Patients with osteoarthritic knees have shorter orientation and tangent indicatrices during gait

Michael Raymond Pierrynowski\textsuperscript{a,}\textsuperscript{*}, Patrick A. Costigan\textsuperscript{b}, Monica R. Maly\textsuperscript{a}, Peter T. Kim\textsuperscript{c}

\textsuperscript{a}School of Rehabilitation Science, McMaster University, Hamilton, Ontario, Canada
\textsuperscript{b}School of Kinesiology and Health Studies, Queen’s University, Kingston, Ontario, Canada
\textsuperscript{c}Department of Mathematics and Statistics, University of Guelph, Guelph, Ontario, Canada

Abstract

Background: This study introduces two novel outcomes that could be used to identify people with knee osteoarthritis from healthy controls. These outcomes examine the lengths of paths on a sphere derived from knee angle and knee position during gait.

Methods: Participants with moderate knee osteoarthritis (n = 47) and no knee pathology (n = 51) walked overground. The time-varying orientation matrices and position vectors of the knee (leg relative to the thigh) were measured, then arclength (constant speed) parameterized. The orientation matrix column aligned with the long axis of the leg, and the tangent, normal and binormal vectors (Frenet Frame) along the position vectors were calculated. These unit length vectors all scribe paths (indicatrices) on a unit sphere. The path lengths of these indicatrices, for all or part of a gait cycle, were the novel outcomes. A stepwise discriminant analysis defined a linear function that included those outcomes that best allocated a participant to the osteoarthritis or control group.

Findings: Group differences were best detected with the indicatrix lengths associated with the orientation of the leg’s long axis over a gait cycle (P < 0.001) and the tangent vector over the stance phase (P = 0.014). Both outcomes were smaller in the knee osteoarthritis compared to control group. Walking speed was poorly correlated with all indicatrix lengths (q < |0.484|) and a discriminate analysis correctly classified 83.7% of the participants.

Interpretation: Smaller indicatrix measures distinguished those with knee osteoarthritis from healthy controls. These outcomes introduce a promising new kinematic approach when examining gait data.

1. Introduction

There is a need to identify people with knee osteoarthritis (KOA). While the exact causes of initiation and progression of KOA are not certain, there is consensus that joint load plays a role. While joint load is difficult to measure directly, an abnormal knee adduction moment profile is associated with both medial joint loading and the severity and prognosis of KOA (Amin et al., 2004; Andriacchi et al., 2004; Gok et al., 2002; Hunt et al., 2006; Hurwitz et al., 2002; Maly, 2009; Newell et al., 2008; Sharma et al., 1998; Weidenhielm et al., 1994). However, the clinical feasibility of measuring the knee adduction moment is limited since it requires expensive equipment to collect synchronized kinematic data and ground reaction force data, dedicated technical staff and the application of complex analysis techniques. Perhaps simpler measurements that reflect the underlying pathology could be developed. For example, abnormal kinematics have recently been proposed as a risk factor for the initiation of KOA (Andriacchi et al., 2004). This theory proposes that abnormal kinematics will lead to load-bearing on regions of the tibial plateau that are poorly conditioned for weight-bearing. Thus, a purely kinematic approach to detecting KOA could be useful in identifying pathology.

In this paper we introduce two novel knee kinematic outcomes that, together, identify patients with moderate KOA compared to healthy controls. These kinematic outcomes only require knowledge of the direction of the leg’s long axis (ankle–knee) and the location of the knee joint’s center as a participant walks, repetitively.

2. Methods

2.1. Participants

Potential participants with and without medial KOA were recruited to participate in this two group comparative study. All
participants signed a University Health Science Ethics Board approved informed consent document. Participants with other medical or musculoskeletal conditions were excluded. The KOA group (n = 51) consisted of community-dwelling adults over age 50 with physician-diagnosed, radiographic medial KOA, consistent with the diagnostic criteria presented by the American College of Rheumatology (Altman et al., 1986). Radiographs taken at the beginning of the study confirmed the diagnosis and that joint space narrowing was greater in the medial than lateral compartment. In cases of bilateral KOA (n = 26), the more painful limb was tested. The control group (CON, n = 47) had no clinical signs or symptoms (e.g., pain, stiffness, difficulty with physical function) and their radiographs showed no evidence of joint disease. The KOA participants were older and heavier than the CON participants (Table 1).

