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<table>
<thead>
<tr>
<th>Scott</th>
<th>Hazelwood</th>
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ASME Paper Title: Knee Angles After Crosstalk Correction With Principal Component Analysis in Gait and Cycling

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Knee Angles After Crosstalk Correction With Principal Component Analysis in Gait and Cycling

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Principal component analysis (PCA) has been used as a post-hoc method for reducing knee crosstalk errors during gait analysis. PCA minimizes correlations between flexion–extension (FE), abduction–adduction (AA), and internal–external rotation (IE) angles. However, previous studies have not considered PCA for exercises involving knee flexion angles that are greater than those typically experienced during gait. Thus, the goal of this study was to investigate using PCA to correct for crosstalk during one exercise (i.e., cycling) that involves relatively high flexion angles. Fifteen participants were tested in gait and cycling using a motion analysis system. Uncorrected FE, AA, and IE angles were compared to those calculated with PCA performed on (1) all angles (FE-AA-IE PCA correction) and (2) only FE-AA angles (FE-AA PCA correction). Significant differences existed between uncorrected and FE-AA-IE PCA corrected AA and IE angles for both exercises, between uncorrected and FE-AA PCA corrected AA angles for both exercises, and between FE-AA-IE and FE-AA PCA corrected IE angles for cycling. Correlations existed before PCA correction and were eliminated following PCA correction with the exception that FE-IE correlations remained following FE-AA PCA correction. Since the two PCA analyses differed only in their IE angle predictions for the high flexion exercise (cycling), IE angle results were compared to previous studies. Using FE-AA PCA correction may be the preferred protocol for cycling as it appeared to retain physiological IE angle correlations at high flexion angles. However, there exists a critical need for studies aimed at obtaining more accurate IE angles in such exercises.

Keywords: crosstalk, principal component analysis, gait, cycling

1 Introduction

Retroreflective markers placed on the skin overlying bony landmarks have been widely used to calculate anatomical three-dimensional (3D) knee joint angles: flexion–extension (FE), abduction–adduction (AA), and internal–external rotation (IE) [1,2]. However, the use of skin-based markers is prone to marker placement error, which has been identified as the largest source of between- and within-laboratory kinematic variability [3–5]. For example, marker placement error on the knee medial or lateral condyle may produce a nonphysiological FE axis alignment. Such errors are referred to as kinematic “crosstalk” [2,6–13] and result in a nonphysiological correlation between FE and AA angles [6,12]. In general, crosstalk leads to increased range and maximum values of AA angles and offsets to IE angle curves [6,12]. Reducing those crosstalk errors in AA and IE angles has several clinical implications. For example, maximum AA angles observed in obese populations [14] and offsets to IE angles in anterior cruciate ligament deficient populations [15] are thought to be related to abnormal tibiofemoral contact loading and, consequently, increased risk for injury and degeneration to soft tissues [13,16].

Several methods have been studied to reduce crosstalk errors [8–10,17,18]. Some methods require a large range-of-motion, such as squats or full knee flexion, to identify the knee FE axis [9,18]. Other methods alter the knee joint coordinate system to zero AA and IE angles at maximum knee FE [17] or minimize the quadratic variations in knee AA and IE angles [10]. Another method uses standard walking trials with a marker offset to minimize knee AA angles [8]. The method studied in this paper is principal component analysis (PCA), which has been used in two prior studies to reduce crosstalk errors in gait analysis [6,12]. Those prior studies implemented PCA differently; one study performed PCA on the FE/AA/IE angles [12] while the other study performed PCA on projections of marker trajectories [6]. An important distinction between those two prior studies is that [12] implemented PCA directly on parameters (i.e., knee angles) that are routinely calculated by motion analysis algorithms whereas [6] implemented PCA in a manner that required substantial post-processing of marker data. Regardless, both of those PCA methods produced knee angle results that compared favorably with other crosstalk reduction methods [6] and offer the advantage that PCA can be used as a post-hoc analysis tool that does not complicate or lengthen the time of the experimental protocol [12].

