SB3C2017
Summer Biomechanics, Bioengineering and Biotransport Conference
June 21 – 24, Tucson, AZ, USA

PRINCIPAL COMPONENT ANALYSIS OF GAIT AND CYCLING EXPERIMENTS: CROSSTALK ERROR REDUCTION AND CORRECTED KNEE AXES

Jordan M. Skaro (1), Harsh Goel (1), Scott J. Hazelwood (1,2), Stephen M. Klisch (1,2)

(1) Mechanical Engineering Department
California Polytechnic State University
San Luis Obispo, CA, USA

(2) Biomedical Engineering Department
California Polytechnic State University
San Luis Obispo, CA, USA

INTRODUCTION

Crosstalk is a leading source of error in motion analysis [1-2]. Due to incorrect flexion axis direction that develops from marker placement error, crosstalk results in a strong, anatomically incorrect correlation between flexion-extension (FE) and adduction-abduction (AA) motions [1-2]. Thus, crosstalk limits the ability of biomechanical models to reflect the "true" motion of the knee. Principal Component Analysis (PCA) has been proposed as a post-hoc correction for crosstalk in prior gait studies [1-2]; however, previous studies have not proposed a method to determine PCA corrected knee axes. Further, it is not clear how PCA should be implemented in motion analysis studies that involve several exercises, on the same subjects, involving a relatively high range of flexion angles.

The long-term goal of this study is to determine accurate knee kinematics in a variety of exercises performed by the same subjects. This study tests two hypotheses: (1) PCA corrects for crosstalk between FE and AA angles in gait and cycling and (2) PCA corrected knee axes are similar for gait and cycling. The aims are to (1) determine PCA corrected knee angles in gait and cycling for the same subjects and their corresponding FE-AA correlations, (2) develop and implement an algorithm for determining PCA corrected knee FE and AA axes, and (3) compare the PCA corrected FE and AA axes for the same subjects to determine if they are similar in gait and cycling.

METHODS

Subject Selection. Subjects were male (n=5) and female (n=1), 21-26 years of age, and non-obese. Subjects were screened for prior leg injuries or malalignment that could bias results. Subjects 1, 2, 4 and 5 were right leg dominant while subjects 3 and 6 were left leg dominant. Protocols were approved by Cal Poly's Human Subjects Committee to minimize risk to human subjects.

Experimental Procedure. An enhanced Helen Hayes marker set with retroreflective markers was used to determine kinematics. A ten-camera motion capture system and Cortex software (Motion Analysis, Santa Rosa, CA, USA) were used to record marker position and process kinematic data. Subjects stood motionless for a static trial to create virtual axes for body segments. Subjects walked across the load cell walkway leading with their dominant leg to capture a full gait cycle. Subjects then pedaled a stationary bicycle (LifeFitness LifeCycle GX, Rosemont, IL, USA) at 70 rpm for 15 seconds.

PCA Analysis. PCA was implemented to reduce crosstalk by conducting a coordinate system transformation of calculated knee angles that minimizes FE-AA correlations [3]. A covariance matrix $[\boldsymbol{S}]$ of the knee angle data was calculated as

$$[\boldsymbol{S}] = \frac{\boldsymbol{1}}{\boldsymbol{n-1}}[\boldsymbol{X_{centered}}]^{\boldsymbol{T}}[\boldsymbol{X_{centered}}] \quad (1)$$

where $[\boldsymbol{X_{centered}}]$ is the original knee angles, $[\boldsymbol{X}]$, with the means of each knee angle subtracted. An eigendecomposition of matrix $[\boldsymbol{S}]$ was calculated to produce a matrix of column eigenvectors, $[\boldsymbol{P}]$, according to

$$[\boldsymbol{S}] = [\boldsymbol{P}]^{\boldsymbol{T}}[\boldsymbol{X}][\boldsymbol{P}]. \quad (2)$$

Finally, the original knee angles, $[\boldsymbol{X}]$, were projected onto a new set of axes, as described by the eigenvectors in matrix $[\boldsymbol{P}]$. This results in the calculation of an *nx3* matrix $[\boldsymbol{Z}]$ which contains PCA corrected FE, internal-external rotation (IR), and AA angles:

$$[\boldsymbol{Z}] = [\boldsymbol{X}][\boldsymbol{P}]. \quad (3)$$

The coefficient of determination (R^2) between FE and AA angles was used to quantify crosstalk both before and after PCA. Larger R^2 values indicate the presence of more crosstalk.

Calculating PCA Corrected Knee Axes. PCA corrected knee axes were determined by finding the axes that, when used with PCA corrected knee angles, resulted in thigh, shank and ankle positions that

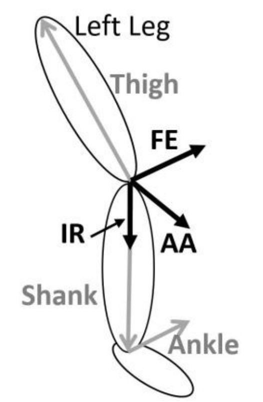

Fig. 1. Axis (FE, IR, AA) and body (Thigh, Shank, Ankle) vectors used in analysis.

were most similar to the corresponding positions determined by Cortex (which used the experimental marker data). A floating axis (i.e. AA axis) coordinate system was used [4]. In a local coordinate system, different for left and right leg dominant subjects, anterior and lateral directions were aligned with positive x- and y-directions, respectively, and inferior directions were defined as positive and negative for left and right leg dominant subjects, respectively (Fig. 1).

