Analysing pre-operative gait patterns in participants undergoing total hip and knee replacement using inertial wearable sensors—an observational study

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Study protocol

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Abstract

Background

Knee and hip arthroplasty are two of the most frequently performed procedures in Orthopaedic surgery. They are associated with positive patient-reported outcomes and significant improvements in quality of life for patients. Despite this success, there may be room for further progress in measuring functional outcomes in the form of gait analysis.

Methods

Gait metrics were obtained from 30 patients requiring either total knee or hip replacement in this cross-sectional observational study, with the use of chest-based wearable sensor. These gait metrics were then compared with 30 healthy controls of similar ages and the differences evaluated using a T-test. Participants were instructed to walked a self-selected distance (15-120m) in a hospital environment (level surface) with chest-based wearable sensor MetaMotionC (Mbientlab Inc., USA) fitted in.

Discussion

Hip and knee osteoarthritis patients have unique gait signatures that can be detected using wearable sensors technology. In total three domains were evaluated including spatiotemporal, variations and asymmetry parameters. From the domains that were obtained there were marked variations in gait asymmetry parameters in both hip and knee osteoarthritis. The magnitude of gait deterioration in terms of step length asymmetry seems greater on average in hip osteoarthritis than knee. A single chest-based sensor was found to be capable of detecting pathological gait signatures in severe osteoarthritis patients requiring surgical intervention, when compared to age-matched controls. Future studies should be conducted to validate the suitability of wearable sensors as a clinical adjunct.

Background

Osteoarthritis (OA) is a disabling condition that affects a significant proportion of the population causing knee pain, muscle weakness and increases the risk of falls (1). Global incidence of hip and knee OA was more than 300 million cases (2). Joint replacements are the recommended treatment for patients who suffer from end-stage OA and it is one of the most common orthopaedic procedures performed (3). The goal of joint replacement is to improve locomotive function of the joint, correct joint deformity, reduce gait instability, and pain (1, 4–6). There are a few methods to quantify the functional severity of OA including the well-known Western Ontario McMaster Universities Osteoarthritis (WOMAC) Index questionnaire and biomechanical gait analysis method (6). In this paper we adopted the latter method of gait analysis using wearable sensor technology.

In recent years, there has been a shift of interests from the gold-standard optoelectronic camera with force plates to lightweight, commercial-use wearable sensors (7). The gold-standard gait analysis is
time-consuming and expensive to set up, meanwhile wearables sensors allow for easier follow up with patients’ post-joint replacement procedures (3, 7).

Previous research explored the postoperative outcomes of joint replacement in terms of monitoring and assessing rehabilitation progress (8). There is a need for further gait analysis research in preoperative analysis of pathological gait to understand the underlying disease progression and to determine whether it changes the preoperative surgical planning. Lofterod et al (2007) found more than half of the study group patients’ surgical planning was altered based on the preoperative gait analysis data (9). Within Lofterod’s study of cerebral palsy children, the total number of surgical procedures pre-planned was reduced by 13%, this demonstrated the disparity of the results between gait analysis and clinical evaluation (9).

There is limited research that adopted only wearable sensors as their mainstay of gait analysis. Most of the research was done with wearable sensors worn on the back and/or shank (7). Knee OA was the most studied outcome, followed by hip OA and ankle OA (7). Within the studies conducted with wearable sensors, the most prevalent biomechanical outcomes were the mean spatiotemporal parameters. Small et al (2019) mentioned there is a need to incorporate wrist-worn wearable sensors (triaxial accelerometers) into gait analysis for OA patients as it is commercially available for patients (10). Huang et al (2020) was unconventional as they conducted the post-operative OA gait analysis with the participants in seating position (8). The ‘gait task’ involves participants flexing and extending the knee with and without motorised equipment ‘Cybex’ (8).

Previously, to examine postoperative outcomes, other than conventional optoelectronic video analyst and force plates, electromyography and 2D-3D fluoroscopy radiographs were used (11). The radiographs are not favoured because it has limited imaging range and difficult in capturing the dynamic motion of joints (11). Meanwhile, the electromyogram was invasive in nature, and does not appear to be more superior than conventional gait analysis technology (11). All of the above-mentioned technology are unable to be generalize to real-world scenarios; therefore, researchers and clinicians have been looking into adopting wearable sensors in their everyday practice.