This study is aimed at addressing a critical knowledge gap regarding the use of PCA for exercises other than gait. In particular, it is unknown how PCA will affect FE-AA and FE-IE curves at relatively high flexion angles such as those that occur during cycling. Moreover, it is not clear if PCA will over-correct the AA and IE angles as there is evidence that physiological FE-AA and FE-IE correlations exist at relatively high flexion angles. Indeed, our preliminary analysis of angle results from a previous study [19] found FE-AA and FE-IE linear correlations during gait (4–62 deg) and cycling flexion ranges (39–95 deg). For example, FE-AA correlations resulted in $R^2$ values of 0.649 and 0.955 for those gait and cycling ranges, indicating stronger correlations at the higher flexion ranges. That preliminary analysis suggested that physiological FE-IE correlations may be more affected by PCA than FE-AA correlations for two reasons. First, the FE-IE correlation slope of 0.211 was substantially higher than the FE-AA correlation slope of 0.048 during cycling flexion ranges. Second, AA errors due to crosstalk reported in previous studies (11–15 deg) [6,12,20] were substantially higher than our predicted AA angle change (2.5 deg) from the physiological FE-AA correlations reported in Ref. [19].

Thus, the goal of this study was to investigate using PCA to correct for marker placement errors during cycling exercises in a manner that preserves physiological FE-AA and FE-IE correlations at higher flexion angles. Here, the PCA method of Ref. [12] (and not Ref. [6]) was selected due to its greater ease of implementation which may render it the more attractive and accessible.
PCA method for routine analysis. The aims were to (1) conduct gait and cycling motion analysis experiments with the same participants; (2) compare FE, AA, and IE angles from three analyses: uncorrected and PCA corrected with inclusion of all FE-AA-IE angles (FE-AA-IE PCA correction) and only FE-AA angles (FE-AA PCA correction); and (3) investigate FE-AA and FE-IE angle correlations for both exercises and analyses.

2 Methods

Protocols were approved by our institutional review board.

2.1 Experiments. Experiments were conducted with 15 participants (nine male and six female) aged 18–26 years. Exclusion criteria included pre-existing conditions that may produce abnormal knee biomechanics (e.g., varus-valgus misalignment, ligament injuries, and obesity).

A motion analysis system with 12 digital cameras (Motion Analysis, Santa Rosa, CA) characterized motion kinematics. Marker trajectories were recorded in CORTEX ANALYSIS software (Version 7.01, Motion Analysis) at 150 Hz and filtered (fourth-order Butterworth filter) using optimal cutoff frequencies of 8 Hz (gait) and 6 Hz (cycling) based on prior methods [21].

After informed consent, each participant completed a 5-minute warm-up exercise, changed into compression clothing, and 32 retroreflective markers were placed by trained Kinesiology faculty or graduate students: toe (second metatarsal), heel (posterior calcaneus), lateral and medial ankle malleoli, anterior midshank, tibial tuberosity, proximal fibula, lateral and medial knee condyles, anterior midthigh, greater trochanter, sacrum, anterior superior iliac spine (ASIS), posterior superior iliac spine, sternum, seventh cervical vertebrae, left and right acromion, and top head. A static pose motion capture was recorded to calculate lower extremity joint centers and initial joint orientations.

Participants repeated each exercise (Fig. 1) until three successful trials were captured. For gait, participants walked across 4 ground force plates (AccuGait, AMTI, Watertown, MA) at self-selected speeds (1.36±0.132 m/s). For cycling, participants pedaled a stationary bicycle (LifeCycle GX, LifeFitness, Rosemont, IL) at 70 revolutions per minute (RPM) and moderate machine resistance of 10 out of 20. The cycling speed was selected to represent an average preferred cycling cadence of “less experienced” cyclists [22].

2.2 Knee Joint Coordinate System. Joint centers were defined in the static pose as virtual markers [23]. The hip joint center (HJC) was defined from the sacral and left and right ASIS markers. The knee joint (KJC) and ankle joint (AJC) centers were defined at the midpoints between their respective medial and lateral markers. The thigh’s frontal plane was defined by the HJC, KJC, and lateral knee marker. The shank’s frontal plane was defined by the KJC, AJC, and lateral ankle marker. Medial ankle and knee markers were removed before dynamic trials. A function provided by the CORTEX was used to redefine the joint centers using markers that defined the corresponding segment and were present in dynamic trials [23]. Knee angles were obtained using an FE/AA/AE Euler-Cardan rotation sequence with a floating axis joint coordinate system (Fig. 2) [24].

