SB3C2015
Summer Biomechanics, Bioengineering and BIotransport Conference
June 17-20, 2015,Snowbird Resort, Utah, USA

PSEUDO-RIGID BODY METHOD FOR REDUCING SOFT TISSUE ARTIFACT: VALIDATION AND APPLICATION TO GAIT

Jake E. Deschamps (1), Karim C. Dudum (2), Eshan M. Dandekar (3), 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

(3) Kinesiology Department
California Polytechnic State University
San Luis Obispo, CA, USA

INTRODUCTION

A common way to study human joint loads during various activities is to use a camera-based motion capture system to film retro-reflective markers adhered to a subject's skin. When reconstructing the underlying bone kinematics, it is often assumed that the skin moves rigidly with the bone. However, skin motion is influenced by muscles, adipose tissue, and flexing joints, introducing errors known as soft tissue artifact (STA). STA is considered the largest source of error in human movement analysis [1]. Considerable effort has been aimed at reducing STA but, even for the most innovative methods, STA persists.

Recently, [2] proposed implementing multi-marker clusters, analyzing each 3-marker subset as a triangular Cosserat point element (TCPE), and applying a filtering algorithm. In a pendulum validation test that simulated STA, this analysis resulted in lower errors than other state-of-the-art methods. However, results were reported only about a known axis and the method has not been applied to gait analysis. Here, the application of TCPEs and filtering algorithm are termed the pseudo-rigid body (PRB) method, which we propose to be a more physical descriptor as the method models each body segment as a "pseudo"-rigid deformable body.

This study aimed to: develop the PRB algorithm; recreate the STA simulation to validate the algorithm and report errors for out-of-plane angles; and contrast the PRB method's performance in gait analysis with a more traditional Helen – Hayes (HH) marker set.

METHODS

PRB Method. For the PRB method used here, seven makers were used for each body segment (Fig. 1A). At each time point, all combinations of three markers are analyzed as TCPEs. A director vector approach [2] is used to determine the deformation gradient (***F***) and Lagrangian strain (***E***) tensors for each TCPE:

$$\boldsymbol{d}_i \otimes \boldsymbol{D}^i = \boldsymbol{F} = \boldsymbol{R}\boldsymbol{U} \qquad (1)$$

$$\frac{1}{2}(\boldsymbol{F}^T\boldsymbol{F} - \boldsymbol{I}) = \boldsymbol{E} \qquad (2)$$

Two present configuration director vectors are formed from subtracting the three marker locations (Fig. 1B), with a third formed by normalizing the cross product of the first two, yielding $\boldsymbol{d}_i$. Reference configuration reciprocal director vectors, $\boldsymbol{D}^i$, are formed by using the previous process to obtain director vectors, and then using cross products to form reciprocals. Using ***F***, ***E*** and rotation (***R***) tensors are calculated. The TCPEs which have the lowest strain magnitudes and most consistent rotation tensors are selected, and rotation vectors are calculated and averaged [2]. An algorithm for this process was coded in MATLAB (MathWorks, Natick, MA) to analyze fully recorded motions.

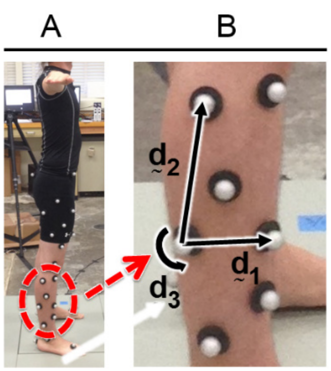

Fig. 1. Director vectors illustrated on the PRB marker set for gait analysis.

Motion Capture System. A motion capture laboratory with eight cameras and Cortex software (Motion Analysis Corp., Santa Rosa, CA) was used to collect data. A walkway and force plate (AMTI, Watertown, MA) was used during gait. Marker trajectories were filtered using a 4th-order Butterworth filter and cutoff frequency of 6 Hz.

Pendulum Validation. Similar to [2], a 300 mL silicone implant was attached to the end of an 80 cm long rigid pendulum to simulate STA. 4 markers were attached to the pendulum to estimate true RB motion.

Seven markers were attached to the implant's surface. Three "free swing" trials were conducted where the pendulum was released and allowed to swing uninterrupted. Three "impact swing" trials were conducted with a simulated impact: the pendulum was grabbed and released before returning to its starting position. The pendulum's RB motion was estimated from markers on the implant using the PRB method. Rotation angles were decomposed into in- and out-of-plane angles. The algorithm's marker usage identified the relative reliability of each marker, allowing for the formation of the most and least reliable marker sets from the three most used and the three least used markers. The performance of these marker sets gives a range of predictions of how limited marker sets compare to the PRB method. Maximum and root mean square (RMS) errors were determined.