There is also an increase interests in the application of machine learning technology in gait analysis. This is due to the capabilities of the software to process large amount of input data and features in a short amount of time.

There is a clear need to analyse how the gait patterns of knee and hip OA differs from healthy control of similar age with the utilisation of wearable sensors. Additionally, identifying the features within a gait cycle that provide diagnostic clues for knee and hip OA, including unilateral or bilateral pathologies. Furthermore, to determine the feasibility of utilising wearable sensors (as an inexpensive clinical tool) in gait differentiation and monitoring of disease progression.

The purpose of this study is to assess whether a chest-based wearable sensor can differentiate the gait patterns of knee OA, hip OA and healthy age-matched controls. The results of the study can be used as a
baseline for follow up post-operatively to monitor their rehabilitation progress. Furthermore, the results of the study are to be used as a benchmark for future studies and research, namely whether it has a substantial effect orthopaedic surgical decision making.

**Methods**

**Objectives**

The present study is a single-surgeon observational (case-control) study of participants with hip and knee osteoarthritis awaiting total hip replacement and total knee replacement respectively. Gait parameters across the domains of spatial, temporal, asymmetric and variability metrics were collected using an inertial wearable sensor. Gait metrics were quantitatively analysed (against the normative gait of age-matched control participants) to profile the pattern of gait deterioration.

**Ethics**

Approval was obtained from the South Eastern Sydney Local Health District, New South Wales, Australia (HREC 17/184). All participants provided written informed consent.

**Study participants**

The participants of this study were a sample of patients presenting to Prince of Wales Hospital in February – July 2021. During their clinic visit, study parameters and risks were discussed, and consent obtained. Patients with diagnoses of either hip or knee osteoarthritis and surgical candidates for total joint replacement were considered for inclusion. TKR and THR participants experienced relapsing and prolonged knee or hip pain, respectively. Exclusion criteria included infection, cancer, and presence of other potentially gait-altering pathologies. Participants completed a questionnaire to obtain demographic and clinical information. ‘Healthy’ participants of similar age bracket (50–70) with pain-free gait were recruited from the community as controls for this study following a similar semi-structured interview and questionnaire and age-matched in a 1:1 ratio.

**Procedure**

Prior to the walk, participants were fitted at the sternal angle (Fig. 2) with the inertial measurement unit: MetaMotion© (MMC) manufactured by Mbientlab Inc (California, USA). Following a short initial pause to orient the MMC device, participants walked a self-selected distance (15–120 m) along an unobstructed hospital corridor pathway on level ground. Trials were discarded if the patient did not (or could not) pause to orient the device, walk more than 30m or required a walking aid during the bout. Further information on wearable device and data processing can be found via [Betteridge C, Mobbs RJ, Fonseka RD, Natarajan P, Ho D, Choy WJ, et al. Objectifying clinical gait assessment: using a single-point wearable sensor to quantify the spatiotemporal gait metrics of people with lumbar spinal stenosis. J Spine Surg. 2021;7(3):254-6.](12)

**Statistical analysis**
Data analyses were performed using Prism 9 (GraphPad Software). Normality was assessed using Shapiro-Wilk tests and inspection of histograms where necessary and statistical significance was considered for p-value < 0.05. Descriptive statistics were calculated for demographic variables including age, gender, height, weight, BMI, presence of diabetes and smoking. Spatiotemporal parameters of gait were calculated, and step measurements (rather than stride) chosen for calculations of gait asymmetry (13). Differences in gait metrics between participants with osteoarthritis and control participants were calculated using Mann Whitney U tests or Independent samples (two-tailed) t-tests.

**Results**

A total of 29 participants undergoing total hip replacement, 27 undergoing total knee replacement and 28 control participants met eligibility criteria and consented for inclusion over the study period spanning February – June 2021.

