifting their weight away from the operated side. Compared to controls, TKA patients took longer to execute the walking task, consistently showing longer overall and individual phase contact times on each limb versus healthy controls. TKA patients also exhibited greater limb loading discrepancy, particularly through mid-foot and toe-off. This may be due to heightened caution and reluctance to take weight through the unstable knee. That there was generally more variation in both time and pressure parameters suggests altered movement strategies in the unstable TKA population that warrant further investigation to discern these differences in greater detail. Results from this study are in concurrence with previous research. Benedetti (2003) suggested that many patients do not regain normal joint function following TKA even during low-level activities such as walking [18]. Even years post-operatively, patients exhibit slower gait, decreased stride length, and abnormal flexion/extension moments particularly during the stance and swing phases [11,17,18].

There are various limitations to this work. As with most proof-of-concept studies, the main limitation is the comparatively small sample size and we are likely substantially underpowered for statistical analysis. We cannot causally ascribe the time-pressure differences found to be the result of TKA instability, but rather suggest this tool may be able to highlight such parameters and is worthy of further study. Nor can we be sure that the patterns of instability exhibited in our 10 patients are necessarily representative of the spectrum of TKA instability. The gait evaluation was necessarily conducted in a constrained clinic space, thus while we advised participants to walk at a steady pace and allowed a short approach prior to making contact with the pressure mat, it may be that these data are more reflective of gait initiation than steady state walking. We think this is particularly likely in the unstable TKA group that anecdotally did not achieve a steady state walking speed. For this pilot study we recruited a convenient sample of healthy individuals, without any knee pathology as a comparator group. While appropriate for our purposes here, it will be important to explore time-pressure parameters in ‘stable’ well-functioning TKA patients before thought can be turned to using this equipment in any diagnostic capacity. Indeed, it is likely that well-functioning TKA patients exhibit different patterns to healthy controls. The pedobarographic contrast of well-functioning and unstable TKAs is recommended as a focus of further research. Despite these limitations and employing only simple low-demand physical tasks of standing and walking, differences in movement patterns were detectable. It may be that more challenging functional tasks that involve loading a flexed knee, such as stairs traverse or squat movement, may highlight more pronounced or illustrative differences in pressure patterns. Importantly, we were able to perform this evaluation in the outpatient clinical setting with minimal equipment, suggesting a potential alternative to full gait laboratory analysis, which is prohibitively expensive and only available at major assessment centres.

This work suggests that pedobarometry could prove a useful method to evaluate biomechanical parameters in patients with problematic or unstable knee replacements. While the stance and simple gait pressure parameters reported here are not as yet indicated as a clinical diagnostic tool, this type of evaluation may yet prove useful, for example, in helping to identify which patients would benefit from either surgical or non-operative management.

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