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Short communication

Assessment of screw displacement axis accuracy and repeatability for joint kinematic description using an electromagnetic tracking device

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Abstract

Screw displacement axes (SDAs) have been employed to describe joint kinematics in biomechanical studies. Previous reports have investigated the accuracy of SDAs combining various motion analysis techniques and smoothing procedures. To our knowledge, no study has assessed SDA accuracy describing the relative movement between adjacent bodies with an electromagnetic tracking system. This is important, since in relative motion, neither body is fixed and consequently sensitivity to potential measurement errors from both bodies may be significant. Therefore, this study assessed the accuracy of SDAs for describing relative motion between two moving bodies. We analyzed numerical simulated data, and physical experimental data recorded using a precision jig and electromagnetic tracking device. The numerical simulations demonstrated SDA position accuracy ($p = 0.04$) was superior for single compared to relative body motion, whereas orientation accuracy ($p = 0.2$) was similar. Experimental data showed data-filtering (Butterworth filter) improved SDA position and orientation accuracies for rotation magnitudes smaller or equal to 5.0°, with no effect at larger rotation magnitudes ($p<0.05$). This suggests that in absence of a filter, SDAs should only be calculated at rotations of greater than 5.0°. For rotation magnitudes of 0.5° (5.0°) about the SDA, SDA position and orientation error measurements determined from filtered experimental data were 3.75 ± 0.30 mm (3.31 ± 0.21 mm), and $1.10 \pm 0.04°$ ($1.04 \pm 0.03°$), respectively. Experimental accuracy values describing the translation along and rotation about the SDA, were 0.06 ± 0.00 mm and $0.09 \pm 0.01°$, respectively. These small errors establish the capability of SDAs to detect small translations, and rotations. In conclusion, application of SDAs should be a useful tool for describing relative motion in joint kinematic studies.

Keywords: Screw displacement axes (SDAs); Electromagnetic tracking device; Relative motion; Accuracy; Repeatability

1. Introduction

Screw displacement axes (SDAs) have been employed to describe joint kinematics in biomechanical investigations. SDAs may be useful for describing unstable joint motion, for evaluating surgical repair techniques, and designing and aligning artificial joints. The joint motion is expressed by a translation along, and rotation about, this directed line in space (Beggs, 1966; Bottlang et al., 1999). The position and orientation of the SDA will generally change throughout the motion (Woltring et al., 1985). A more thorough description of these parameters has been offered in other investigations (Beggs, 1966; Bottlang et al., 1999; Woltring et al., 1985).

Previous reports have investigated SDA accuracy combining motion analysis techniques and smoothing procedures (An et al., 1988; De Lange et al., 1990; Bottlang et al., 1999; Stokdijk et al., 1999). However, to our knowledge, no study has assessed SDA accuracy describing the relative movement between adjacent rigid bodies with an electromagnetic tracking system. This is important, since in relative motion, neither body is fixed

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and consequently sensitivity to potential measurement errors from both bodies may be significant (Woltring et al., 1985).

Therefore, the objective of this study was to determine the accuracy and repeatability of SDAs for describing joint kinematics between two moving bodies using an electromagnetic tracking system.

2. Methods and materials

Numerical simulations describing a simultaneous translation along, and rotation about, a vertical SDA, were designed to investigate the propagation of error through the SDA algorithm for single rigid body motion relative to a fixed source, and relative motion between two bodies. Position and orientation error values, randomly generated using a Gaussian distribution within the ranges ± 0.25 mm and $\pm 0.1°$, respectively, were added to the simulated data, based on the resolution of the Flock-of-Birds electromagnetic tracking system (Ascension Technology, Burlington, VT) reported by Milne (Milne et al., 1996).