2.3 Uncorrected Knee Angles. Uncorrected knee angles (i.e., those directly output by CORTEX) were collected from three trials of the participant’s dominant leg. A custom algorithm (MATLAB, MathWorks, Natick, MA) performed data interpolation to 101-time points corresponding to 1% time increments of a full cycle from 0% to 100%. A full gait cycle was defined from initial heel strike (0%) to next heel strike (100%). A full cycling cycle was defined from top dead center (0%) to next top dead center (100%). Static pose knee angles were subtracted from interpolated angles at each time point to perform a static pose offset [11].

2.4 Principal Component Analysis Corrected Angles. Custom code (MATLAB) implemented PCA [12,25] by performing a

Fig. 1 Left: participant walking along the walkway during a gait experiment, with the right foot contacting one of three ground force plates and motion analysis cameras recording marker trajectories (two cameras are visible to the left and right of the participant’s shoulders). Right: participant pedaling the stationary bike with markers tracking pedal orientation.

Fig. 2 Schematic of floating axis coordinate system used to define anatomical knee angles for the right knee. Uncorrected defines a thigh axis (Z_THIGH) from the HJC to the KJC and a shank axis (Z_SHANK) from the KJC to the AJC. The FE axis is fixed to the thigh body segment and aligned to pass through the lateral knee marker (LKM) and perpendicular to Z_THIGH. The IE rotation axis is fixed to the shank body segment and aligned along Z_SHANK. The AA axis is the floating axis defined to be perpendicular to the FE and IE axes.
Table 1 Maximum (max), minimum (min), and range values for flexion–extension (FE), abduction–adduction (AA), and internal–external rotation (IE) angles in degrees

<table>
<thead>
<tr>
<th>Exercise: analysis</th>
<th>FE</th>
<th></th>
<th></th>
<th>AA</th>
<th></th>
<th></th>
<th>IE</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Max</td>
<td>Min</td>
<td>Range</td>
<td>Max</td>
<td>Min</td>
<td>Range</td>
<td>Max</td>
<td>Min</td>
<td>Range</td>
</tr>
<tr>
<td>Gait: uncorrected</td>
<td>62.7 ± 4.5</td>
<td>0.8 ± 3.8</td>
<td>61.8 ± 4.0</td>
<td>1.3 ± 2.1</td>
<td>-4.1 ± 2.2</td>
<td>5.4 ± 2.1</td>
<td>6.9 ± 4.0</td>
<td>-5.8 ± 4.5</td>
<td>12.7 ± 4.2</td>
</tr>
<tr>
<td>Gait: FE-AA-IE PCA</td>
<td>63.2 ± 4.3</td>
<td>1.0 ± 3.6</td>
<td>62.2 ± 4.2</td>
<td>1.3 ± 1.5</td>
<td>-2.1 ± 1.4^a</td>
<td>3.4 ± 1.2^a</td>
<td>6.5 ± 2.8</td>
<td>-3.3 ± 3.6</td>
<td>9.8 ± 3.6</td>
</tr>
<tr>
<td>Gait: FE-AA PCA</td>
<td>62.8 ± 4.4</td>
<td>0.8 ± 3.8</td>
<td>62.0 ± 4.0</td>
<td>1.2 ± 1.3</td>
<td>-1.9 ± 1.4^b</td>
<td>3.2 ± 1.0^b</td>
<td>6.9 ± 4.0</td>
<td>-5.8 ± 4.5</td>
<td>12.7 ± 4.2</td>
</tr>
<tr>
<td>Cycling: uncorrected</td>
<td>110.2 ± 6.1</td>
<td>38.9 ± 7.2</td>
<td>71.3 ± 5.0</td>
<td>0.0 ± 3.4</td>
<td>-5.3 ± 3.4</td>
<td>5.3 ± 2.6</td>
<td>14.7 ± 7.5</td>
<td>0.6 ± 6.0</td>
<td>14.1 ± 4.7</td>
</tr>
<tr>
<td>Cycling: FE-AA-IE PCA</td>
<td>110.9 ± 6.5</td>
<td>38.1 ± 7.0</td>
<td>72.7 ± 5.2</td>
<td>-3.6 ± 6.3</td>
<td>-6.5 ± 6.5</td>
<td>2.8 ± 0.9^a</td>
<td>-2.2 ± 6.4^b</td>
<td>-6.5 ± 6.6^b</td>
<td>4.3 ± 1.3^b</td>
</tr>
<tr>
<td>Cycling: FE-AA PCA</td>
<td>110.1 ± 6.0</td>
<td>38.7 ± 7.2</td>
<td>71.4 ± 5.1</td>
<td>-2.1 ± 4.8</td>
<td>-5.7 ± 5.7</td>
<td>3.5 ± 1.3^a</td>
<td>14.7 ± 7.5^b</td>
<td>0.6 ± 6.0^b</td>
<td>14.1 ± 4.7^b</td>
</tr>
</tbody>
</table>

