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SOFT TISSUE ARTIFACT QUANTIFICATION AND MINIMIZATION USING COSSERAT POINT ELEMENTS

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INTRODUCTION

The most critical source of error in the evaluation of human skeletal motion by optoelectronic systems recording markers on the skin is the Soft Tissue Artifact (STA). This artifact is caused by the non-rigid relative motion between the markers and the underlying bony segment [1]. The majority of the techniques for reduction of the STA assume rigid body motion of a limb segment and apply various algorithms to obtain an optimal estimate of the underlying rigid skeletal motion. A new method to quantify and compensate for the STA is described, that treats the body segments as non-linearly deformable segments and uses the theory of a Cosserat point to analyze the non-rigid body kinematics.

METHODS

A cluster of markers on the skin of a deformable body segment is divided into groups of three each forming triangles. The kinematics of each triangle at each time step are calculated using Cosserat Point Elements (CPEs) [1]. Specifically, the rotation tensor $\boldsymbol{R}$ and the strain tensor $\boldsymbol{E}$ are calculated from the position vectors of the markers, as described in [2]. For triangles on a rigid body, the strains vanish and the rotation tensors are identical. For markers placed on a non-rigid body, the rotation and strain tensors are used to define two scalar measures of deformations: the magnitude of strain of the Ith CPE

$$\|E\|_I = \sqrt{tr(\boldsymbol{E}_I \boldsymbol{E}_I^T)} \tag{1}$$

and the relative rotation angle between the Ith and Jth CPE is defined by

$$\phi_{I/J} = \cos^{-1}\left[\frac{1}{2}\left\{tr(\boldsymbol{R}_I \boldsymbol{R}_J^T) - 1\right\}\right] \tag{2}$$

Then, the scalar measure of relative rotation $\|\Delta\phi\|_I$ associated with the Ith CPE is defined by

$$\|\Delta\phi\|_I = \sum_{J=1}^{N_{tri}} \Delta\phi_{I/J} \Big/ (N_{tri} - 1) \tag{3}$$

Where N_{tri} is the total number of CPEs.

It is assumed that a CPE having small values of $\|E\|_I$ and $\|\Delta\phi\|_I$ is more likely to represent the underlying rigid body motion than a CPE with large values of these measures. Therefore, at each time step, these two scalar measures of deformation can be used to determine a group of CPEs with the smallest combined strain and relative rotation angle from the group of all CPEs. The rotation tensors of the CPEs in that group are used to calculate an average rotation tensor, and the average rotation tensor is used to obtain the rotation angle by

$$\phi = \frac{1}{2}\cos^{-1}\left[tr(\boldsymbol{R}) - 1\right] \tag{4}$$

The method was tested using an experimental setup that consists of a rigid pendulum with a deformable 300ml silicone breast implant attached to it, as shown in Figure 1. The system is a simulation of the soft tissue around a bony segment. The rotation angles extracted from seven markers on the deformable implant (Figure 1a, markers 5-11) were compared with simultaneous measurements of the rigid pendulum (Figure 1a, markers 1-4) using an optoelectronic system.

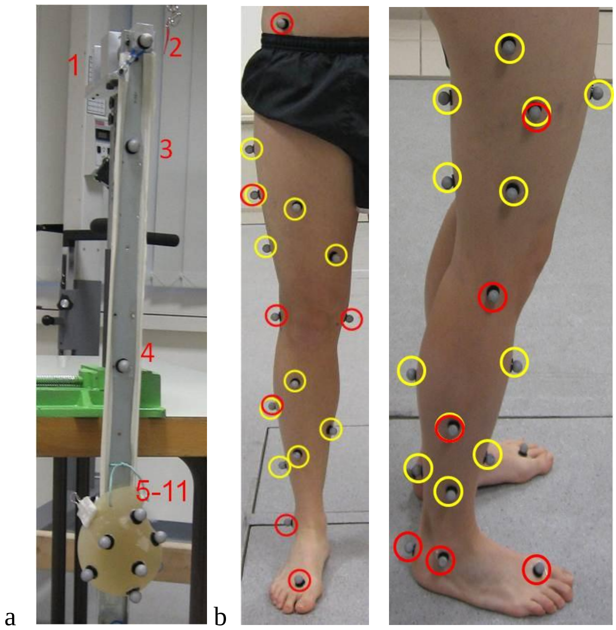

Figure 1: (a) The Experimental Setup: Four markers attached to the rigid pendulum (1-4) and seven markers attached to the deformable silicone implant (5-11). (b) Two clusters of seven markers each on the thigh and the shank (yellow) and markers used by Vicon Nexus Plug-in Gait system (red). Some markers are used in both methods.

Following the validation of the method, it was applied for the determination of the knee Flex/Ext angle during gait. Two clusters of seven markers each were attached to the

Femur and the Tibia, as shown in Figure 1b, and two average rotation tensors were calculated using the proposed method. The relative rotation angle between them about the knee axis was extracted and compared with the angle simultaneously calculated by Vicon Nexus system using Plug-in Gait model.

