Gait analysis of patients with knee osteoarthritis by using elevation angle: confirmation of the planar law and analysis of angular difference in the approximate plane

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ABSTRACT
Evaluating knee osteoarthritis is an important issue. Gait pattern has been suggested to be related to the progression of knee osteoarthritis; however, there are only a few studies elucidating the motion features associated with knee osteoarthritis. Therefore, our objective is to analyze the elevation angle of patients with knee osteoarthritis during gait and to clarify the movement features by an approximate plane of the elevation angle. As a result, the same planar law could be applied to patients with knee osteoarthritis as well as to healthy people. The patients have approximate plane slopes that differ from that of healthy people. Our validation results have shown that these angular differences can distinguish between the patients and healthy people.

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KEYWORDS
Knee osteoarthritis; elevation angle; gait analysis; principal component analysis; planar law

1. Introduction
Knee osteoarthritis is a disease that causes pain from cartilage and meniscus damage. This disease leads to walking disorders and decreases a person’s quality of life. In an aging society, the number of patients who suffer from knee osteoarthritis is increasing. The number of potential patients with knee osteoarthritis is estimated to be over 100 million people in the world.\cite{1} Therefore, effective prevention of the disease is desirable. Knee osteoarthritis is known as an irreversible progressive disease caused by aging. However, it is possible to delay the progress of the disease by appropriate treatments. Therefore, an effective and easy method to evaluate the disease is needed. Currently, radiographic methods are commonly used to evaluate knee osteoarthritis. However, radiographic evaluation does not always correspond to clinical status in some patients with chronic knee pain.\cite{2} Magnetic resonance imaging (MRI) has been reported to have better accuracy for evaluating knee osteoarthritis than conventional radiographic methods.\cite{3} However, the MRI method has some disadvantages: high cost, limited availability, and long examination times. Therefore, evaluation methods to evaluate the disease without MRI have been investigated and one with potential promise is the study of gait motion.

In previous studies, it has been suggested that particular gait patterns, especially lower limb alignment, cause the disease.\cite{4-6} Some gait patterns, for example varus gait, give repetitive loading to anterior cruciate ligament and joint cartilage. This mechanism is one of the hypotheses proposed as an explanation for the progress of the disease. In other studies, patients with knee osteoarthritis have different gait patterns as a result of their pain.\cite{7-11} It is reported that the peak knee flexion angle during the stance phase of the patients is lower than that of healthy people. Thus, it is thought that an abnormal gait is one of cause and effects of the disease and it is also considered that gait patterns can be used as a diagnostic index.

Our proposed gait motion evaluation method has two advantages compared to radiographic evaluation and MRI. First, the patients do not need to be exposed to radiation. Radiographic evaluation can be used to obtain an index with a load and this enables the effect on joint deformity to be determined. A condition with a load means an usual static condition of the knee joint during standing. However, the radiographic method requires that patients be exposed to radiation. Second, our method can evaluate the subject’s locomotion under dynamic conditions rather than just a static condition. Knee dynamic evaluation can measure stress induced by
weight bearing and sometimes the impact by ground contact causing the joint deformity. Because the patients lie on the examination table during MRI, only an unloaded knee condition can be measured. This means that this type of method cannot be used to evaluate the effect of pain on joints of the lower extremities. Moreover, both radiographic and MRI methods can only yield static data, and static data cannot be used to evaluate the mobility of the subjects. A three-dimensional gait analysis evaluation method can provide a dynamic index with various loads and without radiation exposure. This is because gait analysis includes dynamic data from both the stance phase and from swing phase motion. Moreover, it would be useful to detect the disease early even in the clinical environment using easily equipped sensors. Recently, gait analysis has been performed by newly developed sensors, such as a wearable gyroscope sensor, that can measure the joint angle during gait with enough accuracy [12] and at low cost.