Results shown are mean ± 1 standard deviation values from averaging across all participants (n = 15). The data here are averaged across all participant values and, thus, are not equivalent to the max, min, and range values of mean curves shown in Figs. 3 and 4.

^aSignificantly different from uncorrected values.

^bSignificant difference between FE-AA-IE and FE-AA PCA corrected values.

Fig. 3 Flexion, abduction, and internal rotation angles from uncorrected and FE-AA-IE PCA correction for gait and cycling exercises. Results shown are mean (curves) ± 1 standard deviation (shaded regions) values from averaging across all participants (n = 15).
linear transformation of the interpolated uncorrected knee angles to minimize FE-AA-IE and FE-AA correlations. The PCA procedure in Ref. [25] was implemented and briefly summarized below as the equations used here are slightly different due to the equations in Ref. [12] being based on the dataset being transposed compared to the one used for this study. A 303×3 matrix [X] (303 = number of time points for three cycles, 3 = number of knee angles) of the uncorrected knee angle data was formed. The means of each uncorrected knee angle were subtracted from [X] to create a 303×3 matrix [X]centered. A 3×3 covariance matrix [S] was calculated as

$$[S] = (1/(n-1)) [X]_{centered}^T [X]_{centered}$$  \hspace{1cm} (1)

where $T$ indicates transpose. An eigendecomposition of [S] was calculated to produce matrices of eigenvectors [P] and eigenvalues [D]

$$[S] = [P]^T [D] [P]$$  \hspace{1cm} (2)

In this process, the eigenvalues and corresponding eigenvectors were automatically ordered from largest to smallest. Then, we sorted the eigenvector order in [P] to correspond to the order of the anatomical angles in the columns of [X]centered via inspection of the variances and eigenvalues pre- and post-eigendecomposition. Finally, the corrected angles for all three trials, a 303×3 matrix [Z], were determined using the sorted eigenvectors, [P]

Fig. 4 Flexion, abduction, and internal rotation angles from uncorrected and FE-AA PCA correction for gait and cycling exercises. Results shown are mean (curves)±1 standard deviation (shaded regions) values from averaging across all participants ($n = 15$).
Two analyses for obtaining PCA corrected angles were compared. The first analysis used PCA correction on the FE, AA, and IE knee angles, and the second analysis used PCA correction on only the FE and AA knee angles. To perform FE-AA-PCA correction, Eqs. (1) and (2) were used only on the FE and AA angles to determine the two corresponding 1st eigenvectors. The FE and AA eigenvectors, in this order, were placed in the upper left of a 3×3 identity matrix to leave the IE axis unchanged.

For those interested in using PCA to correct for crosstalk, it is noted that MATLAB has a collection of easily implemented built-in functions for performing PCA on raw data sets [26]. The reader is also referred to Ref. [25] for a PCA tutorial.

2.5 Statistics. Uncorrected and PCA corrected knee angles were averaged across three trials for each participant for the statistical analyses. To address the second aim, maximum, minimum, and range values for FE, AA, and IE angles were obtained for each participant, exercise (gait and cycling), and analysis (uncorrected, FE-AA-IE PCA corrected, and FE-AA PCA corrected). Repeated measures analysis of variance, with analysis as the independent variable, was conducted for each angle value and exercise with post-hoc Tukey tests to investigate differences due to analysis (p < 0.05 significant). Regression analyses were performed on FE versus AA and FE versus IE angles pre- and post-PCA correction for each exercise and PCA correction analysis to assess significant (p < 0.05) correlations. The coefficient of determination (R2) was used to quantify correlation, where a larger R2 magnitude indicated greater correlation [6,12] corresponding to a low p-value from the regression analysis. Root-mean-square error (RMSE) between uncorrected and both PCA methods were determined to assess participant-specific variability during gait.