### 2.2. Protocol

The coordinates of markers placed on the thigh and leg were recorded at 50 Hz using motion capture (OptoTrak, Northern Digital, Waterloo, Ontario). In this paper the orientation of the (X, Y, Z) axes are not relevant but for interest were: X was positive in the forward walking direction, Y from lateral to medial, and Z from distal to proximal. The positions of the markers in a static reference position and during multiple overground level walking trials were collected. Each participant walked in a straight line at a self-selected speed multiple times over an in-floor embedded force plate (Model OR6-7, AMTI, Watertown, MA). Orthogonal radiographs were also used to register the positions of the surface markers relative to the coordinate system. For orientation we note that the third ‘‘Z’’ axis is directed parallel to the leg’s long axis (ankle–knee), a direction whose estimate is least dependent on experimenter skill compared to the knee’s shorter medial–lateral and anterior–posterior dimensions (Della Croce et al., 2005). Therefore we focused on the third column of the knee’s orientation matrix (\(\mathbf{R}_3\)). For the knee’s position vectors, we calculated the unit length tangential (\(\mathbf{T}\)) and binormal (\(\mathbf{B}\)) vectors which are intrinsic geometric properties of a position curve (part of the Frenet Frame), that are independent of the user defined coordinate system (Animov, 2001; Pierrynowski, 2009).

### 2.3. Analysis

The time-varying motions of the thigh and leg markers during each walking trial were used to estimate the \(3 \times 3\) orientation matrices of the leg with respect to the thigh and the \(3 \times 1\) position vector of the knee joint center (Costigan et al., 1992). The orientation matrices were parameterized to Cardan angles (alpha, beta, gamma; \(\mathbf{A, B, G}\)) using the XYZ axis sequence, however, any parameterization sequence could have been used. Within these data, the start and end of the stance phase of a gait cycle was defined when the vertical ground reaction force rose above and fell below 5% of its maximum. The end of swing, the subsequent heel contact that occurred between the force plate, was defined as that frame where the positions and velocities of the ankle markers best-matched the positions and velocities at initial heel contact. The distance the knee joint moved forward during a gait cycle provided an estimate of walking speed.

The knee orientation \(\{\mathbf{A, B, G}\}\) and knee position \(\{\mathbf{X, Y, Z}\}\) data for each gait cycle were least-square fitted to equations that included bias \((\text{mean})\), slope, and six sine/cosine curve pairs with periods 2\(\pi\), \(2/3\pi\), 1/1|2\pi, 2/3\pi, 1/3\pi (routine DFNLSQ, part of the IMSL Math Library, Visual Numerics, Inc., Houston, Texas, 1997). The summation of the upper sine/cosine pairs that contributed <5% to the spectral power were removed from further consideration. These equations, with slope omitted (linearly detrended), cyclically fit the knee orientation and position. We note that detrending the data made it appear that the participant was walking cyclically, as on a treadmill, the purpose of which is explained below.

The orientation and position knee kinematics within one gait cycle were collected at equal spaced times in the interval \([0, 2\pi]\). Consider an arclength parameterization where the knee orientation/position moves at constant angular/linear speed (i.e., moving equal angle/distance in each non-uniform time interval). This was accomplished by defining 701 unequal time steps within \([0, 2\pi]\) where the orientation matrix and the position vector moved at constant Riemannian and Euclidean speeds, respectively (Pierrynowski and Ball, 2009).

The arclength parameterized knee’s orientation matrices and position vectors were collected in an experimenter defined XYZ knee coordinate system. For orientation we note that the third ‘‘Z’’ axis is directed parallel to the leg’s long axis (ankle–knee), a direction whose estimate is least dependent on experimenter skill compared to the knee’s shorter medial–lateral and anterior–posterior dimensions (Della Croce et al., 2005). Therefore we focused on the third column of the knee’s orientation matrix (\(\mathbf{R}_3\)). For the knee’s position vectors, we calculated the unit length tangential (\(\mathbf{T}\)) and binormal (\(\mathbf{B}\)) vectors which are intrinsic geometric properties of a position curve (part of the Frenet Frame), that are independent of the user defined coordinate system (Animov, 2001; Pierrynowski, 2009).

Recall that we forced the knee’s motion during one gait cycle to be a closed loop and that \(\mathbf{R}_3\), \(\mathbf{T}\) and \(\mathbf{B}\) can be visualized as each tracing closed paths (indicatrices) on a unit sphere (Animov, 2001). We label the lengths of these indicatrices \(R_3i\), Ti and Bi. Additionally, we calculated the lengths of the indicatrices during stance (labeled by appending .st) to explore these outcomes when the knee is being used for support.

### 2.4. Statistics

Walking speed and the indicatrix lengths \([R_3i, Ti, Bi, R_3i.st, Ti.st, Bi.st]\), averaged over each participant’s multiple walks, were the primary outcomes. Pairwise scatterplots and Spearman rank correlations (\(\rho\)) were used to visually and numerically explore outcome distribution and independence. Additionally, the Kolmogorov–Smirnov statistic formally tested if each outcome was normally distributed and the Mann–Whitney U statistic indicated if an outcome differed between groups. A stepwise discriminant analysis was used to define a linear function that included those outcomes that best allocated a participant to the KOA or CON group. Statistics were obtained using SPSS V17.0 (SPSS, Inc., Chicago, Illinois) or R (R Development Core Team, 2007) and alpha less than 0.05 was used to statistically reject all null hypotheses.