However, there are few studies in which gait pattern features of knee osteoarthritis patients have been extracted. Previous studies have focused on the knee flexion angle in gait and have revealed certain features. [7–11] In one of these studies, patients were discriminated based on the range of motion of knee joint flexion. [8] However, the diagnostic accuracy of the knee flexion measurement was not high, with the area under the receiver operating characteristic curve (AUC) which is a common evaluation metric for binary classification problems, falling 0.63 it is between 0.5 and 0.7. [13–15] In that study, they just focused on knee joint movement but did not address other joint movements. In general, the patients have different joint movements from those of healthy people. Therefore it is thought that gait features including hip, knee, and ankle motion are needed. Recently, robot technology used in medical applications and human motion analysis has become a topic in robot research. [16] Moreover, a walking assist robot become popular and such robot can be utilized as a joint angle sensor to analyze gait motion.

The elevation angle (the angle between the limb segment and the vertical) is one known method used to elucidate gait pattern features of healthy people. [17,18] In this method, time-varying joint angle changes of the hip, knee, and ankle joints can be projected onto a single plane. This method demonstrated the validity of the planar law for the gait patterns of healthy people: A point group appears on a single plane when the three elevation angles during one gait cycle are plotted in three-dimensional space. This method would be useful for understanding features of patients with knee osteoarthritis during bipedal gait. If different features between healthy people and patients with knee osteoarthritis can be identified, this could be an important diagnostic index.

Therefore there are two objectives in this study. First, we investigate the locomotion pattern of patients with knee osteoarthritis to clarify the characteristic gait pattern calculating angular changes by motion analysis. Second, we validate a new diagnostic index of knee osteoarthritis by analyzing the gait features. Compared to the previous idea, in which the peak knee flexion angle during the stance phase is used, we confirm that the new diagnostic index of knee osteoarthritis is a valid metric.

2. Method

2.1. Calculation of approximate plane

One of the common features of the human gait is the planar law, revolutionary finding in gait research. [17,18] Figure 1 shows the definition of the elevation angle of the lower limb (thigh, shank, and foot). Elevation angles are between the segment and the vertical direction in the sagittal plane. When these three angles during one gait cycle are plotted in three-dimensional space, a point group appears on one plane. This is called the planar law. Figure 2 shows an example of the elevation angle of one leg during one gait cycle. The black mesh indicates the approximate plane of the point group of the elevation angles. Green and red lines indicate two basis vectors of the approximate plane. The blue line indicates the normal vector of the approximate plane. In the figure, ‘hs’ and ‘to’ indicate the gait event timings of heel strike and toe off. The planar law means that these elevation angles are not independent but can be explained by two degrees of freedom. Investigating whether or not the planar law applies to the patients’ gait can perhaps provide an index of gait disorder. If the planar law can explain the patients’ gait, then the slope of the approximate plane can be an index of gait disorder.

In this study, principal component analysis (PCA) is used to calculate the approximate plane from measurement data. PCA is a method to rotate rectangular Cartesian coordinates and extract principal components to maximize the variance in the new coordinate system. By this method, the first and second principal components can explain three elevation angles when the planar law holds. The first and the second principal component vectors are the basis vector of the approximate plane. The third principal component vector is the normal vector of the approximate plane. The process of using PCA to calculate the approximate plane of the elevation angles
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Figure 1. Definition of elevation angles. Elevation angles are between the segment and the vertical direction in the sagittal plane. $\theta_{\text{thigh}}$ is the angle between the thigh (between the hip joint and the knee joint) and the vertical direction. $\theta_{\text{shank}}$ is the angle between the shank (between the knee joint and the ankle joint) and the vertical direction. $\theta_{\text{foot}}$ is the angle between the foot (between the ankle joint and the toe) and the vertical direction.