2.6 Validation. A validation was performed with two participants, similar to that performed in Ref. [6], using 0.75\()^\circ\) lateral knee marker offsets in both the anterior and posterior directions from “standard” placement. Standard-PCA (i.e., “standard” placement with FE-AA-IE PCA correction) was used as a baseline, and validation was assessed by (1) R2 values being reduced, (2) RMSE values being reduced, and (3) qualitative inspection of plots following PCA correction of angles from the anterior and posterior placements.

3 Results

Flexion–Extension–Abduction–Adduction–Internal–External Principal Component Analysis Corrected Versus Uncorrected Angles. There existed significant differences between uncorrected and PCA corrected AA and IE, but not FE, angles for both exercises (Table 1 and Fig. 3). For AA angles, minimum values were different for gait (p = 0.008). A decrease in the range from uncorrected to PCA corrected AA angles existed for gait (p = 0.002) and cycling (p = 0.002).

For IE angles, maximum and minimum values were different for cycling (p < 0.001 and p = 0.011, respectively). A decrease in range from uncorrected to PCA corrected IE angles existed for cycling (p < 0.001).

Flexion–Extension–Abduction–Adduction Principal Component Analysis Corrected Versus Uncorrected Angles. There existed significant differences between uncorrected and PCA corrected AA, but not FE or IE, angles for both exercises (Table 1 and Fig. 4). For AA angles, minimum values were different for gait (p = 0.004). A decrease in range from uncorrected to PCA corrected AA angles existed for gait (p = 0.001) and cycling (p = 0.032). It is emphasized that uncorrected and FE-AA PCA corrected IE angles are, by definition, equal as FE-AA PCA correction corresponds to an identity mapping on the uncorrected IE angles.

Flexion–Extension–Abduction–Adduction–Internal–External Principal Component Analysis Corrected Versus Flexion–Extension–Adduction Principal Component Analysis Corrected Angles. There existed significant differences between FE-AA-IE and FE-AA PCA corrected IE, but not FE or AA, angles for cycling (Table 1, Figs. 3 and 4). For IE angles, maximum and minimum values were different for cycling (p < 0.001 and p = 0.011, respectively). A difference in range for FE-AA-IE and FE-AA PCA corrected IE angles existed for cycling (p < 0.001).

Flexion–Extension–Adduction Correlations. For uncorrected angles, FE-AA correlations existed for gait (p = 0.001) and cycling (p = 0.011) (Table 2). For FE-AA-IE PCA corrected angles, R2 values were reduced and correlations in gait (p = 0.915) and cycling (p = 0.942) were not significant. For FE-AA PCA corrected angles, R2 values were reduced and correlations in gait (p = 0.769) and cycling (p = 0.856) were not significant.

Flexion–Extension–Internal–External Correlations. For uncorrected angles, FE-IE correlations existed for gait (p = 0.001) and cycling (p < 0.001) (Table 2). For FE-AA-IE PCA corrected angles, R2 values were reduced and correlations in gait (p = 0.830) and cycling (p = 0.671) were not significant. For FE-AA PCA corrected angles, R2 values and correlations were essentially unchanged from uncorrected values for both exercises due to FE and IE angles being only slightly altered and unaltered, respectively, in that analysis.

Participant-Specific Variability. RMSE values (Table 3) showed both small and large differences between uncorrected and PCA corrected gait AA and IE angles, except for IE angles after FE-AA PCA correction due to IE angles not being modified.

Validation. FE-AA-IE PCA reduced the R2 values as discussed above (Table 2), similar to other studies [6,12]. For both anterior- and posterior-lateral knee marker placements, the effect of FE-AA-IE PCA was to transform the AA and IE curves in a convergent manner toward the curves for the standard-PCA (Fig. 5). RMSE values averaged between participants (n = 2) quantified the convergence toward the AA and IE curves for the standard placement (Table 4).