**Participant Characteristics**

<table>
<thead>
<tr>
<th></th>
<th>TKR</th>
<th>THR</th>
<th>Controls</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>28</td>
<td>29</td>
<td>28</td>
</tr>
<tr>
<td>Age</td>
<td>62.5 + 15.2</td>
<td>60.1 + 10.0</td>
<td>57.2 + 9.77</td>
</tr>
<tr>
<td>Female (%)</td>
<td>15 (54)</td>
<td>18 (62)</td>
<td>18 (64)</td>
</tr>
<tr>
<td>Height (m)</td>
<td>171 + 9.48</td>
<td>169 + 10.0</td>
<td>165 + 9.34</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>82.9 + 17.8</td>
<td>80.2 + 18.2</td>
<td>71.4 + 12.1</td>
</tr>
<tr>
<td>BMI</td>
<td>28.2 + 5.4</td>
<td>27.8 + 4.46</td>
<td>26.2 + 4.15</td>
</tr>
<tr>
<td>Smoking (%)</td>
<td>1 (7.1)</td>
<td>0 (0)</td>
<td>3 (11)</td>
</tr>
<tr>
<td>Diabetes (%)</td>
<td>2 (3.6)</td>
<td>3 (10)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Daily Step Count</td>
<td>5800 + 3000</td>
<td>3500 + 2200</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Participants undergoing TKR, THR and healthy controls were of similar mean (+/- standard deviation: 60.1 +/- 10.0 versus 62.5 +/- 15.2 versus 57.2 +/- 9.77) age. There were no significant differences in participant characteristics such as age, body mass index, smoking and diabetes) when compared to controls as seen in Table 1 below.

**Pathological Gait Signatures**

THR participants demonstrated variations in temporal and spatial gait metrics, along with gait asymmetry. They typically walked with lower gait velocity (-22.2%, p<0.001) and shorter step length...
(-10.1%, p=0.0115) whilst temporal parameters such as step time (+17.3%, p<0.001), stance time (+16.2, p<0.001), swing time (+17.2%, p<0.001), single support time (+19.5%, p<0.001), double support time (+10.8%, p=0.0024) were increased. Most notably, THR participants have markedly increased gait asymmetry in terms of step length asymmetry (+180%, p<0.001), step time asymmetry (+142%, p=0.0011), stance time asymmetry (+125%, p=0.0018), swing time asymmetry (+129%, p=0.0021) and single support time asymmetry (+126%, p=0.0066). THR group also walked with gait variability with increased step length variability (+83.2, p<0.001), stance time variation (+4.3%, p=0.0018) and swing time variation (+24%, p=0.0021). The gait metrics allow for a preliminary model for disease-specific gait pattern in THR patients.

Overall THR and TKR demonstrate similarities when compared to the control group. TKR group also involved deteriorations in the spatial and temporal metrics of gait mostly to a lesser extent than THR group. TKR participants walked with a lower gait velocity (-21.5%, p<0.001) and a shorter step length (-12.7%, p=0.006), whilst step time (+15.2%, p<0.001), stance time (+14.8%, p<0.001), swing time (+13.6%, p<0.001), single support time (+13.9%, p<0.001) and double support time (+13.8%, p<0.001) were increased. TKR participants also demonstrated marked gait asymmetry which involved step length asymmetry (+129%, p=0.001), step time asymmetry (+121%, p=0.003), stance time asymmetry (+151%, p=0.002), swing time asymmetry (+138%, p=0.006) and single support time asymmetry (+104%, p=0.005). The largest difference between THR and TKR groups was step length asymmetry with a 51% difference. In terms of gait variability, TKR group demonstrated only increased step length variability (+59.5%, p=0.001) as seen in Figure 2. The pattern of gait deterioration between THR and TKR groups are albeit similar when considering spatial and temporal metrics. However, a greater magnitude of deterioration across all asymmetry metrics and step length variation was present as shown in Figure 3.
Table 2. Quantitative Gait Signature of THR participants (sensor-derived).

