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Accuracy of a System for Measuring Three-Dimensional Torso Kinematics During Manual Materials Handling

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This paper describes a procedure developed and validated to assess the accuracy of an infrared-based motion measurement system used to perform a kinematic analysis of the torso with respect to the pelvis during simulated lifting tasks. Two rigid reflective marker triads were designed and fabricated for attachment to the thorax over the 6th thoracic vertebra and the pelvis. System accuracy was assessed for planar rotation as well as rotations about multiple orthogonal axes. A test fixture was used to validate known triad orientations. The spatial coordinates of these triads were collected at 120 Hz using a ProReflex motion measurement system. Single value decomposition was used to estimate a rotation matrix describing the rigid body motion of the thorax triad relative to the sacral triad at each point in time. Euler angles corresponding to flexion, lateral bending, and twisting were computed from the rotation matrix. All measurement error residuals for flexion, lateral bending, and twisting were below 1.75°. The estimated mean measurement errors were less than 1° in all three planes. These results suggest that the motion measurement system is reliable and accurate to within approximately 1.5° for the angles examined.

Key Words: spine, lifting, motion measurement

Spinal kinematic analyses require accurate and reliable methods for studying spinal motion. Stereoradiographic methods have been proven to very accurately assess vertebral displacements (Brown, Burstein, Nash, & Schock, 1976; Frymoyer, Frymoyer, Wilder, & Pope, 1978; Pearcy & Whittle, 1982) but are not

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practical for evaluating continuous, dynamic lifting. Electrogoniometers have also been developed for measuring torso kinematics (Marras, Fathallah, Miller, Davis, & Mirka, 1992). However, the significant mass of these electrogoniometers may affect torso kinematics. Tracking reflective markers has been validated for kinematic analyses of the human back (Culham & Peat, 1993; Pearcy, Gill, Whittle, & Johnson, 1987), the shoulder (Peterson & Palmerud, 1996), and the knee (DeLuzio, Wyss, Li, & Costigan, 1993). This paper presents the methodology and validation of a system for measuring torso kinematics using triads of reflective markers for ergonomic studies of torso motion.

The objective of this study was to quantify the accuracy of the kinematic measurement system for measuring (a) planar torso postures, and (b) complex three-dimensional torso postures during manual materials handling.

Methods

The experimental setup consisted of a 3-D rotating laser fixture, perpendicular front and overhead surfaces (each surface was a square, with a linear dimension of 2.44 m per side), and a six-camera ProReflex motion capture unit (Qualisys, Glastonbury, CT). The custom-fabricated laser fixture was used to project laser beams a linear distance from the point of rotation. The fixture was built with insertion points for three laser pens set up in a right-handed 3-D system. The rotating head was designed to simulate the 3-D movements of the torso during lifting tasks. Two 1.22 3 2.44-m panels of wood reinforced by metal corner angles were used for each of the front and overhead surfaces. These panels were assembled onto a uni-strut base to provide perpendicular surfaces for laser beam projection. The ProReflex system was calibrated using a CAB1000 calibration frame (Qualisys).

Two triads of reflective markers were placed on the laser fixture. Each triad consisted of three reflective markers placed on the ends of 13-cm wooden dowels attached to a wooden base. One triad was placed on the rotating head of the fixture and the second triad on a stabilized base. The motion data collected for the two triads was used as input for the simulated spine kinematic analysis (Figure 1).

A local coordinate system was developed from three markers placed about the center of rotation (COR) for the laser fixture in a neutral position. The first marker was affixed on top of the y-axis laser above the COR, a second was placed on a plumb-bob string directly beneath the COR, and a third was attached at the end of the x-axis laser horizontally from the COR.

A "neutral posture" calibration trial was performed prior to a series of rotational motion measurements. This neutral posture was captured with the triads arranged such that the lasers were projected onto the origins for each set of axes on the overhead and front surfaces. This arrangement represented a posture with no flexion, lateral bending, or twisting rotations. The data collected from the neutral posture was used as the reference frame for a standard starting point for the rotational motions tested in this study.

