These results demonstrate that simultaneous measurement of 3D soft tissue strain and 3D joint kinematics can be performed while achieving excellent accuracy for both sets of measurements.

**Discussion**

This study demonstrated that the 3D system could accurately measure strain and kinematics using a FOV that accommodates simultaneous tracking of markers for both measurements. Results showed that a reduced camera angle marginally improved uncertainty for frontal plane (z-axis) displacements, while an increased camera angle slightly improved uncertainties of sagittal plane (x-axis) displacements. Moreover, in comparison to similar systems using proprietary vendor-specific hardware, this system is a small fraction of the cost. The measurements of system precision were calculated using the length of the position vectors of the markers, and thus these measurements should be considered average errors that take into account the precision in all three spatial directions. In contrast, the measurements of strain were made along the z-axis direction. Since the z-axis and y-axis are closest to perpendicular to the camera line of sight, these directions will correspond to the best accuracy for the camera angles used in this study. Thus, measurements of strain accuracy should be considered a best case when considering general measurements in 3D using similar camera angles.

Although a similar argument applies to the kinematic measurements, the "gold standard" for these measurements was based on a combination of digitizer, actuator encoder, or digital caliper measurements. Because of the differences in the accuracy of these measurement techniques and the propagation of errors in these kinematic measurements, the results for translational and rotational kinematic accuracies likely represent worst cases.

As with any research or testing system based on video or digital cameras, the most important determinants of precision and accuracy are the resolution of the CCD and the FOV used for measurements. In this study, the FOV was chosen to allow simultaneous tracking of markers for strain and kinematic measurements in the context of studying the human MCL [2,3]. Limitations on the rate of data transfer from the camera to the framegrabber boards and then to computer memory, primarily imposed by the bandwidth of the computer system's bus, result in a tradeoff between the frame rate and spatial resolution of the CCD. Cameras with higher resolution CCDs typically have slower frame rates. This limitation will likely disappear with improvements in computer architecture. Marker contrast is also very important, with improved contrast yielding better system precision and thus accuracy. Finally, the physical size of the CCD influences the sensitivity, with larger CCDs yielding better sensitivity and thus better image quality. The cameras used in this study had 1" CCDs, the largest size that is available.

In summary, the 3D measurement system provided excellent accuracy for strain measurement and very good accuracy for kinematic measurements. The absolute and percent errors are considered to be more than acceptable for use in our studies of ligament strains and joint kinematics.

**References**