<table>
<thead>
<tr>
<th>Spatial Gait Metrics</th>
<th>THR (n=28)</th>
<th>Controls (n=33)</th>
<th>Group Difference (controls – THR)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± SD</td>
<td>95% CI</td>
<td>%</td>
</tr>
<tr>
<td>Gait Velocity (m/s)</td>
<td>1.05 ± 0.212</td>
<td>1.35 ± 0.177</td>
<td>-0.400; -0.189</td>
</tr>
<tr>
<td>Step Length (cm)</td>
<td>0.624 ± 0.0990</td>
<td>0.694 ± 0.694</td>
<td>-0.123; -0.0163</td>
</tr>
<tr>
<td>Temporal Gait Metrics</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Step Time (ms)</td>
<td>0.609 ± 0.0965</td>
<td>0.519 ± 0.519</td>
<td>0.0513; 0.128</td>
</tr>
<tr>
<td>Stance Time (ms)</td>
<td>0.754 ± 0.116</td>
<td>0.649 ± 0.0323</td>
<td>0.0595; 0.152</td>
</tr>
<tr>
<td>Swing Time (ms)</td>
<td>0.456 ± 0.0667</td>
<td>0.389 ± 0.0200</td>
<td>0.0405; 0.0942</td>
</tr>
<tr>
<td>Single Support Time (ms)</td>
<td>0.472 ± 0.102</td>
<td>0.395 ± 0.0223</td>
<td>0.0364; 0.117</td>
</tr>
<tr>
<td>Double Support Time (ms)</td>
<td>0.292 ± 0.0510</td>
<td>0.260 ± 0.0130</td>
<td>0.0119; 0.0524</td>
</tr>
<tr>
<td>Gait Asymmetry</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Step Length Asymmetry (cm)</td>
<td>0.148 ± 0.101</td>
<td>0.0529 ± 0.0168</td>
<td>0.0556; 0.135</td>
</tr>
<tr>
<td>Step Time Asymmetry (ms)</td>
<td>0.0906 ± 0.0785</td>
<td>0.0374 ± 0.0166</td>
<td>0.0223; 0.0841</td>
</tr>
<tr>
<td>Stance Time Asymmetry (ms)</td>
<td>0.0742 ± 0.0635</td>
<td>0.0330 ± 0.0152</td>
<td>0.0160; 0.0663</td>
</tr>
<tr>
<td>Swing Time Asymmetry (ms)</td>
<td>0.0764 ± 0.0671</td>
<td>0.0334 ± 0.0169</td>
<td>0.0163; 0.0696</td>
</tr>
<tr>
<td>Single Support Time Asymmetry (ms)</td>
<td>0.0864 ± 0.0869</td>
<td>0.0383 ± 0.0175</td>
<td>0.0140; 0.0823</td>
</tr>
<tr>
<td>Double Support Time Asymmetry (ms)</td>
<td>0.0272 ± 0.0519</td>
<td>0.0116 ± 0.00414</td>
<td>-0.00440; 0.0357</td>
</tr>
<tr>
<td>Gait Variability</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gait Velocity Variability (CoV)</td>
<td>9.62 ± 2.91</td>
<td>10.5 ± 3.08</td>
<td>-2.46; 0.783</td>
</tr>
<tr>
<td>Step Length Variability (CoV)</td>
<td>17.0 ± 9.75</td>
<td>9.28 ± 2.26</td>
<td>3.86; 11.6</td>
</tr>
<tr>
<td>Step Time Variability (CoV)</td>
<td>12.77 ± 7.31</td>
<td>11.03 ± 4.44</td>
<td>-1.54; 5.02</td>
</tr>
<tr>
<td>-----------------------------</td>
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</tr>
<tr>
<td>Stance Time Variation (CoV)</td>
<td>8.74 ± 4.74</td>
<td>8.38 ± 3.15</td>
<td>-1.81; 2.55</td>
</tr>
<tr>
<td>Swing Time Variation (CoV)</td>
<td>17.21 ± 16.7</td>
<td>13.88 ± 7.16</td>
<td>-3.67; 10.3</td>
</tr>
<tr>
<td>Single Support Time Variation (CoV)</td>
<td>25.5 ± 22.9</td>
<td>27.7 ± 19.3</td>
<td>-13.7; 9.19</td>
</tr>
<tr>
<td>Double Support Time Variation (CoV)</td>
<td>14.3 ± 19.3</td>
<td>12.0 ± 7.32</td>
<td>-5.59; 10.3</td>
</tr>
</tbody>
</table>

Value presented as mean ± SD or as median (range) for metrics with normal and non-normal distributions, respectively. P value represents statistical significance of difference between groups derived from Independent Samples two-tailed t-tests (with Welch's correction applied if unequal variance), or Mann Whitney U tests (if non-normal distribution). CoV = Coefficient of Variance, cm = centimetres, m = metres, s = seconds, ms = milliseconds.
Table 3. Quantitative Gait Signature of TKR participants (sensor-derived).