In the figure, HAT is the upper body includes the head, arms, and trunk.

follows that used in a previous study.\[18\] The input data for the PCA are

$$X = \begin{bmatrix}
\theta_{\text{thigh}}(t) \\
\theta_{\text{shank}}(t) \\
\theta_{\text{foot}}(t)
\end{bmatrix} = \begin{bmatrix}
\theta_{\text{thigh}}(1) & \theta_{\text{thigh}}(2) & \cdots & \theta_{\text{thigh}}(T_{\text{max}}) \\
\theta_{\text{shank}}(1) & \theta_{\text{shank}}(2) & \cdots & \theta_{\text{shank}}(T_{\text{max}}) \\
\theta_{\text{foot}}(1) & \theta_{\text{foot}}(2) & \cdots & \theta_{\text{foot}}(T_{\text{max}})
\end{bmatrix}. \quad (1)$$

Elevation angles are taken during one gait cycle ($1 \leq t \leq T_{\text{max}}$). The output data from the PCA are composed of three eigenvectors and three eigenvalues. The first eigenvector ($u_1$), the second eigenvector ($u_2$), and the third eigenvector ($u_3$) are the first basis vector, the second basis vector and the normal vector of the approximate plane, respectively. The first eigenvalue ($\sigma_1^2$), the second eigenvalue ($\sigma_2^2$), and the third eigenvalue ($\sigma_3^2$) are the variance of the first principal component, the variance of the second principal component and the variance of the third principal component, respectively.

Contribution ratios of the first and the second principal components are calculated to investigate how the approximate plane fits the measurement data. The sum of the contribution ratios of the first and the second principal components gets closer to 1.0 when the planar law holds. The sum of the contribution ratios is called the cumulative contribution ratio. The contribution ratio is the variance of the $j$th principal component divided by the sum of the variance of all principal components:

$$CR(j) = \frac{\sigma_j^2}{\sum_{i=1}^{3} \sigma_i^2}. \quad (2)$$

Figure 2. An example of a three-dimensional plot of elevation angles. Purple points indicate elevation angle data taken at the same time. The figure shows elevation angle data during one gait cycle. The three axes indicate $\theta_{\text{thigh}}, \theta_{\text{shank}}$, and $\theta_{\text{foot}}$, respectively. The black mesh indicates the approximate plane of the point group of elevation angles. Green and red lines indicate two basis vectors of the approximate plane. The blue line indicates the normal vector of the approximate plane. In the figure, ‘hs’ and ‘to’ indicate the gait event timings of heel strike and toe off, respectively.

In this study, the contribution ratios of healthy elderly people, healthy young people, and the patients are calculated to compare healthy people and the patients.

2.2. Angular difference of approximate plane slope

In this study, data from healthy young people, healthy elderly people, and the patients are used. In general, it is known that elderly people and young people have different gait patterns due to aging.\[19\] Moreover, it is important to correctly distinguish between the patients and the elderly for clinical use. To investigate how to distinguish between the effects of disease and those of age, young healthy people data were used as representative data in the proposed method. If the proposed method is not influenced by the age effect, the representative data of young healthy people data can distinguish the disease data and elderly healthy data clearly.

The representative plane is defined as the approximate plane of all healthy young people data. It is assumed that all healthy people have approximate planes with the same slope. Healthy young people data are used for both the representative plane and the individual plane. In this study, 13 patients with knee osteoarthritis, 13 healthy elderly people, and 13 healthy young people were chosen as participants. In total, 14 affected legs are used because one of the patients has both legs affected by knee osteoarthritis. Subject details are presented in Section 2.5.1. Therefore, a total of 67 planes need to be calculated:
To calculate the representative plane, PCA is applied with the substitution of $X^{\text{allyoung}}$ for $X$. The angular difference between the representative plane and each plane is calculated to understand the difference between the approximate planes of healthy elderly people from those of the patients. It is calculated with the angular difference of the first basis vector, the second basis vector, and the normal vector, respectively, by

$$
\phi_{i}^{\text{patient}} = \cos^{-1}\left(\frac{u_{i}^{\text{patient}} \cdot u_{i}^{\text{allyoung}}}{\|u_{i}^{\text{patient}}\| \|u_{i}^{\text{allyoung}}\|}\right), \quad (4)
$$

$$
\phi_{i}^{\text{elderly}} = \cos^{-1}\left(\frac{u_{i}^{\text{elderly}} \cdot u_{i}^{\text{allyoung}}}{\|u_{i}^{\text{elderly}}\| \|u_{i}^{\text{allyoung}}\|}\right), \quad (5)
$$

$$
\phi_{i}^{\text{young}} = \cos^{-1}\left(\frac{u_{i}^{\text{young}} \cdot u_{i}^{\text{allyoung}}}{\|u_{i}^{\text{young}}\| \|u_{i}^{\text{allyoung}}\|}\right). \quad (6)
$$