4 Discussion

A novel feature of this study was that it was the first to investigate and compare two PCA analyses for reducing crosstalk errors in a group of participants for gait and cycling exercises, the latter

| Table 2 | R2-values for angle regressions for gait and cycling exercises: uncorrected angles, FE-AA-IE PCA corrected angles, and FE-AA PCA corrected angles |
|-----------------|-------------------------------|-------------------------------|
| Exercise: analysis | FE-AA correlations | FE-IE correlations |
| Gait: uncorrected | 0.612 ± 0.287* | 0.340 ± 0.255* |
| Gait: FE-AA-IE PCA | 0.001 ± 0.001 | <0.001 ± 0.001 |
| Gait: FE-AA PCA | <0.001 ± 0.001 | 0.340 ± 0.255* |
| Cycling: uncorrected | 0.415 ± 0.296* | 0.872 ± 0.226* |
| Cycling: FE-AA-IE PCA | <0.001 ± 0.001 | <0.001 ± <0.001 |
| Cycling: FE-AA PCA | <0.001 ± <0.001 | 0.871 ± 0.226* |

Results shown are mean ± 1 standard deviation values from averaging across all participants (n = 15).

*Angles significantly correlated (p < 0.05).
of which involves relatively high flexion angles. Several results were as expected. First, FE-AA-IE PCA correction considerably reduced FE-AA and FE-IE correlations in both exercises while leaving FE angles essentially unchanged. Second, FE-AA-IE PCA correction considerably changed AA angles for both exercises, while inducing offsets in IE angles for gait on a participant-specific basis that canceled out when considering mean values averaged across all participants (as discussed in more detail below). Third, FE-AA PCA correction left both FE and IE angles essentially unchanged, while only changing AA angles, for both exercises.

The goal of this study was to investigate using PCA to correct for marker placement errors in cycling where physiological correlations at high flexion angles may exist. Novel and/or unexpected results of this study were as follows: (1) FE-AA-IE PCA correction led to considerable changes in IE angles and FE-IE correlations were eliminated for cycling and (2) the two PCA correction analyses resulted in neither different AA angles for either exercise or different IE angles for gait. Several reasons suggest that FE-AA PCA correction may be the preferred protocol.

First, the FE-AA PCA correction protocol produced IE kinematics in cycling most similar to those found in previous studies for a non-weight bearing leg [27,28]. Our previous study comparing externally applied foot loads during gait and cycling found cycling, at all flexion angles, to have relatively low vertical pedal loads (i.e., always less than 0.18 times body weight) [29]. Thus, cycling IE angles during high flexion should be similar to previous results for non-weight bearing high flexion activities. Such previous studies found 14 deg of tibial internal rotation from 0 to 120 deg of flexion with most of the internal rotation after 45 deg [27] and 5 deg of internal rotation from 40 to 85 deg of flexion [28]. This study found 13 deg of internal rotation from 40 to 110 deg of flexion in cycling when FE-AA PCA corrected but only 0.2 deg of internal rotation from 40 to 110 deg of flexion when FE-AA-IE PCA corrected. Also, FE-AA PCA produced IE and AA ranges more similar to a previous study [19] than FE-AA-IE PCA correction (Table 5). Thus, FE-AA PCA correction, but not FE-AA-IE PCA correction, appeared to retain physiological FE-IE correlations at high flexion angles during cycling.