Statistics. Regression analyses were performed on FE vs. AA angles pre- and post-PCA treatment to assess FE-AA correlations in gait and cycling. Spherical directional statistics (i.e. Watson-Williams tests) [5-6] were used to assess for significant differences in the directions of the PCA corrected FE and AA axes between gait and cycling across all subjects. A one sample t-test was performed on the calculated angles between the corrected FE axes for gait and cycling to test if these angles were statistically similar to zero. For all statistical analysis tests, $p<0.05$ denotes statistical significance.

RESULTS

R^2 correlation values (Table 1) between FE and AA knee angles (Fig. 2) were reduced by 3 and 4 orders of magnitude for gait and cycling, respectively. Regression analyses found reduced correlations for gait FE-AA knee angles (p=0.000 for pre-PCA [strongly correlated] and p=0.857 for post-PCA [not correlated]) and for cycling FE-AA knee angles (p = 0.000 for pre-PCA and p=0.956 for post-PCA). The spherical directional statistical tests found FE (Table 2) and AA (Table 3) axes to be similar among subjects for gait and cycling (p=0.289 for FE and p=0.259 for AA). The one sample t-test on the angles between the corrected FE axis for gait and cycling showed significant differences from zero (p=0.022).

Table 1: R^2 values (mean ± 1 standard deviation) for FE-AA angles pre- and post-PCA correction for gait and cycling.

	Gait	Cycling
Pre	.66 ± .28	.21 ± .28
Post	2.5E-04 ± 2.7E-04	6.7E-05 ± 1.5E-04

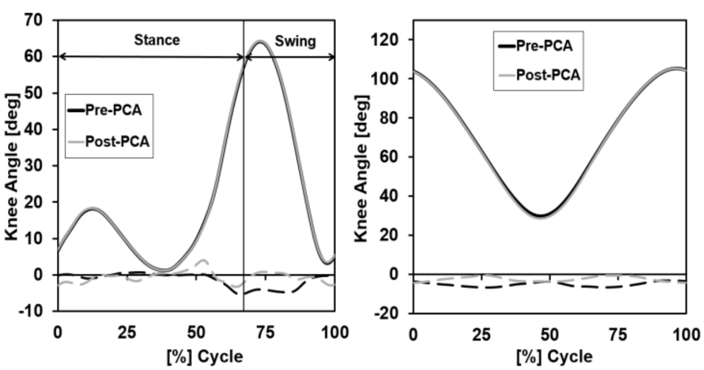

Fig 2: FE and AA knee angles pre- and post-PCA correction for gait and cycling for one subject. Solid/dashed lines = FE/AA.

Table 2: PCA corrected FE axes (in [x,y,z] format) and angle between axes (in degrees) for gait and cycling.

Subject	Gait	Cycling	Angle
1	[0.28,0.96,0]	[0,1,0]	16
2	[0.28,0.96,0]	[0.31,0.95,0]	2
3	[0.10,0.99,0]	[0.62,0.79,0]	32
4	[0.28,0.96,0]	[0.10,0.99,0]	10
5	[0.50,0.87,0]	[0.10,0.99,0]	24
6	[-0.17,0.98,0]	[0.62,0.79,0]	48

Table 3: PCA corrected AA axes (in [x,y,z] format) and angle between axes (in degrees) for gait and cycling.

Subject	Gait	Cycling	Angle
1	[0.96,-0.28,0.02]	[1.00,0,0.02]	16
2	[0.95,-0.27,-0.04]	[0.94,-0.31,-0.04]	2
3	[0.99,-0.10,0.08]	[0.79,-0.61,0.07]	32
4	[0.96,-0.27,0.05]	[0.99,-0.10,0.05]	10
5	[0.86,-0.50,-0.05]	[0.99,-0.10,-0.03]	24
6	[0.97,0.17,-0.13]	[0.78,-0.61,-0.05]	48

DISCUSSION

The statistical analyses demonstrated that there is substantial crosstalk between knee axes for gait and that PCA can correct for it. It is unsure if the corrected knee axes are similar between gait and cycling due to the large angles between corrected and uncorrected FE and AA axes. Similarities between those axes were found using the spherical statistical analysis while the one sample t-test indicates the FE axis between gait and cycling may be different. However, the spherical statistical test may find significant differences with more subjects. Other studies reported that a correlation exists between FE and AA angles at high flexion angles (> 60 deg.) [7]; thus, the predicted knee axes may be incorrect for cycling due to the high flexion angles measured in cycling (maximum flexion angles were 106 deg. in cycling and 62 deg. in gait). Thus, when using PCA to correct for crosstalk error in subjects performing exercises with high-flexion motions, these results suggest that PCA corrected axes from gait analysis may be used as a standard set of knee axes for other motions.

This study has several limitations. First, the number of subjects was relatively low; inclusion of additional subjects may lead to detected differences in the corrected knee axes for gait and cycling using the spherical directional statistics test. Second, methods were not used to reduce errors induced by soft tissue artifact, which is considered another leading source of error in motion analysis. Despite these limitations, this study has shown that PCA can be used to correct for crosstalk in both gait and cycling experiments and may be used to motivate further studies to determine the optimal method for reducing crosstalk when analyzing knee motion for subjects performing multiple exercises or high-flexion motions.

ACKNOWLEDGEMENTS

This work was supported by the Donald E. Bently Center (SK), W.M. Keck Foundation (JS), and the Defense Health Program (JS, SH, SK) through the Department of Defense Broad Agency Announcement for Extramural Medical Research Program #W81XWH-BAA-14-1 under Award No. W81XWH-16-1-0051. Opinions, interpretations, conclusions and recommendations are those of the authors.

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