### 3. Results

The KOA and CON groups’ walking speeds were normally distributed but the indicatrix outcomes were not (see diagonal plots within Fig. 1 and the Kolmogorov–Smirnov statistics in Table 2). This finding suggests the use of non-parametric statistics.

The KOA group had statistically lower walking speeds compared to the CON group (Mann–Whitney U, \(P = 0.046\)). More compelling group differences were detected with the \(R_3i\) (\(P < 0.001\)), \(R_3i.st\) (\(P < 0.001\)), and \(Ti.st\) (\(P = 0.014\)) indicatrix outcomes. The Ti, Bi and Bi.st outcomes did not discriminate between the two groups (see Table 2).

The associations between pairs of outcomes were explored using pairwise scatterplots (Fig. 1 upper tableau) and Spearman rank correlations (Fig. 1, lower tableau). Walking speed was poorly correlated with \(R_3i\) and \(R_3i.st\). Figure 1 and Table 2 provide a summary of the pairwise scatterplots and the corresponding parameter estimates, with standard deviations (SD), correlation coefficients (\(\rho\)), and p-values.

### Table 1

Descriptive characteristics of the knee osteoarthritis (KOA) and the healthy control (CON) groups.

<table>
<thead>
<tr>
<th>Variable</th>
<th>KOA group (n = 51)</th>
<th>CON group (n = 47)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean (SD)</td>
<td>Range</td>
<td>Mean (SD)</td>
</tr>
<tr>
<td>Age (years)</td>
<td>68 (9)</td>
<td>50–87</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>82 (15)</td>
<td>52–127</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>169 (10)</td>
<td>149–191</td>
</tr>
<tr>
<td>Body mass index (kg/m²)</td>
<td>29 (3)</td>
<td>20–44</td>
</tr>
</tbody>
</table>

### Table 2

Body mass index (kg/m²) 29 (3) 20–44 26 (4) 18–36

### Table 3

Height (cm) 169 (10) 149–191 167 (10) 150–186

### Table 4

Mass (kg) 82 (15) 52–127 75 (15) 48–110

### Table 5

Age (years) 68 (9) 50–87 67 (9) 46–87

### Table 6

correlated with all indicatrix lengths \((\rho < 0.484)\). The Ti–Ti.st, Bi–Bi.st, and R3i–R3i.st pairs demonstrated high correlations \((\rho = 0.853, 0.836, \text{and } 0.890, \text{respectively})\) which suggest that these indicatrix lengths during stance versus the total gait cycle are associated.

Stepwise discriminant analysis was used to determine a discriminate score \((ds)\) that separate the KOA and CON groups using progressively larger sets of the walking speed and indicatrix length outcomes \((\text{Fig. 2})\). The function \(ds = 0.5227 \text{ Ti.st} + 3.4748 \text{ R3i} – 12.1138\), where scores less than zero indicate KOA group membership, correctly classified 83.8% of the cases with eight false positives \((\text{eight CON with } ds < 0.0)\) and eight false negatives \((\text{eight KOA with } ds > 0)\). For the KOA and CON participants used in this study the ds range was \([-3.078 \text{ to } 3.068]\).

**Table 2**

<table>
<thead>
<tr>
<th>Outcome</th>
<th>Group</th>
<th>Quartiles</th>
<th>Kolmogorov–Smirnov</th>
<th>Mann–Whitney U</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>25 50 75</td>
<td>Statistic Probability</td>
<td>Statistic Probability</td>
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<tr>
<td>Speed</td>
<td>CON</td>
<td>0.977 1.118 1.253</td>
<td>0.085 0.073</td>
<td>937 0.046*</td>
</tr>
<tr>
<td></td>
<td>KOA</td>
<td>0.868 0.996 1.152</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ti</td>
<td>CON</td>
<td>8.862 10.145 11.378</td>
<td>0.100 0.016*</td>
<td>976 0.085</td>
</tr>
<tr>
<td></td>
<td>KOA</td>
<td>8.629 9.506 10.651</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bi</td>
<td>CON</td>
<td>10.969 12.173 13.631</td>
<td>0.112 0.004*</td>
<td>1202 0.892</td>
</tr>
<tr>
<td></td>
<td>KOA</td>
<td>10.706 12.289 13.644</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R3i</td>
<td>CON</td>
<td>2.613 2.756 2.933</td>
<td>0.139 &lt;0.001*</td>
<td>350 &lt;0.001*</td>
</tr>
<tr>
<td></td>
<td>KOA</td>
<td>1.978 2.421 2.548</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ti.st</td>
<td>CON</td>
<td>5.865 6.650 7.671</td>
<td>0.142 &lt;0.001*</td>
<td>873 0.014*</td>
</tr>
<tr>
<td></td>
<td>KOA</td>
<td>5.385 5.924 6.714</td>
<td></td>
<td></td>
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<tr>
<td>Bi.st</td>
<td>CON</td>
<td>7.240 8.228 9.701</td>
<td>0.107 0.007*</td>
<td>1030 0.180</td>
</tr>
<tr>
<td></td>
<td>KOA</td>
<td>7.529 8.845 10.208</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R3i.st</td>
<td>CON</td>
<td>1.421 1.511 1.601</td>
<td>0.137 &lt;0.001*</td>
<td>494 &lt;0.001*</td>
</tr>
<tr>
<td></td>
<td>KOA</td>
<td>1.074 1.288 1.439</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