<table>
<thead>
<tr>
<th></th>
<th>TKR (n=28)</th>
<th>Controls (n=33)</th>
<th>Group Difference (controls – TKR)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± SD</td>
<td>95% CI</td>
<td>%</td>
</tr>
<tr>
<td><strong>Spatial Gait Metrics</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gait Velocity (m/s)</td>
<td>1.06 ± 0.264</td>
<td>1.35 ± 0.180</td>
<td>0.163; 0.405</td>
</tr>
<tr>
<td>Step Length (cm)</td>
<td>0.616 ± 0.106</td>
<td>0.694 ± 0.101</td>
<td>0.0231; 0.134</td>
</tr>
<tr>
<td><strong>Temporal Gait Metrics</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Step Time (ms)</td>
<td>0.598 ± 0.0867</td>
<td>0.519 ± 0.0266</td>
<td>-0.114; -0.0443</td>
</tr>
<tr>
<td>Stance Time (ms)</td>
<td>0.745 ± 0.105</td>
<td>0.649 ± 0.0329</td>
<td>-0.139; -0.0541</td>
</tr>
<tr>
<td>Swing Time (ms)</td>
<td>0.450 ± 0.0683</td>
<td>0.389 ± 0.0203</td>
<td>-0.0885; -0.0336</td>
</tr>
<tr>
<td>Single Support Time (ms)</td>
<td>0.459 ± 0.0797</td>
<td>0.395 ± 0.0227</td>
<td>-0.0958; -0.0320</td>
</tr>
<tr>
<td>Double Support Time (ms)</td>
<td>0.296 ± 0.0387</td>
<td>0.260 ± 0.0132</td>
<td>-0.0517; -0.0203</td>
</tr>
<tr>
<td><strong>&lt;Gait Asymmetry</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Step Length Asymmetry (cm)</td>
<td>0.121 ± 0.0936</td>
<td>0.0529 ± 0.0171</td>
<td>-0.105; -0.0318</td>
</tr>
<tr>
<td>Step Time Asymmetry (ms)</td>
<td>0.0828 ± 0.0738</td>
<td>0.0374 ± 0.0167</td>
<td>-0.0746; -0.0162</td>
</tr>
<tr>
<td>Stance Time Asymmetry (ms)</td>
<td>0.0710 ± 0.0583</td>
<td>0.0330 ± 0.0155</td>
<td>-0.0613; -0.0147</td>
</tr>
<tr>
<td>Swing Time Asymmetry (ms)</td>
<td>0.0714 ± 0.0660</td>
<td>0.0334 ± 0.0172</td>
<td>-0.0643; -0.0117</td>
</tr>
<tr>
<td>Single Support Time Asymmetry (ms)</td>
<td>0.0781 ± 0.0679</td>
<td>0.0383 ± 0.0178</td>
<td>-0.0668; -0.0127</td>
</tr>
<tr>
<td>Double Support Time Asymmetry (ms)</td>
<td>0.0189 ± 0.0202</td>
<td>0.0116 ± 0.0042</td>
<td>-0.0153; 0.00700</td>
</tr>
<tr>
<td><strong>Gait Variability</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gait Velocity Variability (CoV)</td>
<td>10.2 ± 3.02</td>
<td>10.5 ± 3.14</td>
<td>-1.41; 1.90</td>
</tr>
<tr>
<td>Step Length Variability (CoV)</td>
<td>14.8 ± 7.54</td>
<td>9.28 ± 2.30</td>
<td>-8.53; -2.46</td>
</tr>
</tbody>
</table>
## Discussion