### Table 3 RMSEs between uncorrected and both PCA correction methods for each participant during gait

<table>
<thead>
<tr>
<th>Participant</th>
<th>FE</th>
<th>AA</th>
<th>IE</th>
<th>FE</th>
<th>AA</th>
<th>IE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.67</td>
<td>1.23</td>
<td>21.45</td>
<td>&lt;0.01</td>
<td>2.04</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>2</td>
<td>3.18</td>
<td>4.84</td>
<td>48.29</td>
<td>0.02</td>
<td>5.50</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>3</td>
<td>0.14</td>
<td>10.56</td>
<td>11.45</td>
<td>0.02</td>
<td>10.09</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>4</td>
<td>&lt;0.01</td>
<td>2.26</td>
<td>1.18</td>
<td>0.00</td>
<td>2.09</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>5</td>
<td>0.12</td>
<td>0.05</td>
<td>6.86</td>
<td>&lt;0.01</td>
<td>0.06</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>6</td>
<td>0.65</td>
<td>6.26</td>
<td>15.78</td>
<td>0.04</td>
<td>6.06</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>7</td>
<td>0.06</td>
<td>6.09</td>
<td>3.23</td>
<td>0.01</td>
<td>6.16</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>8</td>
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<td>24.43</td>
<td>33.17</td>
<td>0.04</td>
<td>13.12</td>
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</tr>
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<td>9</td>
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<td>5.02</td>
<td>0.04</td>
<td>0.01</td>
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<td>10</td>
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<td>22.31</td>
<td>14.60</td>
<td>0.08</td>
<td>10.62</td>
<td>&lt;0.01</td>
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<tr>
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<td>0.25</td>
<td>7.29</td>
<td>&lt;0.01</td>
<td>0.23</td>
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<tr>
<td>12</td>
<td>&lt;0.01</td>
<td>0.48</td>
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<td>0.49</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>13</td>
<td>0.10</td>
<td>1.31</td>
<td>5.43</td>
<td>&lt;0.01</td>
<td>1.24</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>14</td>
<td>0.29</td>
<td>5.88</td>
<td>11.47</td>
<td>0.04</td>
<td>7.21</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>15</td>
<td>0.04</td>
<td>0.34</td>
<td>2.35</td>
<td>&lt;0.01</td>
<td>0.38</td>
<td>&lt;0.01</td>
</tr>
</tbody>
</table>

### Table 4 RMSEs for AA and IE angles between standard-PCA and anterior and posterior placements of lateral knee marker

<table>
<thead>
<tr>
<th>Angle</th>
<th>Standard—PCA versus anterior placement</th>
<th>Standard—PCA versus posterior placement</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA—uncorrected</td>
<td>2.66</td>
<td>3.24</td>
</tr>
<tr>
<td>AA—PCA</td>
<td>1.05</td>
<td>1.21</td>
</tr>
<tr>
<td>IE—uncorrected</td>
<td>3.25</td>
<td>5.97</td>
</tr>
<tr>
<td>IE—PCA</td>
<td>2.74</td>
<td>2.84</td>
</tr>
</tbody>
</table>

### Table 5 AA and IE ranges for 39–95 deg of flexion in cycling from all methods in this study and a previous study on passive limb motion [19]

<table>
<thead>
<tr>
<th>Method</th>
<th>AA range</th>
<th>IE range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wilson et al. [19]</td>
<td>2.5</td>
<td>11.9</td>
</tr>
<tr>
<td>Uncorrected</td>
<td>1.9</td>
<td>10.4</td>
</tr>
<tr>
<td>FE-AA PCA</td>
<td>2.2</td>
<td>10.3</td>
</tr>
<tr>
<td>FE-AA-IE PCA</td>
<td>0.9</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Here, results are only presented for the range of flexion angles (i.e., 39–95 deg) that was common between this study and Ref. [19], thus, differ from results presented elsewhere. Results shown from this study are mean values from averaging across all participants (n = 15).
Second, since the IE axis does not depend explicitly on the FE axis orientation, then IE angles should not experience as much crosstalk as AA angles as remarked in a previous study [30]. However, it should be noted that the IE axis does depend on the KJC, and since the KJC is defined by collateral knee markers, then marker placement error can affect the IE angles primarily through an offset of the IE angle curves [6,30]. As noted earlier, it is possible that such offsets toward internal and external rotation due to random errors in marker placement may effectively cancel and not affect mean results [6]. In this study’s gait results, we found that uncorrected and FE-AA-IE PCA corrected IE angle curves averaged across all participants were qualitatively similar; closer inspection of the data revealed that the corrected IE angle curves experienced internal rotation, external rotation, and no discernible offsets in nine, four, and two participants, respectively, relative to the uncorrected IE angle curves. Thus, in this study, the random errors in marker placement on IE angles (but not AA angles) appeared to mostly cancel when using FE-AA-IE PCA correction. It is emphasized that this conclusion is only offered for studies that are comparing results from a large number of participants, as individual IE results varied considerably, via, primarily an offset, among individual participants.

