http://dx.doi.org/10.2106/JBJS.15.01080

Appendix

Technique Validation

This study used the principles of stereophotogrammetry to measure the operative orientation of the cup for each task. Photogrammetry provides a method of obtaining quantitative data and can be defined, according to the *Oxford English Dictionary*, as "the use of photography to ascertain measurements between objects." Stereophotogrammetry allows the spatial measurement of three-dimensional objects from a stereopair of images and has been used in different fields, such as meteorology and geology[18-20]. Common points are identified on each image and if the location of each camera relative to the image plane is known, the three-dimensional coordinates, and hence location and orientation of the object of interest, can be determined.

A custom application, Fotop, written in MATLAB (R2011; The MathWorks) was developed by an engineer to capture the data and perform the measurements. The object of interest in this study was the cup introducer. The three-dimensional orientation of the cup introducer was measured; as the impactor is rigidly attached to the cup during impaction, the cup orientation could therefore be deduced.

Software Considerations, Design, and Technique Used

To obtain three-dimensional coordinates of any object in space using stereophotogrammetry at least two images of the object of interest are required. Two factors important for the calculations are the relative position of the two cameras to each other and the internal parameters of the cameras, most importantly the focal length during image capture. A calibration object was used to determine the relative locations of the cameras and the internal camera parameters for each case. The calibration object consisted of 12 easily identifiable markers whose relative positions were known, having been measured accurately using the Vicon system (see Measurement Validation section below). Capturing a stereopair of images of the calibration object prior to commencement of each case (i.e., subject being tested) allowed the software to determine the positions of the cameras relative to each other and the camera parameters (i.e., account for change in the desired height of the table). Once the cameras were calibrated, further stereopair images could then be used to measure three-dimensional data in the volume in view of both cameras as long as the cameras were not moved and the focus of the cameras was not altered. For all of the stereophotogrammetric measurements, the autofocus feature of the cameras was turned off to ensure focal length did not change.

To ensure that the stereopairs of images were correctly identified for each case, and that the calibration images were distinct from the measurement images, a custom software application, Fotop, was developed by one of the authors of this study. The Fotop software incorporated a database, electronically controlled the simultaneous image capture from the two cameras, stored the images in the database, and performed the stereophotogrammetric calibrations and measurements on the images. Prior to each case, the investigator entered the case (using anonymized codes to identify subjects) in the software. The subsequent calibration and measurement stereopairs of images were then stored in the database, with the Fotop software ensuring that images were correctly associated with the appropriate task. After the measurements were taken, the Fotop software was then used to process the images. This consisted of digitization, which provided the location of points of interest in each image, calibration calculations, and three-dimensional reconstruction of data. From the three-dimensional reconstruction of the impactor, the orientation of the acetabular cup was calculated by the Fotop software using the various reference systems described by Murray[15].

Calibration Object

A calibration object was constructed by the Department of Engineering Science (University of Oxford) workshop with specific characteristics and dimensions. The calibration object had to be of specific dimensions that allowed positioning in the operating theater (calibration object frame width = 40 cm). To perform the spatial calibration, each leg had a specific number of phenolic balls at given distances from the base (Fig. E-1). Phenolic balls were used as they are both bright and retroreflective and hence can easily be detected both by photography and by the infrared cameras at the Oxford Gait Laboratory.

Following manufacturing, the calibration object was measured using the Vicon Nexus Motion Analysis System (Vicon Motion Systems), a method previously demonstrated to have accuracy better than 1 mm^3 at the Oxford Gait Laboratory. The coordinates obtained from the Vicon system were incorporated in the Fotop software and were used for any calculations subsequently made.

Measurement Validation

The validity of the stereophotogrammetry technique described above was tested at the Oxford Gait Laboratory. The laboratory is equipped with a 12-camera Vicon Nexus Motion Analysis System, which captures video data at a rate of 100 Hz (Fig. E-2). Following static and dynamic laboratory calibration, the error of the motion analysis system (the mean error between the constructed marker position and the actual marker position) on the day of validity testing was 0.66 mm. Each of the 12 markers of the calibration object was reconstructed in both the gait laboratory and the photogrammetry coordinate frames. Transposition of the two coordinate frames demonstrated that the stereophotogrammetry method had an accuracy (and standard deviation) within 0.1 ± 2 mm. In addition, a wand with three retroreflective markers was placed within the calibration volume, simulating a possible orientation and location of a cup impactor. The location and orientation of the wand were captured by both the Vicon system and the stereophotogrammetry technique. Transposition of the two coordinate frames demonstrated that the stereophotogrammetry technique had a mean accuracy of 0.1 ± 2 mm in terms of translation and 0.03° ± 1.6° in terms of rotation. These provided validity that the stereophotogrammetry method accurately measured the three-dimensional coordinates of the objects of interest in this study.