The aim of the present study was to investigate the use of wearable sensors in identifying pathological gait signatures of hip and knee OA. Previous research explored preoperative and postoperative TKR and THR gait extensively with traditional laboratory-based gait analysis equipment and electromyography (EMG) (4–6, 11, 14–20). Some of the gait parameters obtained from traditional gait analyses are not directly translatable to wearable sensor technology, for example knee adduction moment KAM (7). A comparative study of pathological gait between preoperative TKR and THR has not previously been performed. Our observational study was performed using the minimum number of wearable sensors (one chest-based wearable sensor). These findings validated that wearables are sufficient to highlight relevant gait parameters for gait differentiation and profiling. In support of utilising simplified methodology, Kobsar et al (2017) found that the classification accuracy of two-sensor arrays was not significantly different from a three-sensor array while delivering similar results (21).

In terms of methodology, wrist-based wearable sensors are one of the most common placement locations for gait analysis due to the ease of attachment. However, for this observational study, the preferred placement location was the chest. Chest-based wearables are more suitable for ambulatory activities such as jumping and running, as it provides holistic representation of body including upper body balance (22–24). Also, chest-based wearables are in line with the centre-of-gravity and can better quantify the energy expenditure of the participants (22, 25). In terms of percentage accuracy of results, the hip and waist are generally preferred, but tends to have lower wear-compliance from participants due to physical discomfort of wear-site and negative feelings about the visibility of the device (25). Zhang et al (2016) found that chest-based wearables only performed marginally worse than hip or waist wearables, and therefore can be seen as a suitable alternative (25). Chest-based wearables are also subject to lesser disruptions from upper limb movements (25).

### Table 1: Mean Coefficient of Variance (CoV) for Various Gait Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean ± SD</th>
<th>Median (Range)</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step Time Variability (CoV)</td>
<td>12.0 ± 7.21</td>
<td>11.0 ± 4.52</td>
<td>-4.19; 2.28</td>
</tr>
<tr>
<td>Stance Time Variation (CoV)</td>
<td>8.59 ± 4.51</td>
<td>8.37 ± 3.20</td>
<td>-2.31; 1.88</td>
</tr>
<tr>
<td>Swing Time Variation (CoV)</td>
<td>14.2 ± 10.4</td>
<td>13.9 ± 7.29</td>
<td>-5.17; 4.47</td>
</tr>
<tr>
<td>Single Support Time Variation (CoV)</td>
<td>24.1 ± 21.7</td>
<td>27.7 ± 19.7</td>
<td>-7.51; 14.7</td>
</tr>
<tr>
<td>Double Support Time Variation (CoV)</td>
<td>12.6 ± 11.4</td>
<td>12.0 ± 7.45</td>
<td>-5.82; 4.55</td>
</tr>
</tbody>
</table>

Value presented as mean ± SD or as median (range) for metrics with normal and non-normal distributions, respectively. P value represents statistical significance of difference between groups derived from Independent Samples two-tailed t-tests (with Welch's correction applied if unequal variance), or Mann Whitney U tests (if non-normal distribution). CoV = Coefficient of Variance, cm = centimetres, m = metres, s = seconds, ms = milliseconds.
For knee OA, the most common affected location is the medial compartment of the knee (14). The severity and progression of knee OA can be quantified with changes in knee adduction moments (KAM), knee flexion moments (KFM) and knee flexion angle (KFA) (14, 15). OA patients typically present with smaller mid-stance KFM peaks and larger KFA and KAM (15). Favre et al (2016) proposed that healthy patients with larger heel-strike KFA might contribute to initiation of idiopathic OA (15).

The results showed that there are marked differences between control participants and the pre-operative of patients awaiting TKR and THR surgery (and similarities between the two pathological gaits) that can be detected with a single tri-axial wearable sensor. Both pathological gait signatures demonstrated significant abnormalities in the asymmetry of gait (excluding double support time asymmetry) and step length variations (26). There was also less significant increase in the duration of spatiotemporal parameters (step time, stance time, swing time, single support time and double support time) and reduction in step length and gait velocity. The overall magnitude of gait deterioration was more significant with preoperative THR patients. Hip OA patients have weak hip adductor muscles; therefore, to stabilise the hips, patients will mobilise with exaggerated lateral bending of their bodies (27). The hallmark of compensatory gait patterns is known as ‘Duchenne Limp’ (27). External hip adductor moment impulse (HAM), much like KAM, are mentioned in many studies as a measurable outcome for increased hip loading and progression of disease (17). Moreover, there are radiographic evidence of progression of disease in patients with larger HAM impulse and mean number of steps per day (17).