In Equations (4)–(6), $u_{i}$ is the $i$th eigenvector of the PCA (as is shown in Section 2.1). It is expected that the angular difference between the representative plane and the approximate plane of healthy elderly people is smaller than that of the patients because the patients have different gait patterns. In this study, $\phi_{3}^{\text{elderly}}$ and $\phi_{3}^{\text{young}}$ are used as a gait evaluation index. $\phi_{3}^{\text{patient}}$ is the angular difference between the normal vector of the representative plane and that of the approximate plane of each patient with knee osteoarthritis. $\phi_{3}^{\text{elderly}}$ is the angular difference between the normal vector of the representative plane and that of the approximate plane of each healthy elderly person.

### 2.3. Peak knee flexion angle during the stance phase

To compare our diagnosis methodology to the previous idea, the knee flexion angle is analyzed.\[9–11\] Figure 3 shows the definition of the knee flexion angle. SIMM (MusculoGraphics Inc.) software is used to calculate the knee flexion angle during gait motion. For the knee flexion angle, a positive value means flexion and a negative value means extension. Humans have two knee flexion angle peaks during one gait cycle. The peak angle during the stance phase is different between healthy people and the patients in previous studies. Therefore, peaks of knee flexion angle during the stance phase of healthy elderly people and the patients are analyzed in this study. It is known that the peak of knee flexion angle during the stance phase of the patients is smaller than that of healthy people.\[9–11\]

### 2.4. Validation

#### 2.4.1. Cross-validation

Cross-validation is conducted to confirm the decision accuracy between the patients and elderly healthy people of the proposed diagnostic index and the previous index. The results of the diagnostic decision are divided into four types: patients classified as diseased (true positive), healthy people classified as diseased (false positive), patients classified as healthy (false negative), and healthy people classified as healthy (true negative). $TP$, $FP$, $FN$, and $TN$ indicate the numbers of true positives, false positives, false negatives, and true negatives, respectively. Accuracy ($ACC$), precision ($PRE$), recall ($REC$), and F-measure ($F$) are calculated using

$$
ACC = \frac{TP + TN}{TP + FP + FN + TN}.
$$

![Figure 3. Definition of the knee flexion angle. The knee flexion angle is defined as that between the thigh segment and the shank segment.](image)

[Figure 3. Definition of the knee flexion angle. The knee flexion angle is defined as that between the thigh segment and the shank segment.]


\[
PRE = \frac{TP}{TP + FP}, \tag{8}
\]

\[
REC = \frac{TP}{TP + FN}, \tag{9}
\]

\[
F = \frac{2 \cdot PRE \cdot REC}{PRE + REC}. \tag{10}
\]

ACC indicates the ratio of the number of truly classified patients to all participants. **PRE** indicates the ratio of the number of truly classified patients to all diagnosed patients. **REC** indicates the ratio of the number of truly classified patients to all actual patients. **F** indicates the harmonic mean of **PRE** and **REC**. The relationship between precision and recall is a trade-off. Therefore, in this study the F-measure is maximized to determine a good balance threshold.

It is thought that the lower the angular difference of the normal vector is, the closer the subject is to being healthy. Therefore, subjects over the threshold are classified into the disease group and those under the threshold are classified into the healthy group. First, three legs of elderly healthy people and three legs of the patients are excluded. Then the remaining 23 legs of elderly healthy people and 11 legs of the patients are included in the training data to determine the threshold of discrimination.

The threshold is determined by maximizing **F**. These processes are conducted on the angular difference of the normal vector of the approximate plane and the peak knee flexion angle, respectively. To confirm the accuracy of the two methods, the three legs of elderly healthy people and three legs of the patients are tested by the calculated threshold. **F** is searched as the threshold is changed between 0 and 50 by 0.1. There are combinations of 3 legs in 26 legs of the elderly healthy people and combinations of 3 legs in 14 legs of the patients. All combinations are tested. The means and standard deviations (SDs) of **ACC**, **PRE**, **REC**, **F**, and the threshold are calculated.