Two physical experimental tests were conducted using a jig consisting of two concentric cylinders (Fig. 1A). In the physical ‘‘continuous’’ experiment, a peg affixed to the inner cylinder coursed along the smooth helical surface machined in the outer cylinder (Fig. 1B). Relative motion was achieved by manually rotating the cylinders in opposing directions. In the physical ‘‘incremental’’ experiment, measurements were accomplished by manually positioning the inner cylinder's peg into notches machined into the outer cylinder's cut surface (Fig. 1C). The stepping distance between each notch corresponded to a rotation and axial translation of $5.00 \pm 0.25°$ and 0.50 ± 0.05 mm, respectively. Motion was recorded using the tracking system, consisting of sensors and a transmitter. This six degree-of-freedom device measures the location of multiple sensors simultaneously in a pulsed DC magnetic field (Ascension Technology, 1996).

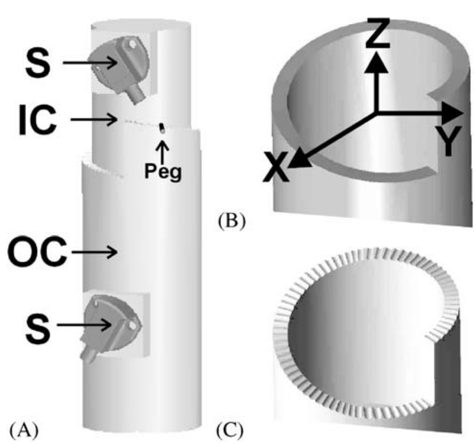

Fig. 1. (A) The calibration jig consisted of an inner cylinder (IC) that rotated on a helix machined into an outer cylinder (OC). An electromagnetic sensor (S) was rigidly secured to each cylinder. Figures (B) and (C) illustrate the outer cylinder with a smooth and indexed surface, respectively, used for generating continuous and incremental measurements, respectively. X-, Y- and Z-axes represent the reference coordinate system on the outer cylinder. The notches in the jig (C) were cut using a vertical manual milling machine (Excello, London, Canada). The accuracy of the machined notches was 0.25° (rotation) and 0.05 mm (position). The two concentric cylinders were machined as a slip fit, with clearance less than 0.025 mm.

Data from the physical ‘‘continuous’’ experiment were smoothed using a double low-pass Butterworth filter. SDAs were calculated for rotation magnitudes ranging from 0.5° to 16° (Beggs, 1966; Bottlang et al., 1999), and expressed in a reference system determined for the outer cylinder. This reference system was calculated by digitizing landmarks using a stylus probe mounted to a third sensor.

The position and orientation of the SDAs, and the magnitude of rotation about and translation along the SDAs, was calculated. Accuracy was defined as the average absolute difference between the known and measured values. SDA position and orientation accuracy was determined from the physical ‘‘continuous’’ experiment. SDA translation and rotation accuracy was determined from the physical ‘‘incremental’’ experiment. Repeatability was measured over 100 and 5 trials for the numerical simulated and physical experimental data, respectively, using the standard deviation as the measurement variable. Statistical comparison was performed using one and two-way repeated measures ANOVAs, and Student Newman-Keul's tests with significance (p) set at 0.05.

3. Results

SDA position error and standard-deviation decreased with increasing rotation magnitude for the numerical simulations of both single-body and relative motion (Fig. 2A). The relative motion was less accurate ($p = 0.04$) but demonstrated similar repeatability ($p = 0.1$) compared to single-body motion. Unfiltered physical ‘‘continuous’’ experimental data also demonstrated this decreasing trend, and was less accurate compared to both numerical simulations ($p < 0.05$) (Fig. 2B). Data-filtering improved the position accuracy of the physical experimental data for rotations smaller or equal to 4°, with no effect for larger rotations ($p < 0.05$) (Fig. 3A and B). Repeatability improved after data-filtering ($p = 0.02$).