For knee OA, Kobsar et al (2020) and Mills et al (2013) found that stride time is the single most consistent gait parameters in severe disease progression (7, 28). Pertaining to spatial gait metrics, some studies reported lower gait speed due to decreased cadence and decreased stride length (27, 29–32). Tadano et al (2016) did not comment on gait speed however did highlight shorter gait cycle in severe OA patients (33). This is further supported by Boyer et al (2019) and Tadano et al (2016), as there were lesser knee-extension (heel-strike), ankle flexion (toe-off) and abduction motion (toe-ing out) in severe knee OA patients (29, 33). On the flip side, Sagawa et al (2013) suggested that gait speed may vary with OA of various hip-knee-angle (HKA) (6). Many literatures explored KAM, KFA and KFM as the parameters for identifying severity of knee OA (14, 15). Changes in the parameters can indicate increase cartilage loss and more severe disease progression (15). Favre et al (2016) proposed that healthy patients with larger heel-strike KFA might contribute to initiation of idiopathic OA (15). Some studies discovered that pain relief medications can lead to rapid disease progression, as there are demonstrated higher joint loading and peak adduction moments (19, 20). In the present study, those parameters are not taken into account as it will require specialise equipment (such as motion-cameras, force plates) for measurements of ground reaction forces and degree of angles (such as toe-in angle, toe-out angle) (14, 34).

**Strengths**

The present study captured the pathological gait signatures of severe hip and knee OA patients requiring surgical interventions as a basis for future longitudinal study involving gait rehabilitation and monitoring.
Our novel finding of step length asymmetry as an identifiable feature separating knee and hip OA, would require further reaffirmation in larger cohort of patients of different disease severity. This study further strengthens existing notable features of lower gait speed and decrease stride length. Gait modifications training is theorised to allow for offloading pressure on affected joints (i.e., decrease HAM impulse) allowing for slower disease progression (17). Thus, identifying the gait parameters is critical for rehabilitation in mild-to-moderate OA patients. This study differs from mainstream wearables research as it has a different wearable placement location and seeks to use the minimal number of wearables (more discreet and has better wearer compliance) (22, 24, 25). Some studies would beg to differ on the number of wearables. The reason would be that more wearables would provide additional compensatory joint motions that is difficult to discriminate from a single wearable sensor (21). However, this increases the complexity in interpreting the high-dimensional data to provide clear distinguishable gait signatures (21). The present study recruited participants with similar background characteristics (i.e. age, weight, BMI) that could influence compensatory gait movements (such as trunk lean). Furthermore, as the study was conducted in the same laboratory setting, the results are not subjected to operator-dependent bias.

**Limitations**

There are a few limitations that merit consideration when interpreting the results. This study recruited patients with severe OA requiring surgical intervention therefore the results are not generalizable to all OA patients. One notable limitation is that the study did not including ‘free-living’ gait and was conducted in a well-lit, obstacle-free hospital environment. Therefore, the results are not generalizable to the real-world conditions. Another limitation of this study is the lack of knee joint loading data to estimate the KFA and KAM values. This observational study did not incorporate force plates or pressure-sensitive shoes to measure the ground reaction force, which is required to calculate the KFM and KFA values. KFM and KFA have previously been demonstrated to correlate with disease progression. Stetter et al (2020) proven that with the use of machine learning technology (artificial neural network) with wearable sensors, the KFM and KFA values can be estimated (35). Furthermore, the recruitment process of the participants is limited to a single-center and single-surgeon practise. It is important to note that participants in this study was scheduled for joint replacement, therefore might not represent patients with less severe osteoarthritis. Despite the chest-based location, upper body motions were not evaluated in this study and potentially important discriminatory parameters are not studied (32).