Intraoperative Orientation Measurements: Photogrammetric Technique Used

Two cameras (Webcam Pro 9000 HD; Logitech) were mounted on the operating room's laminar air flow hoods, orientated at approximately 90° to each other and arranged so that the operating field was fully captured. The hemipelvis was positioned in the middle of the table in a neutral alignment. The table was set in the middle of the operating space as defined by the laminar flow hoods. The calibration object was aligned to the operating space (i.e., parallel to the walls and the floor) and was placed over the hemipelvis, and then a stereopair of images was captured. The calibration object was removed and the various tasks were begun, with a stereopair of images being captured for each task. Knowledge of the three-dimensional location of the cup introducer relative to the operating table allowed for the calculation of the operative cup inclination and operative cup anteversion. These angles

http://dx.doi.org/10.2106/JBJS.15.01080

were calculated on the basis of the definitions of operative inclination and anteversion according to Murray, referencing off the plane perpendicular to the operating table and pelvis[15].

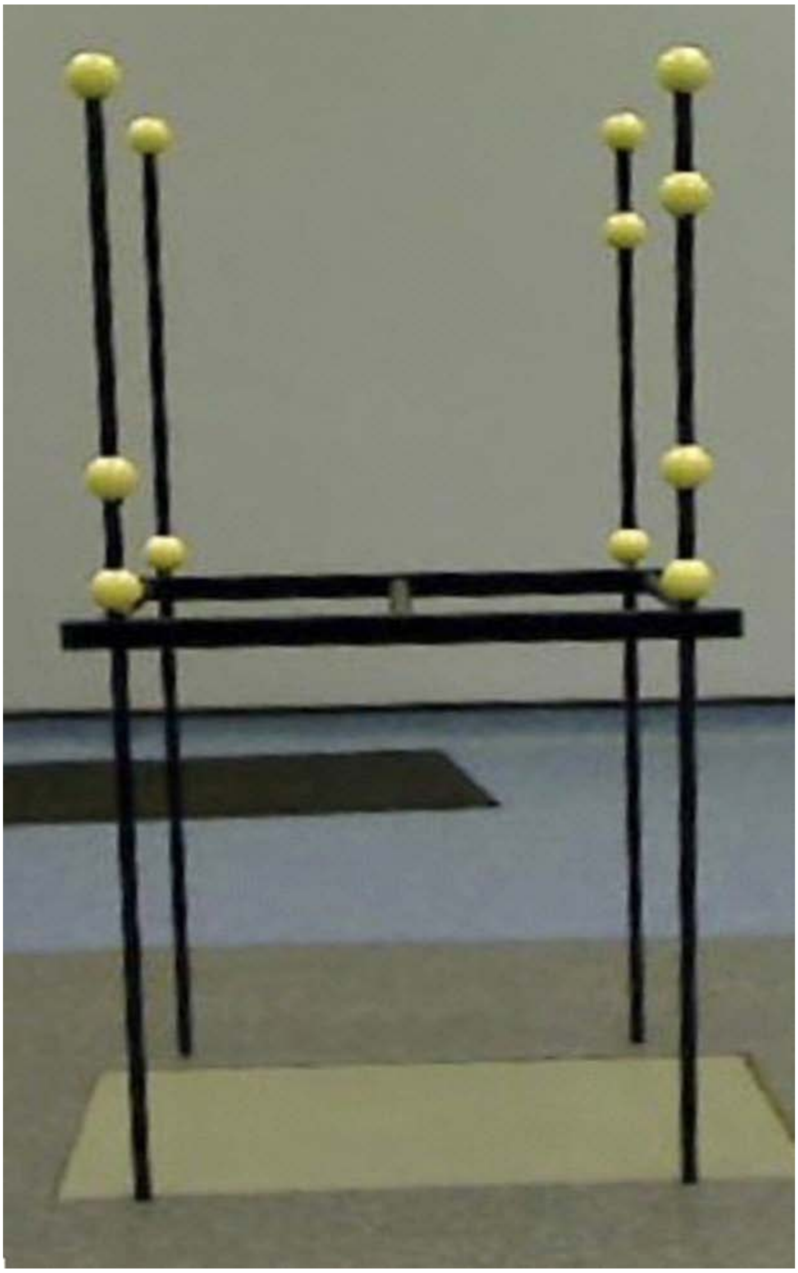

Fig. E-1
A photograph showing the schematic of the calibration object used for the manufacturing process and the object during measurements performed at the Oxford Gait Laboratory.