The first series of tests for assessing the accuracy of the motion measurement system involved uniplanar movement. These tests included both positive and negative rotations about each of the three orthogonal axes. The magnitudes of single axis rotations that were tested included: 5, 15, 30, and 40° rotations for flexion; 5, 10, 15, and 30° rotations for lateral bending; and 5, 10, 20, and 30° rotations for twisting. These uniplanar tests were conducted to investigate the ef-

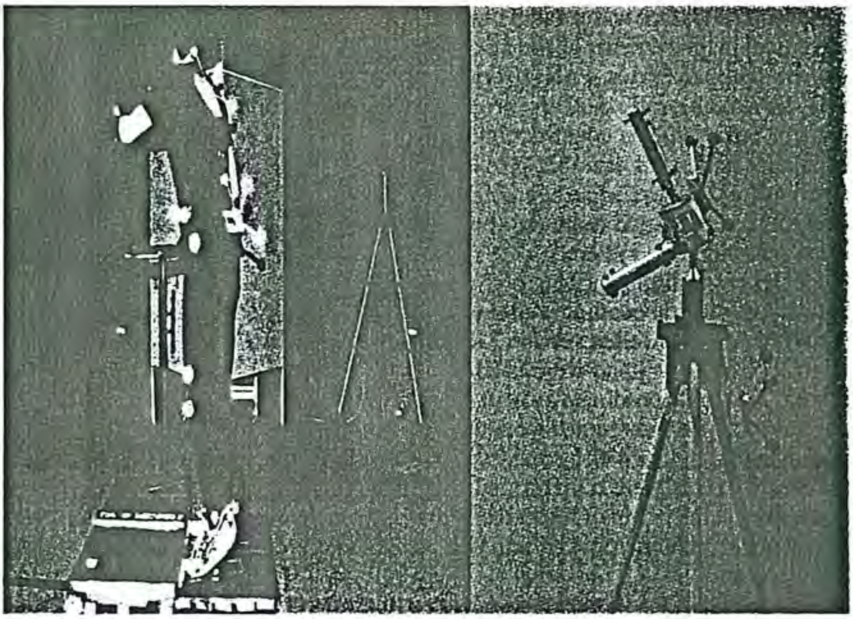

Figure 1 — Illustration of torso motion simulation using the rotating laser fixture. (Left) Participant doing a lift-and-place task with triads attached to thorax and lumbar regions. (Right) Rotating fixture simulating this type of task with triads placed on rotating head and stabilized base. The three lasers are configured onto the rotating head in a right-handed 3-D system to project a linear distance from point of rotation.

fects of magnitude and direction of rotation about any axis on the accuracy of the motion measurement system.

The second series of tests were conducted to evaluate various combinations of the uniplanar rotational magnitudes, referred to as complex planar rotations. This set of experiments was developed to simulate a lifting and placing task where a worker bends forward to pick up an item and then twists to the side to place it on a shelf. The magnitudes and combinations of rotational angles were chosen assuming that the largest rotations would be about the x-axis (forward flexion) and the smallest rotations would be about the z-axis (lateral bending). The twisting direction in this experimental setup was to the right. Therefore the rotations examined in combinations included positive flexion angles, positive lateral bending angles, and negative twisting angles.

Three sequential elemental rotation matrices were used to determine the horizontal and vertical displacements for each laser beam that corresponded to the desired angles of rotation. Given the positions for two of three orthogonal axes, the position of the third axis can be derived. Therefore, only two lasers were needed to define the motions of the fixture. Due to the setup of the uni-strut structure relative to the camera system, the walls perpendicular to the Z-axis (front surface) and Y-axis (overhead surface) were used to minimize markers blocked from camera views. The fixture was rotated into position based on the calculated horizontal and vertical displacements of the laser beams along the perpendicular surfaces. A FaroArm (Bronze Series, FARO Technologies, Inc., Lake Mary, FL) was used to verify the actual locations of the projected laser beams onto these surfaces to account for errors due to construction inaccuracies. The FaroArm is a multi-axis portable measurement arm that provides the 3-D coordinates of a single point in space with a 2-sigma accuracy ± 0.406 mm. The angles calculated using the FaroArm were assumed to be the true angles for assessing bias in the ProReflex motion measurement system.