RESULTS AND DISCUSSION

For the Experimental Setup, the strain and rotation tensors were calculated for each of the 35 triangular CPEs formed by the markers on the silicone implant. Figure 2a shows the rotation angles for all CPEs plotted in grey lines. At each time step, the CPEs with the combined smallest strain and smallest relative rotation angle were chosen from the collection of CPEs, and their averaged rotation angle is shown in blue. The true rotation angle obtained from the rigid pendulum is plotted in red. The same data is plotted in Figure 2b for a shorter time period which corresponds to a region of the motion with high deformation. The results indicate that the rotation angles calculated from the group of CPEs associated with small deformation measures were 33% more accurate than the average rotation angles calculated from the group of all CPEs. In the regions where large deformations occur (highlighted regions in figure 2a), the error reduction was close to 44%. The maximal magnitude of strain recorded during the experiment was 1.27 in the group of all CPEs and 0.09 in the group of CPEs selected for averaging. The maximal relative rotation angle was 99.75 degrees in the group of all CPEs and 20.87 degrees in the group of CPEs selected for averaging.

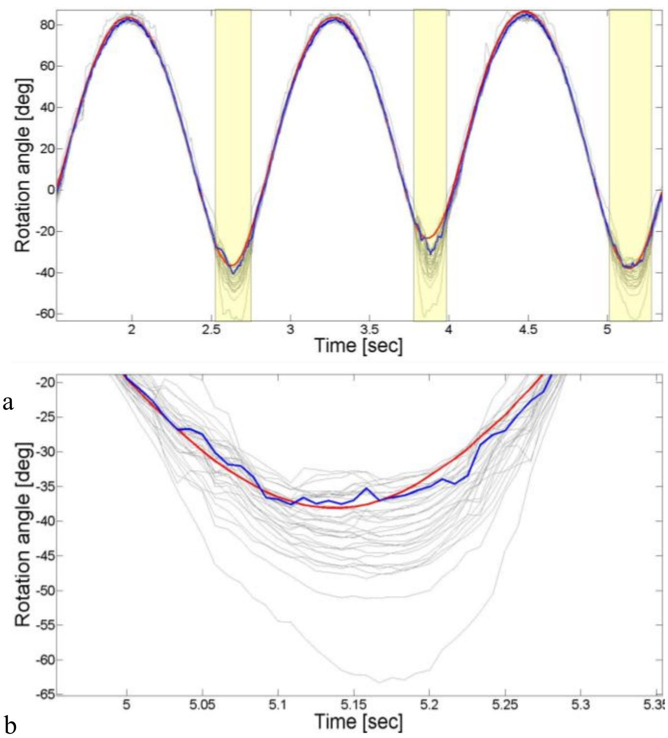

Figure 2: Rotation angles of the pendulum as functions of time predicted from individual CPEs on the implant (grey) and from the optimized group of CPEs (blue) compared with the true angle (red). (a) Three cycles of the pendulum (b) short time period with high deformation.

In the experiment for the determination of knee Flex/Ext angle, the maximal strain was 0.28 in the group of all CPEs and the maximal relative rotation angle between two CPEs was 20.6 degrees. These numbers indicate that the body segment is highly non-rigid. Both maximal measures were recorded in the segment of the thigh. The CPEs on the shank experienced smaller measures of deformation.

Figure 3 shows Flex/Ext angles as a function of time for the right knee of one subject during one gait cycle. The angles calculated from Vicon Nexus Plug-in Gait Model are plotted in red and the angles calculated from the CPE method are plotted in blue. The results of 5 trials of two gait cycles each demonstrated that the difference between the angles calculated from the CPEs and the angles calculated from Vicon Nexus system ranged from –3.4 to 5.6 degrees. The root mean squared error was 2.07 degrees.

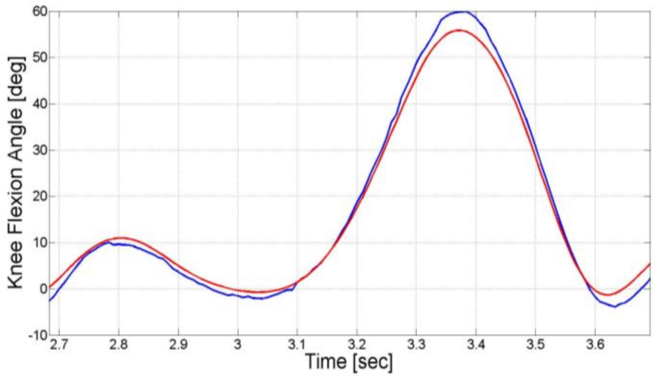

Figure 3: Flex/Ext Right knee angle as a function of time for one gait cycle of one subject. Angles calculated from Vicon Nexus Plug-in Gait Model (red) and from the CPE method (blue).

CONCLUSIONS

The method provides information on the strains of the soft tissue in the body segment as well as the relative rotational motion within the body segment. This method can be used to minimize the soft tissue artifact when analyzing the motion of an underlying bone, as well as to estimate soft tissue motion and deformation. The experimental simulation demonstrated that the error due to non-rigid motion of the markers relative to the underlying rigid body could be substantially reduced by accounting for the deformation measures of strain and relative rotation of the CPEs, despite the high magnitudes of strain and relative rotation.

The comparison with the Vicon Nexus system showed that the method is suitable for the measurement of the knee Flex/Ext angles without the need for accurate placement of the markers in anatomical landmarks, despite the high magnitudes of deformation. A future study is planned to examine the suitability of the method for STA reduction by comparing the angles extracted using the proposed method with the joint angles measured using an invasive method such as 3D fluoroscopy.

REFERENCES

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