http://dx.doi.org/10.2106/JBJS.15.01080

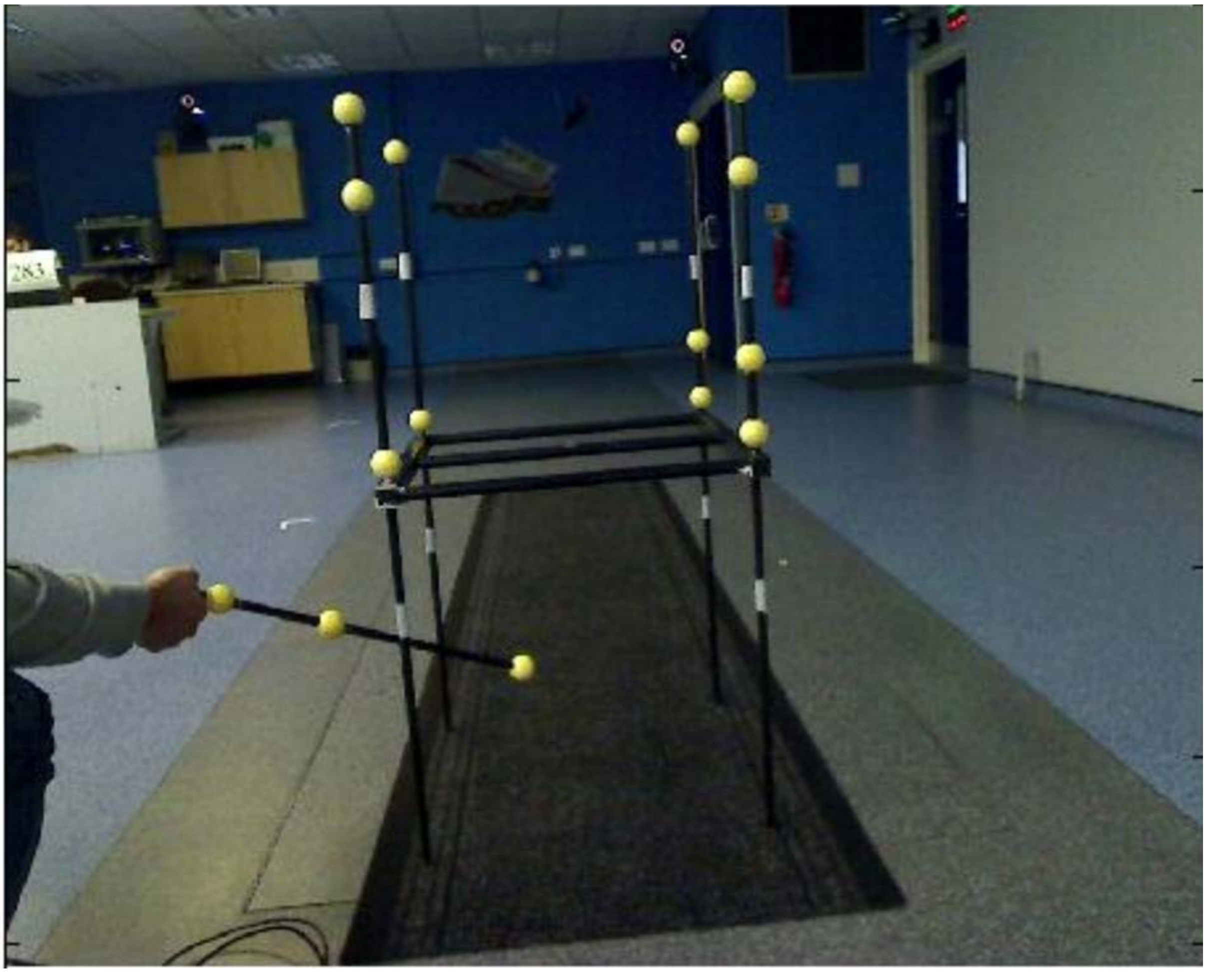

Fig. E-2
Photograph captured during technique validation demonstrating the calibration object and the testing wand in the Oxford Gait Laboratory.