Marker location data were converted into angular rotations corresponding to torso twisting, lateral bending, and flexion. First, marker location data were tracked at 120 Hz using MacReflex version 3.41 PPC software (Qualisys). The three marker locations on the test stand were used to construct an orthogonal local coordinate system. This local coordinate system corresponded to a local anatomic coordinate system that can be constructed from the anterior and posterior superior iliac spines on participants in kinematic experiments. All marker location data for the pelvic and thoracic triads were transformed into the local coordinate system. Since the two triads generally cannot be perfectly aligned with zero rigid body rotation on a live person, a "neutral" posture was used to define the state of no twisting, bending, or flexion.

Similarly, in this accuracy experiment the rotation of the thoracic triad was decomposed into two components: (1) rotation of the triads from perfect alignment to the orientations in the neutral posture, and (2) rotation from the neutral posture to the posture of interest. The two rotation matrices were denoted $\mathbf{R}_0$ and $\mathbf{R}_i$, respectively, and they were computed using the method of Soderkvist and Wedin (1993). Therefore, the rotation matrix defining the rotation of the thoracic triad during the i[th] data collection relative to the neutral position when all data are represented in a pelvic local coordinate system was $\mathbf{R}_i^{\text{ modified}} = \mathbf{R}_i\mathbf{R}_0^T$. This rotation matrix was used for computing 2-3'-1" Euler angles (Crawford, Yamaguchi, & Dickman, 1996) as follows:

$$\textit{Lateral bending angle} = L_i = -\sin\,(\mathbf{R}_{1,2}^{\text{modified}})$$

$$\textit{Twisting angle} = T_i = \sin^{-1}\left(\frac{\mathbf{R}_{1,3}^{\text{modified}}}{\cos(L_i)}\right)$$

$$\textit{Flexion angle} = F_i = \cos^{-1}\left(\frac{\mathbf{R}_{2,2}^{\text{modified}}}{\cos(L_i)}\right)$$

If flexion exceeded $\pi/2$ ($\mathbf{R}_{3,3} < 0$ and $\mathbf{R}_{2,3} < 0$), then $F_i = \pi - F_i$. For hyperextension ($\mathbf{R}_{2,3} < 0$), $F_i = -F_i$. Note that the flexion, twisting, and lateral bending angles were all zero in the neutral position since $\mathbf{R}_0$ is orthonormal.

The differences between angles computed from the motion measurement system data and angles determined from the FaroArm were used to generate residual measurement error plots and estimates of the mean measurements error to assess the accuracy for flexion, lateral bending, and twisting.