R3i and Ti.st are typically smaller for a person with KOA. A visual representation of R3i and Ti.st for a KOA (ds = -2.817) and CON (ds = 2.781) participant are plotted in Figs. 3 and 4.

4. Discussion

This study uses a novel method to examine knee kinematic gait data. We have shown that the time-varying 3D knee kinematics, summarized to two arclength parameterized values, identified healthy and mildly osteoarthritic knees with high diagnostic sensitivity and specificity. Specifically, the length of the tangent indicatrix during stance derived from the knee’s position (Ti.st) and the gait cycle length of an indicatrix derived using the direction of the ankle to the knee (R3i) in participants with KOA are significantly shorter.

The smaller values of R3i and Ti.st outcomes compactly summarize the altered kinematics of knees with KOA compared to healthy knees. These reduced lengths may reflect structural limitations at the level of the joint, such as cartilage degradation, osteophyte formation, altered joint geometry and misalignment (Andriacchi et al., 2004; Sharma et al., 1998). Structural changes may obstruct normal articulation between the femoral and tibial surfaces. However, smaller R3i and Ti.st outcomes may also reflect altered neuromuscular control of the knee. Muscle atrophy, inactivation and altered coordination may limit the control of knee motion (Bennell et al., 2008). Similar to control of the center of mass within the base of support, limited neuromuscular control may translate into limited excursions of the knee joint center during dynamic activity. Further work is necessary to identify the causes of altered R3i and Ti.st values among the KOA group.

The R3i and Ti.st outcomes provide a useful approach to detect knee kinematic differences between KOA and healthy subjects. To date, discriminating between these groups has focused on the peak knee adduction moment, though few well-controlled studies have distinguished patients with KOA (Foroughi et al., 2009), perhaps due to methodological challenges (Newell et al., 2008). Principal components analysis (PCA) of knee kinematics and kinetics has proven useful in identifying patients with severe KOA (Deluzio et al., 2000).
and Astefan, 2007), with a misclassification rate of 8%. In this study R3i and Ti misclassified 16 of 98 knees. Given that the kinematic method used here summarizes relatively little information compared to the PCA and looked at moderate KOA compared to severe KOA, the R3i and Ti.st outcomes performed well in identifying the pathological gait patterns. Additionally, the R3i and Ti.st outcomes show good potential for use within clinical settings. Simple instrumentation, such as inertial measurement units, firmly attached to the thigh and leg, provides the minimum information necessary for these outcomes (Gouwanda and Senanayake, 2008). Marker-less motion capture also provide similar data with even less equipment attached to each patient (Corazza et al., 2006).

Limitations of this study include generalizability to the KOA sample in this study. The KOA subjects included in this study demonstrated both radiographic signs and symptoms consistent with the diagnostic criteria presented by the American College of Rheumatology. Because diagnosis may be confirmed with either radiographic signs or clinical symptoms this sample represents a smaller subgroup of patients with KOA.

Our findings highlight the importance of examining gait kinematics to understanding KOA. It has been proposed that abnormal knee kinematics are involved in the initiation of KOA (Andriacchi et al., 2004). Altered kinematics may shift load-bearing contact to regions within the knee that are poorly adapted for weight-bearing (Andriacchi et al., 2004). Several studies have described discrete kinematic abnormalities unique to KOA, such as restrictions in sagittal knee motion (Kaufman et al., 2001; Messier et al., 1992) that reflect a conservative approach to knee motion during walking. The shortened indicatrix lengths indicative of altered kinematics in subjects with KOA appear consistent with these studies. Finally, the R3i and Ti.st outcomes show promise to be used in future investigations that endeavor to identify knee kinematic gait changes during the pre-clinical stages of the disease.

Acknowledgements

This work was supported by McMaster and Queen’s Universities and the Natural Sciences and Engineering Council of Canada.

References