### 2.4.2. Receiver operating characteristic analysis

Receiver operating characteristic (ROC) analysis is performed to confirm the decision accuracy between the patients and healthy elderly people of the proposed methodology and the previous methodology. ROC analysis has been used in many clinical studies to calculate the accuracy of the suggested diagnostic index.[20–22] The ROC curve is data plotted with **REC** on the vertical axis and 1–specificity (SPE) on the horizontal axis. **SPE** is calculated by

\[
1 - SPE = 1 - \frac{FP}{FP + TN}. \tag{11}
\]

In this study, the ROC curve-plotted threshold is changed between 0 and 50 by 0.01. The area under the curve (AUC) is the area under the line of the ROC curve. This index indicates the total quantitative accuracy of discrimination.[13–15] AUC values are between 0.5 and 1.0. Higher values indicate a higher accuracy of classification.

### 2.5. Measurement

#### 2.5.1. Subjects

Measurement were made on 13 patients (3 male and 10 female) with knee osteoarthritis. Their average age was 71.1 ± 8.4; seven had their right leg affected, five had their left leg affected, and one had both legs affected. Almost all the patients participating in this study have some degree of knee osteoarthritis in their both legs. However, since the apodictic legs with knee osteoarthritis are needed in this study, only legs that are diagnosed by a medical doctor and also need artificial knee joint replacement in a few days are used as affected legs. All patients with knee osteoarthritis had knee replacement arthroplasty a few days after measurement. Before starting the experiment, details of the experiment were explained to the participants and their written consent was obtained. This study was conducted with the approval (1264) of the Ethics Committee of the University of Tokyo. Data from 13 healthy elderly people (3 male and 10 female) of average age of: 69.7 ± 2.3 and 13 healthy young people (3 male and 10 female) of average age of: 42.5 ± 4.9 from the AIST gait database are used.[23] Tracked marker data during one gait cycle from the AIST database 2013 are used.

#### 2.5.2. Experimental environment and procedure

Nine optical motion capture cameras (VICON Motion Systems, Ltd.) were used to measure the patients’ gait motion. The sampling rate was 100 Hz. A plug-in-gait marker set was used. In this study, eight markers, (right anterior superior iliac spine (RASI), left anterior superior iliac spine (LASI), right knee (RKNE), left knee (LKNE), right ankle (RANK), left ankle (LANK), right toe (RTOE) and left toe (LTOE)) on the hip, knee, ankle joints, and foot toe were used. For the data for healthy people, the raw marker trajectory from the AIST gait database (whose sampling rate is 200 Hz) was used. The trajectory of each marker was normalized to 100 % by the cubic spline interpolation method (1 ≤ t ≤ 101). Markers were attached to the subject’s body surface or tightly onto clothes. First, static poses were measured. Then subject walked in the measurement field. About three gait cycle were measured. One gait cycle was defined as the duration between every heel contact of the right leg. The subjects walked at their usual walking speed. There were no guidelines about arm movement or line of sight. All tracking marker data were filtered through a 6 Hz low pass filter.
3. Results

3.1. Confirmation of the planar law

Figure 4 shows three-dimensional plots of elevation angles of the right leg of 13 healthy elderly people. Figure 5 shows three-dimensional plots of the elevation angles of the affected 14 legs during locomotion of patients with knee osteoarthritis. These figures show elevation angle data during one gait cycle. Purple points indicate time-series data of elevation angles. The three axes indicate $\theta_{\text{thigh}}$, $\theta_{\text{shank}}$, and $\theta_{\text{foot}}$, respectively. The black mesh indicates the approximate plane of the point group of elevation angles. Green and red lines indicate two basis vectors of the approximate plane. The blue line indicates the normal vector of the approximate plane. Plots of healthy elderly people are visually similar though plots of the patients are not similar to each other.