Thus, the results suggest that using FE-AA PCA correction may be the preferred protocol for cycling as its primary effect, in contrast to using FE-AA-IE PCA correction, was to retain physiological FE-IE angle correlations at high flexion angles. However, this conclusion must be treated with caution, and methods such as bone pins or in vivo imaging are needed to measure AA and IE angles more accurately during cycling to reach a more accurate conclusion regarding the preferred PCA protocol. Also, for studies that include gait analysis, the results suggest that FE-AA PCA correction may be suitable for comparing averaged results for a large number of participants as random marker placement errors on IE angle results tend to cancel each other and because FE-AA PCA correction predicted FE, AA, and IE angles that did not differ from those predicted by FE-AA-IE PCA correction. For studies with only one or several participants, FE-AA-IE PCA correction may continue to be the preferred analysis for gait.

The PCA knee angles observed in this study during gait were similar to those found in a previous study of crosstalk in gait [20], gait using bone pins [31] and in previous studies that used PCA [6,12]. However, some comparison with those previous studies should be noted. The previous study [20], reported control FE, AA, and IE ranges, without crosstalk, of 57.1, 2.9, and 10.7 degrees, respectively. The PCA corrected FE, AA, and IE angle ranges reported in Fig. 2 of Ref. [12] were approximately 47.7, 1.9, and 5.2 deg, respectively. The PCA corrected FE, AA, and IE angle ranges reported in Fig. 7 of Ref. [6] were 64.8, 6.0, and 18.3 deg, respectively. The FE-AA-IE and FE-AA PCA corrected FE, AA, and IE angles ranges found in this study were 62.2, 3.4, and 9.8, then 62.0, 3.2, and 12.7, respectively. Thus, our PCA corrected FE, AA, and IE angle ranges were similar to those reported without crosstalk [20] and fell between the ranges reported in those two previous PCA studies [6,12]. Discrepancies in these reported IE angle ranges may be due to two reasons: (1) Reference [12] averaged angles from 42±19 cycles for each participant, in contrast to three (this study) and four cycles [6], which should considerably reduce participant-specific variability, and (2) possible differences in data smoothing and filtering procedures. Furthermore, for cycling the observed knee FE angles were similar to those found in previous studies [32,33].

This study has a few limitations. First, from a technical standpoint, PCA is appropriate when the input data is formed by rows of data corresponding to vectors. Thus, where it was assumed that a FE/AA/IE angle set at a time point corresponded to a vector, which is an erroneous assumption. However, in preliminary analysis for this paper, it was found that the FE/AA/IE angle sets that are typical for gait and cycling motion do essentially obey the addition rule of vectors, likely because the FE angles are much higher than the AA and IE angles [34]. Regardless, a future study should compare the results of the PCA approach used here and adopted from Ref. [12] with the PCA approach of Ref. [6]. Second, it did not address errors induced by soft tissue artifact, which is considered another leading source of error in motion analysis studies. However, PCA can be implemented on any set of FE/AA/IE angles obtained after using a soft tissue artifact correction algorithm. Third, artifacts may have been introduced by placing several markers (left and right ASIS, sacrum) directly on clothing that may have moved relative to the skin, especially during motion at high flexion angles. To enhance participant comfort, participants were given the option of wearing clothing where hip markers needed to be placed; 9/15 participants chose that additional clothing option that required all five hip markers to be placed on clothing. Thus, those markers may have introduced error into the joint center definitions which then may have affected the FE axis. Fourth, the PCA protocol assumed that the anatomical and functional knee axes were equivalent and did not move during motion; this limitation should be addressed in future studies, especially for the high flexion activities. Fifth, there was participant-specific variability and PCA may over-correct more for some participants compared to others.

In summary, this study suggests that: (1) both FE-AA-IE and FE-AA PCA correction are appropriate for gait (since FE, AA, and IE angles did not differ between analyses) and (2) FE-AA PCA correction appears to be an appropriate correction analysis for obtaining corrected IE angles in cycling as its primary effect, in contrast to using FE-AA-IE PCA correction, is to retain physiological FE-IE angle correlations at high flexion angles. However, due to the uncertainty in the IE angles and the effect on physiological correlations at high flexion angles, care should be taken when considering PCA as a post-hoc correction tool for AA and IE angles in exercises that involve relatively high flexion angles. Thus, there exists a critical need for more cycling studies with more accurate knee angle measurement techniques in order to assess that extent to which PCA reduces or eliminates physiological FE-AA or FE-IE correlations.

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References