Table 1 Angular Measurement Results for Uniplanar Rotations

Protocol Test Angles Angles (deg)			Motion Measurement System Values Angles (deg)			Standard Deviation			True Angles (FaroArm) Angles (deg)		
Flex	Bend	Twist	Flex	Bend	Twist	Flex	Bend	Twist	Flex	Bend	Twist
0	0	0	0.4	0.0	0.0	0.1	0.1	0.4	0.2	–0.1	0.0
–5	0	0	–4.8	0.7	0.2	0.0	0.0	0.0	–4.8	–0.1	0.0
5	0	0	4.9	–0.2	0.5	0.0	0.0	0.0	5.1	–0.2	0.0
–15	0	0	–14.9	1.2	0.1	0.1	0.1	0.0	–14.9	–0.1	0.0
15	0	0	14.4	–0.4	–0.6	0.1	0.1	0.1	15.0	–0.1	0.0
–30	0	0	–30.3	0.7	–0.1	0.1	0.1	0.0	–30.1	–0.1	0.1
30	0	0	29.7	–0.1	–0.6	0.0	0.0	0.0	30.1	–0.1	0.0
40	0	0	39.7	–0.3	–0.5	0.1	0.1	0.1	40.2	0.0	0.0
0	–5	0	0.4	–4.7	0.4	0.2	0.2	0.1	0.1	–5.2	0.0
0	5	0	0.2	5.0	0.3	0.2	0.2	0.1	0.1	4.9	0.0
0	–10	0	0.2	–9.9	0.6	0.1	0.2	0.1	0.2	–10.2	0.1
0	10	0	0.6	9.6	–0.1	0.2	0.2	0.0	0.1	9.9	0.0
0	–15	0	0.7	–15.5	–0.1	0.2	0.1	0.1	0.2	–15.2	0.0
0	15	0	0.8	14.6	–0.2	0.1	0.1	0.0	0.1	14.9	–0.1
0	30	0	0.7	29.1	–0.9	0.2	0.2	0.1	0.1	29.9	–0.2
0	0	–5	0.6	–0.3	–5.3	0.2	0.1	0.1	0.1	–0.1	–5.0
0	0	5	0.6	0.1	4.5	0.2	0.1	0.2	0.2	–0.1	5.1
0	0	–10	0.3	0.5	–9.5	0.2	0.2	0.0	0.0	–0.1	–9.9
0	0	10	0.2	0.1	10.1	0.3	0.1	0.2	0.1	–0.1	10.0
0	0	–20	0.3	–0.4	–20.2	0.1	0.2	0.1	0.0	–0.1	–20.0
0	0	20	0.5	–0.4	20.2	0.4	0.2	0.3	0.1	–0.1	20.1
0	0	–30	0.3	–0.5	–30.4	0.1	0.2	0.2	0.1	0.0	–30.0
0	0	30	0.3	0.2	30.4	0.1	0.1	0.1	0.1	0.0	30.1

Table 2 Angular Measurement Results for Complex Rotations

Protocol Test Angles Angles (deg)			Motion Measurement System Values Angles (deg)			Standard Deviation			True Angles (FaroArm) Angles (deg)		
Flex	Bend	Twist	Flex	Bend	Twist	Flex	Bend	Twist	Flex	Bend	Twist
5	5	−10	4.2	4.3	−10.4	0.2	0.2	0.0	5.1	4.9	−10.0
5	5	−20	4.6	4.3	−20.2	0.1	0.2	0.0	5.1	5.0	−20.0
5	5	−30	4.6	4.5	−30.4	0.1	0.2	0.1	5.0	4.9	−30.0
5	10	−10	4.2	9.3	−10.6	0.2	0.2	0.0	5.1	10.0	−10.1
5	10	−20	4.5	9.0	−20.3	0.1	0.2	0.0	5.2	9.9	−20.0
5	10	−30	4.7	9.1	−30.2	0.1	0.2	0.1	5.1	10.0	−30.1
5	15	−10	4.3	14.2	−10.6	0.2	0.2	0.0	5.2	14.9	−10.0
5	15	−20	4.5	13.8	−20.4	0.2	0.2	0.2	5.1	14.9	−20.1
5	15	−30	4.8	14.0	−30.3	0.1	0.2	0.1	5.1	15.0	−30.1
15	5	−10	14.3	4.2	−10.2	0.2	0.2	0.0	15.1	4.9	−9.9
15	5	−20	14.5	4.2	−20.4	0.1	0.2	0.1	15.0	5.1	−20.0
15	5	−30	14.6	3.9	−30.3	0.1	0.2	0.1	15.1	5.0	−29.9
15	10	−10	14.3	9.2	−10.3	0.2	0.2	0.0	15.0	10.0	−9.9
15	10	−20	14.6	9.0	−20.3	0.1	0.2	0.0	15.1	9.8	−19.9
15	10	−30	14.8	8.8	−30.3	0.1	0.2	0.0	15.1	9.9	−30.0
15	15	−10	14.6	13.7	−11.2	0.1	0.1	0.0	15.0	14.8	−9.9
15	15	−20	14.6	14.0	−20.5	0.1	0.2	0.0	15.0	14.9	−20.0
15	15	−30	15.0	13.7	−30.3	0.1	0.3	0.0	15.2	14.8	−30.0
30	5	−10	29.4	3.9	−10.4	0.2	0.2	0.0	30.2	4.9	−9.9
30	5	−20	29.7	3.8	−20.4	0.1	0.2	0.0	30.2	4.9	−19.9
30	5	−30	29.9	4.0	−30.4	0.1	0.2	0.1	30.3	4.9	−29.9
30	10	−10	29.3	9.0	−10.7	0.2	0.2	0.0	30.1	9.9	−9.9
30	10	−20	29.6	8.9	−20.4	0.1	0.2	0.1	30.1	10.0	−19.9
30	10	−30	29.8	8.8	−30.5	0.1	0.2	0.1	30.2	9.9	−29.9
30	15	−10	29.3	13.8	−10.8	0.2	0.2	0.0	30.2	15.0	−9.9
30	15	−20	29.7	13.8	−20.6	0.1	0.2	0.0	30.2	15.0	−19.9
30	15	−30	29.8	13.8	−30.6	0.1	0.2	0.1	30.2	15.0	−30.0