Table 1 shows the contribution ratios of the first and the second principal components of the patients, healthy elderly people, healthy young people, and the representative plane. The right column shows the sum of contribution ratios of the first and the second principal components. All of the cumulative contribution ratios, including that for the patients’ data, are >0.98. Thus, we conclude that the planar law can hold for the patients as well as for healthy people. The table also shows that all healthy young people have approximate planes with similar slope.

3.2. Angular difference in the approximate plane

Figure 6 shows a scatter plot of the diagnostic index and the threshold. The horizontal axis indicates the value of the diagnostic index. The red diamonds indicate the patient data, the blue circles indicate healthy elderly people data, and the black-dotted line indicates the threshold and standard deviations (indicated by upper and lower light color lines).

Table 2 shows the angular difference between the first and the second basis vectors and the normal vector of the representative plane from healthy young people data and the approximate plane of the patients, healthy elderly, and healthy young people. All of the angular differences of the first basis, second basis, and normal vectors of the patients are larger than those of healthy elderly people. A t-test computed for the angular difference between the patients and healthy elderly people confirms that these differences are significant ($p < 0.01$). These $p$ values are shown in Table 2. The approximate plane of the patients has a different slope from that of healthy people. However, the angular differences of the healthy elderly people is similar to those of healthy young people. Therefore the angular difference is not influenced by the age effect and it is thought to be better diagnostic index.

Table 3 shows the results of the AUC, accuracy, precision, recall, F-measure, and threshold of the proposed method and the previous method. The proposed method indicates discrimination by the angular difference of the normal vector of the approximate plane. The previous method indicates discrimination by the peak knee flexion angle during the stance phase. Compared with the previous method, in the proposed method the AUC, accuracy, precision, recall, and F-measure are all increased. Figure 7 shows the ROC curves for the proposed method and for the previous method. In the figure, one sees that the curve for the proposed method is closer left and upper area than the previous method.

4. Discussion

Our results demonstrate that the planar law is applicable to the patients gait analysis because the cumulative contribution ratio is > 0.98. The angular difference of the normal vector of the approximate plane can be used to distinguish the patients and healthy elderly people.

The sums of contribution ratios of the first and the second principal components, including the patients’ data, are >0.98, which means that the planar law is also applicable to the gait pattern of the patients. One study shows that the planar law can be applicable even to bipedal walking of the Japanese macaque.[24] Thus there is high possibility that the planar law can be applicable when

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Table 1. Contribution ratio.

<table>
<thead>
<tr>
<th></th>
<th>CR(1)</th>
<th>CR(2)</th>
<th>CR(1)+CR(2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patients</td>
<td>0.869 ± 0.017</td>
<td>0.118 ± 0.019</td>
<td>0.986 ± 0.005</td>
</tr>
<tr>
<td>Elderly people</td>
<td>0.887 ± 0.015</td>
<td>0.102 ± 0.015</td>
<td>0.989 ± 0.003</td>
</tr>
<tr>
<td>Young people</td>
<td>0.886 ± 0.011</td>
<td>0.104 ± 0.012</td>
<td>0.990 ± 0.002</td>
</tr>
<tr>
<td>Representative plane</td>
<td>0.881</td>
<td>0.105</td>
<td>0.986</td>
</tr>
</tbody>
</table>

Notes: Values are the mean ± SD (without the representative plane). CR(1) is the contribution ratio of the first principal component. CR(2) is the contribution ratio of the second principal component. CR(1) + CR(2) is the sum of CR(1) and CR(2).

Table 2. Angular differences between the patients, elderly people, and young people.

<table>
<thead>
<tr>
<th></th>
<th>$\phi_1$ [deg]</th>
<th>$\phi_2$ [deg]</th>
<th>$\phi_3$ [deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patients</td>
<td>4.54 ± 3.43</td>
<td>11.74 ± 7.59</td>
<td>11.12 ± 7.43</td>
</tr>
<tr>
<td>Elderly people</td>
<td>2.02 ± 1.33</td>
<td>4.89 ± 3.31</td>
<td>5.01 ± 3.43</td>
</tr>
<tr>
<td>Young people</td>
<td>2.32 ± 1.66</td>
<td>4.82 ± 3.27</td>
<td>4.70 ± 3.10</td>
</tr>
</tbody>
</table>