**Future Research**

Future avenues of research should seek to explore wearable sensors’ diagnostic capabilities of different degrees of osteoarthritis severity according to radiographic evidence and clinical correlation. Furthermore, to incorporate machine learning technology with the use of wearable sensors for diagnosing, disease monitoring and/or rehabilitation in patients with osteoarthritis (355). Gait analysis using machine learning technology has seen increased utilisation in diseases involving balance (such as Parkinson Disease and Cerebellar Ataxia) and in upper limb ataxic movements (36–38). Despite the higher computational requirements, machine learning has shown great promise in accurately differentiating different types of pathological gait. Future studies should conduct a multi-center
recruitment process with a longer pre- and post-op study period inclusive of ‘free-living gait’. A larger cohort size allows for subgroup analysis of participants and for easier accommodation of participants dropout. Future studies can consider venturing into correlating the clinical findings (for example WOMAC score) with individual gait profiles. In addition to utilising objective scoring system, future studies could consider incorporating upper body motion as Boekesteijn et al (2021) highlighted the possibility of compensatory action with increase trunk range of motion (RoM) (32).

Conclusion

This study reported similar changes in speed related gait parameters of OA patients, as previously identified in other studies. In addition to that, this present study captured other domain of gait: step length asymmetry as a discriminatory feature between hip and knee OA. Our present study identifies that hip and knee OA patients have unique pathological signatures of gait impairment. Hip OA patients has overall larger percentage values for domains of asymmetry and variation gait parameters compared to knee OA. This present study validates that wearables are sufficient to detect and examine disease specific gait parametrics. Future steps should explore incorporating the use of wearable technology in clinical practise as a diagnostic tool or clinical adjunct in assessment and identification of gait disorders.

Abbreviations

OA Osteoarthritis
BMI Body Mass Index
SD Standard Deviation
CI Confidence Interval
IMU Inertial Measurement Unit
MMC MetaMotion® Wearable Sensor
IMUPY Modified IMUGaitPy Program
WOMAC Western Ontario McMaster Universities Osteoarthritis Index
KFM Knee Flexion Moments
KFA Knee Flexion Angle
KAM Knee Adduction Moments
HAM Hip Adductor Moment Impulse
HKA Hip-knee Angle
Declarations

Ethics approval and consent to participate

Ethics for this study was obtained from the South-Eastern Sydney Local Health District Ethics Board under reference code HREC: 17/184. Written consent was obtained from included participants prior to participation in this study.

Consent for publication

Not applicable

Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Author contributions

(I): Conception and design: RJM, MMM

(II): Administrative support: RJM, MMM, KR, LK

(III): Provision of study materials or patients: RJM, KR

(IV): Collection and assembly of data: RJM, KR

(V): Data analysis and interpretation: PN, RDF

(VI): Manuscript writing: All Authors

(VII): Final approval of manuscript: All authors

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References


**Figures**
Figure 1

Radar plot of walking metrics of THR group compared to age-matched controls. Percentage values represent magnitude of group difference* of walking metrics for THR participants (brown, n=29) from normative control participant values (grey, n=28) placed at 0%. *Calculated using Student's Independent t tests or Mann-Whitney U tests with normality confirmed using Shapiro-Wilk tests and inspecting histograms, with statistical significance at p < 0.05.
Figure 2

Radar plot of walking metrics of TKR group compared to age-matched controls. Percentage values represent magnitude of group difference* of walking metrics for TKR participants (orange, n=28) from normative control participant values (grey, n=28) placed at 0%. *Calculated using Student's Independent t tests or Mann-Whitney U tests with normality confirmed using Shapiro-Wilk tests and inspecting histograms, with statistical significance at p < 0.05.
Figure 3

Radar plot of walking metrics of THR and TKR groups compared to age-matched controls. Percentage values represent magnitude of group difference* of walking metrics for THR participants (brown, n=29) and TKR participants (orange, n=28) from normative control participant values (grey, n=28) placed at 0%. *Calculated using Student's Independent t tests or Mann-Whitney U tests with normality confirmed using Shapiro-Wilk tests and inspecting histograms, with statistical significance at $p < 0.05$. 