Gait Analysis. Knee kinematics for three subjects were obtained using both HH and PRB marker sets. For the HH method, markers were attached to the skin over the ASISs, sacrum, medial and lateral femoral condyles, medial and lateral malleoli, and tops of the feet. Asymmetric offset markers were placed on each thigh and each shank. For the PRB method, seven markers were evenly distributed on both the right thigh and shank. Reference position information was gathered with each subject standing with feet roughly hip width apart. A Cortex script was used to determine the functional centers of the ankle, knee, and hip joints. After the reference trial, medial markers were removed to allow subjects to walk normally. After a warm-up period, each subject walked across the room six times at a self-selected pace. Cortex was used to determine knee kinematics for the HH marker set. The PRB algorithm was adapted to determine knee kinematics. Each trial was normalized to consist of one gait cycle, and average plots were created to present mean and standard deviation for each method across the gait cycle. Experimental protocols were approved by Cal Poly's Human Subjects Committee and were designed to minimize risk to human subjects.

RESULTS

Pendulum Validation. The PRB method's error was lower than those of the limited marker sets (Table 1), with one exception. The least reliable marker set had relatively high errors. Out-of-plane angles (Fig. 2) were low for most of the motion, but were considerably larger when the pendulum was stopped at an angle.

Table 1. RMS and maximum errors averaged across free and impact swing trials for the PRB method and two limited marker sets.

Trial	Error Type	PRB	Most Reliable	Least Reliable
Free Swing Averages	RMS Error	.68	.89	3.59
	Maximum Error	2.41	3.13	14.46
Impact Swing Averages	RMS Error	.75	2.07	6.24
	Maximum Error	5.03	14.01	25.92

Gait Analysis. Kinematics differed between the PRB and HH methods (Fig. 3). The PRB method showed larger knee flexion angles for most of the motion. Near the end of stance, varus rotations diverged for the two methods. Internal rotations differed during the entire gait cycle.

DISCUSSION

Pendulum Validation. RMS error was lower than the value reported by [2]. Although a direct comparison cannot be made, this suggests that the PRB algorithm was properly implemented. Large errors observed with limited marker sets imply that the PRB method is more accurate than limited marker sets, even when those are well devised.

Results in [2] took advantage of the known axis of rotation. This information is usually unavailable in gait analysis, as neither the knee nor hip can be modeled as a simple pin joint. Out-of-plane rotations during the pendulum test would manifest as varus or internal rotations during gait, which would have strong, erroneous connotations. The largest out-of-plane rotations occurred when the pendulum was being initially displaced. The implant was attached to the pendulum with one clamp at the top and one at the bottom, allowing the implant to rotate about the pendulum to an extent likely beyond what occurs during gait. Since skin does not terminate at single connection points, it is unlikely that the out-of-plane rotation magnitudes seen here would occur during gait.

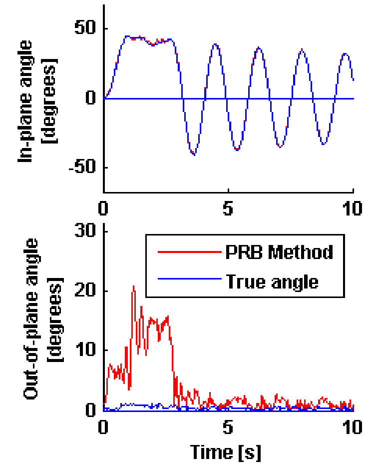

Fig. 2. True and PRB determined in- and out-of-plane rotations for a free swing trial.

Gait Analysis. Differences were observed between the two methods for all kinematic components. These kinematics are compared with those reported in studies that used invasive methods to circumvent STA. The varus rotation identified by the PRB method near the end of stance closely matches [3]. The internal rotations from the PRB method correlate with one subject examined in [4], while those identified by the HH method seem to have an unreasonably large range of motion. These comparisons must be interpreted with caution due to high subject variability in knee kinematics. The results support the development of several future aims: comparing the PRB method to the rigid body least-squared optimization method [3]; expanding the pendulum STA simulation to more accurately model the knee joint; and integrating the PRB method with inverse dynamic analysis.

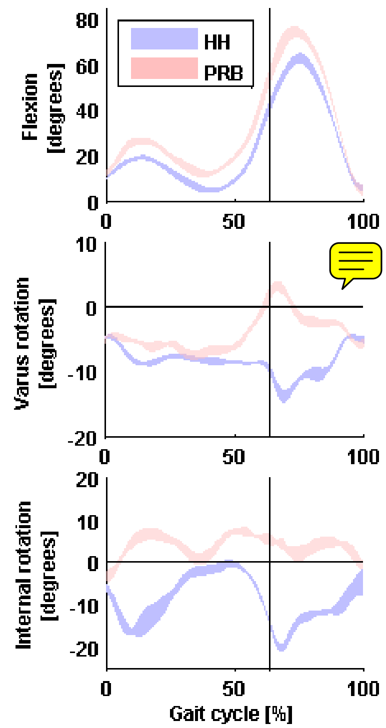

Fig. 3. Knee kinematics determined using HH and PRB methods averaged across six trials. Plot thickness indicates one standard deviation.

ACKNOWLEDGEMENTS

Funding received from Quartus Engineering, Inc. and Cal Poly's Donald E. Bently and STRIDE Centers.

REFERENCES

[1] Leardini, A. et al., *Gait Posture*, 21.2:212-225, 2005. [2] Solav, D. et al., *Int J Eng Sci*, 85:1-9, 2014. [3] Andriacchi, P. et al., *J Biomech Eng*, 120.6:743-749, 1998. [4] Reinschmidt, C. et al., *Gait Posture*, 6.2:98-109, 1997