Notes: Values in the first and second rows are the mean ± SD. $\phi_1$ is the angular difference between the first basis of the representative plane and that of each approximate plane. $\phi_2$ is the angular difference between the second basis of the representative plane and that of each approximate plane. $\phi_3$ is the angular difference of the normal of the representative plane and that of each approximate plane. The $p$ value is calculated between data for the patients and for elderly people.
Figure 4. Three-dimensional plots of elevation angles of the right legs of 13 healthy elderly people. These figures show elevation angle data during one gait cycle. Purple points indicate time-series data of elevation angles. The three axes indicate $\theta_{\text{thigh}}$, $\theta_{\text{shank}}$, and $\theta_{\text{foot}}$, respectively. The black mesh indicates the approximate plane of a point group of elevation angles. Green and red lines indicate two basis vectors of the approximate plane. The blue line indicates the normal vector of the approximate plane.

Table 3. Comparison of AUC, accuracy, precision, recall, F-measure and threshold.

<table>
<thead>
<tr>
<th>Method</th>
<th>AUC</th>
<th>ACC ± DEG</th>
<th>PRE ± DEG</th>
<th>REC ± DEG</th>
<th>F ± DEG</th>
<th>Threshold (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proposed</td>
<td>0.767</td>
<td>0.69 ± 0.14</td>
<td>0.84 ± 0.23</td>
<td>0.57 ± 0.26</td>
<td>0.66 ± 0.15</td>
<td>8.56 ± 1.80</td>
</tr>
<tr>
<td>Previous</td>
<td>0.574</td>
<td>0.60 ± 0.14</td>
<td>0.76 ± 0.30</td>
<td>0.38 ± 0.27</td>
<td>0.56 ± 0.14</td>
<td>35.12 ± 7.72</td>
</tr>
</tbody>
</table>

patients can walk without walking aids (such as a t-cane or a circular walker). One study shows that the elevation angle can be interpreted by harmonic analysis and the researchers investigated the planar law requirement by a mathematical model with various frequency and phase of the gait.[25] As a result, the planar law can be applicable when all fundamental frequencies are equal or if the frequency of the shank and foot are equal while the phase of the shank and foot are also equal. Some elevation angles of the patients can be understood by harmonic analysis. When their frequencies of the thigh, shank, and foot are equal, this corresponds to the result of the previous study. Therefore, it is thought that the planar law can be applicable to patients with knee osteoarthritis. However, this is not proven by the harmonic analysis, so this is a limitation of this study.

The approximate plane is thus confirmed to be a discriminative index between the patients and healthy people. The reason why the proposed method has a higher accuracy of decision is thought to be that the new index can include the abnormal motion of patients with knee osteoarthritis. In general, gait patterns of the patients are different from those of healthy people. The approximate plane is made by the elevation angles of the thigh, shank, and foot. Therefore, the position of the plane is affected by gait patterns. Table 4 shows the range of motion calculated by the elevation angle (thigh, shank, and foot) of the patients and healthy elderly people. These values indicate the difference between maximum and minimum elevation angles in one gait cycle. Each value indicates an average of the individual subject and a standard deviation. The last row indicates the difference between the average of the patients and that of healthy elderly people. The range of thigh angles of the patients is similar to that of healthy elderly people. However, the ranges of shank and foot movement are 10 degrees smaller than those of healthy elderly people. Thus the lower limb motions of the patients have different relationship from those of
Figure 5. Three-dimensional plots of elevation angles of the patients with knee osteoarthritis-affected legs (14 in total). These figures show elevation angle data during one gait cycle. Purple points indicate elevation angle data taken at the same time. The three axes indicate $\theta_{\text{thigh}}$, $\theta_{\text{shank}}$, and $\theta_{\text{foot}}$, respectively. The black mesh indicates the approximate plane of the point group of elevation angles. Green and red lines indicate two basis vectors of the approximate plane. The blue line indicates the normal vector of the approximate plane. The lower right figure with axis label is the three-dimensional plot of elevation angles of the healthy elderly people.