Results

Mean measurement errors for postures involving rotations about a single axis (flexion, lateral bending, or twisting) were small (Table 1). The mean and standard deviation values for flexion errors involving only uniplanar rotations were 0.3 and 0.1, respectively. The mean and standard deviation values for lateral bending errors involving only uniplanar rotations were <–0.1 and 0.1, respectively. The mean and standard deviation values for twisting errors involving only uniplanar rotations were –0.1 and 0.1, respectively.

Errors occurring in postures involving rotations about multiple axes were slightly larger than for single axis rotations (Table 2). The mean and standard deviation values for flexion errors involving complex planar rotations were –0.4 and 0.1, respectively. The mean and standard deviation values for lateral bending errors involving complex planar rotations were –1.0 and 0.2, respectively. The mean and standard deviation values for twisting errors involving complex planar rotations were –0.4 and 0.1, respectively.

Residual error box plots for flexion, lateral bending, and twisting (Figure 2) illustrate that residual errors never exceeded 1.75°, and residual errors for flexion and twisting were below 1.5°. With respect to the direction of measurement error, ProReflex estimates for flexion showed a general tendency toward a positive bias from the camera system with increasing flexion angle (either negative or positive in nature), with a slight negative bias at the neutral position (0°). Lateral bending also had a consistent positive bias for angles above 5°, but showed a trend toward a negative bias for negative angles. Residual measurement errors for twist did not show any clear trends.

Discussion

The purpose of the study was to quantify the accuracy of a triad-based system for measuring torso kinematics during manual materials handling. We found the system to have excellent average accuracy, with mean measurement errors less than a degree. Residual measurement errors were consistently below 1.75° for flexion, lateral bending, and twisting, even during complex motions.

The accuracy of this method compares well with other methods for torso measurement. For example, the lumbar motion monitor, which is used extensively in field (Marras, Lavender, Leurgans, et al., 1993) and laboratory studies (Granata, Marras, & Davis, 1997; Sparto, Parnianpour, Reinsel, & Simon, 1998) of 3-D torso motion, has a reported accuracy of up to 3.07° during complex motions (Marras et al., 1992). Electromagnetic trackers have been reported to have smaller errors in ideal environments (An, Jacobsen, Berglund, & Chao, 1988; Milne, Chess, Johnson, & King, 1996), but they are known to be strongly affected by metal in the experimental environment (Milne et al., 1996; Stone, Currier, Neibur, & An, 1996). Analysis of a light-emitting diode-based motion measurement system showed average errors up to 3.8° when motions involving adduction, flexion, and longitudinal rotation were considered (DeLuzio et al., 1993).