Figure 6. Scatter plot of the diagnostic index and the threshold. The horizontal axis indicates the value of the diagnostic index. The red diamonds indicate patient data, the blue circles indicate data from healthy elderly people, and the black-dotted line indicates the threshold and standard deviation (upper and lower light color lines).

healthy people as a result of the knee osteoarthritis. This is the reason for the angular difference of the approximate plane.

In Section 2.4.1, the number of training data for healthy people is larger than that for the patients. Therefore, the threshold is more affected by the healthy people compared to the case in which two groups have the same number of subjects. The value of the healthy people's index obtained from the proposed method is expected to be zero because it is assumed that healthy people have a common slope of the approximate plane. Therefore, the threshold in this study is expected to be lower than the case for the same number of healthy people and patients. This is an important point to consider when using the proposed index at a clinical site.

The AUC of the proposed method was 0.767 (Table 3), which indicates a moderate accuracy ($>0.700$).[13–15] Moreover, 0.767 is a higher AUC than that of previous a study, which was 0.63.[8] In that study, the authors discriminated the patients using the range of motion of
Figure 7. ROC curves of the proposed and previous methods. The ROC curve indicates data plotted with REC on the vertical axis and 1–specificity (SPE) on the horizontal axis. Better discrimination is obtained in the upper left area. The curve for the proposed method is plotted as a solid red line. The curve for the previous method is plotted as a dotted blue line. The dotted black line indicates the coincident case.

Table 4. Range of motion calculated by elevation angle (thigh, shank and foot) of the patients and healthy elderly people.

<table>
<thead>
<tr>
<th></th>
<th>$\theta_{\text{thigh}}$ (deg)</th>
<th>$\theta_{\text{shank}}$ (deg)</th>
<th>$\theta_{\text{foot}}$ (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patients</td>
<td>36.85 ± 8.92</td>
<td>64.51 ± 10.71</td>
<td>77.94 ± 17.87</td>
</tr>
<tr>
<td>Elderly people</td>
<td>39.67 ± 2.94</td>
<td>77.58 ± 3.37</td>
<td>92.48 ± 7.76</td>
</tr>
<tr>
<td>Mean difference</td>
<td>2.82</td>
<td>13.07</td>
<td>14.54</td>
</tr>
</tbody>
</table>

Notes: These values indicate the difference between maximum and minimum elevation angles in one gait cycle. Each value indicates an average of an individual subject and a standard deviation. The last row indicates the difference between the average of the patients and that of healthy elderly people.

In a clinical situation, a medical doctor comprehensively evaluates osteoarthritis by radiographic data, questionnaires of pain, joint deformity with appearance and gait pattern. In this study, it is shown that gait motion evaluation using the elevation angle offers a valid diagnosis metric for knee osteoarthritis with a single index. Diagnosing a gait pattern is difficult for non-expert medical doctors. Therefore, our proposed method will be beneficial to support their judgment to provide useful information about the gait pattern.

Lastly, we compare our method with the use of MRI. In a previous study using MRI [26] to discriminate patients from healthy people, it was reported that $\text{ACC} = 0.69$ and AUC was 0.804. In terms of ACC, our proposed method has an accuracy similar to that of the MRI study. The AUC of the proposed method is lower than that of the MRI study, but the MRI scan requires a long time and specific equipment and space, whereas we can obtain the lower limb motion by easily equipped sensors, enabling clinicians to use our proposed method in a daily clinical setting with accuracy similar to that of MRI. Further research is needed to prove that the proposed method can be applied by wearable sensors.

5. Conclusion

In this study, the gait pattern of patients with knee osteoarthritis was analyzed by the elevation angle method. We clarified the movement features by the approximate plane of the elevation angle compared with those of healthy young and elderly people. We have two main findings: (1) We confirmed that the planar law is applicable to the patients' gait, though the gait pattern is different from that of healthy people. (2) The angular difference of the normal vector of the approximate plane can be applied to disease evaluation. We confirmed the decision accuracy of the proposed method by cross-validation and ROC analysis.

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Disclosure statement

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