There are three primary limitations to this study. First, the gold standard against which measurements were compared is not perfectly accurate. The apparatus used for the calibration was estimated to have an accuracy of within 0.25°. The mean measurement errors recorded were on the same order of magnitude as this

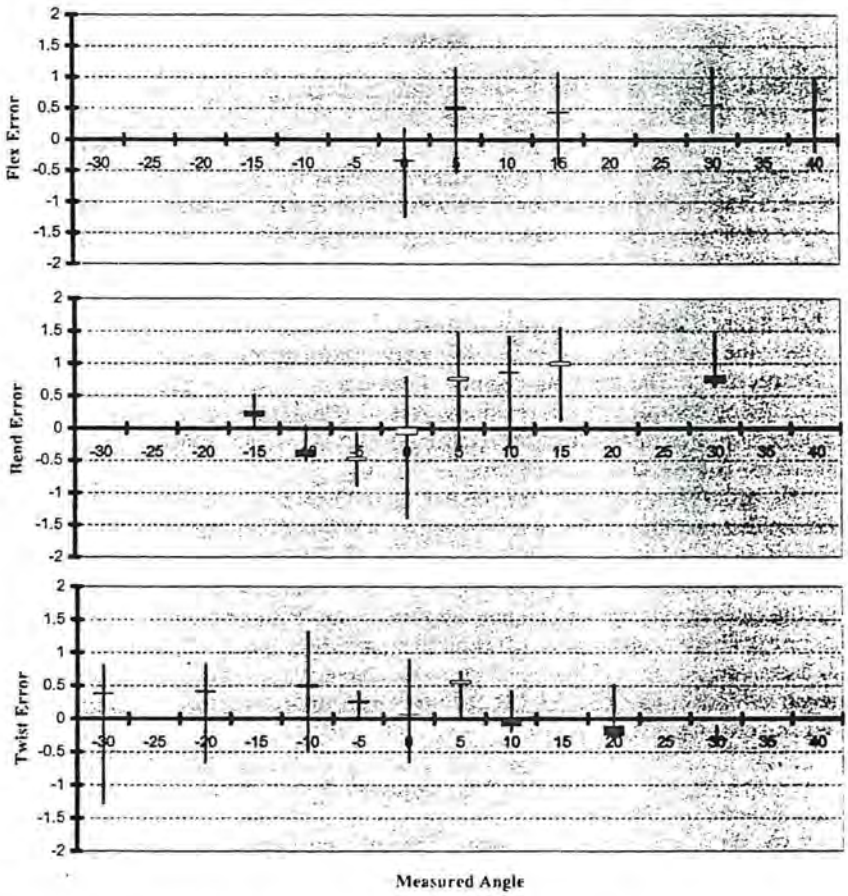

Figure 2 — Box plots of residual errors for flexion, bending, and twisting. Results from: (Top) isolating flexion errors; (Middle) bending errors; (Bottom) twisting errors, for all uniplanar and complex rotations. Vertical bar for each angle measured displays range between min and max values. For each min/max range, the difference between median and mean is indicated with a horizontal bar. Thicker horizontal bars indicate greater differences. White bars indicate the median > the mean.

error. Although it is impossible to separate the error due to the test fixture from the optimal measurement system when the error is a small fraction of a degree, we can conclude that the magnitude of this error is smaller than a degree. The second limitation of the study is that it was not conducted on a living person. An inanimate fixture was used to obtain known angles for comparison, and that task would be extremely difficult using live participants. Third, due to limitations on the surface area of the wooden panels and the range of motion for the rotating fixture, the angular rotations did not span the full torso range of motion expected in healthy persons.

The major strength of this study was that it analyzed errors when the test fixture was placed in orientations that required rotations about the three anatomic axes; accuracy studies often focus solely on planar rotations (Culham & Peat, 1993; Klein & DeHaven, 1995; Milne et al., 1996; Scholz & Millford, 1993). Analysis of errors in complex orientations of reflective marker triads is the major contribution of this work.

We conclude that the reflective marker triads are suitable for measuring 3-D torso kinematics in laboratory ergonomics studies. It is important to note that the triads were constructed from wood, and the fabrication tolerances were those that would be commonly found in a wood shop. High-precision machining was not necessary for fabricating the triads. In fact the triads were not identical. The least-squares method for estimating the rotation matrix can account for such imperfections in fabrication (Soderkvist & Wedin, 1993). The triad method of assessing torso kinematics also has the advantage of minimizing the chance of reflective markers being obscured by the body or object being lifted, especially when cameras are placed behind the participant.

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