SDA orientation error and standard deviation decreased with increasing rotation magnitude for both numerical simulations and unfiltered physical experimental data (Fig. 2C–E). The accuracy ($p = 0.2$) and repeatability ($p = 0.3$) of the two simulations was

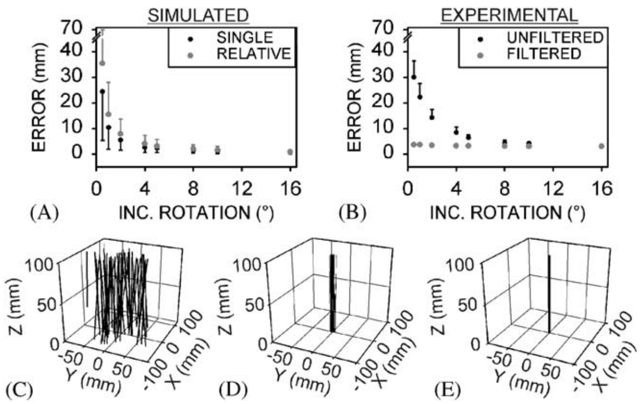

Fig. 2. This figure shows the increase in positional accuracy and standard deviation at larger rotations. SDA position accuracy plotted relative to incremental rotation for: (A) single and relative rigid body numerical simulations, and (B) unfiltered and filtered physical "continuous" experimental source data. Figures (C), (D) and (E) show SDAs determined from numerical simulated motion data, for rotations of 0.5°, 5°, and 16°, respectively. Note the increase in accuracy progressing from (C) to (E). The intersections of the SDAs with the XY plane depict their position.

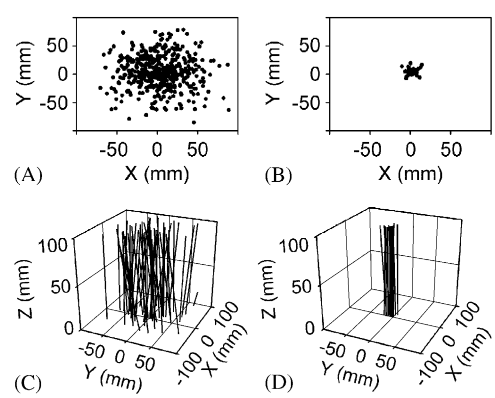

Fig. 3. This figure shows the increase in SDA accuracy subsequent to data-filtering. These four plots represent SDAs determined at a rotation of 0.5°, for unfiltered (A and C) and filtered (B and D) physical experimental "continuous" data. Figures (A) and (B) represent intersection of the SDAs with the XY plane, and (C) and (D) depict the SDAs in three-dimensional space. The filter effectively reduced error in SDA prediction ($p<0.05$).

similar. Data-filtering increased the orientation accuracy of the physical experimental data for rotations less than or equal to 5°, but demonstrated no change at larger rotation magnitudes ($p<0.05$) (Fig. 3C–D).

SDA translation error was unaffected by the rotation magnitude for both simulations, although measurements were slightly more accurate ($p<0.001$) and repeatable ($p<0.001$) for one compared to two-body motion. The translation error was 0.06 ± 0.00 mm for the physical incremental experiment (Table 1).

SDA rotation error was similar for both simulations, although measurements were slightly more accurate ($p<0.001$) and repeatable ($p<0.001$) for one compared to two-body motion. The rotation error was $0.09 \pm 0.01°$ for the physical incremental experiment (Table 1).

4. Discussion

This study agrees with previous reports that have demonstrated SDA position and orientation errors to be inversely proportional to, and rotation and translation parameters independent of, the rotation magnitude (Woltring et al., 1985; Bottlang et al., 1999; An et al., 1988). This is the first reported investigation to document SDA accuracy and repeatability for relative motion using numerical simulated data and physical experimental data recorded using electromagnetic tracking and a precision jig.

Potential limitations are inherent in electromagnetic tracking systems. The sensor furthest from the transmitter will contain greater noise in its measurements (Ascension Technology, 1996). However, no sensor will suffer in performance if each transmitter-to-sensor separation range is 23–64 cm (Milne et al., 1996). The transmitter-to-sensor distance in this study was approximately 30 cm. Additionally, we ensured no metallic objects were near the experiment (Milne et al., 1996). Furthermore, measurement errors may result if the sensor is moved too rapidly, since the sensor's location is determined from DC magnetic fields delivered sequentially from the transmitter's three antennae (i.e. X, Y, Z) (Ascension Technology, 2000). For the rotation rate in this study (average: $42.1 \pm 8.8°$/s), the sensor moved an average of 0.005 mm between antennae recordings, far less than the tracking system's resolution (0.25 mm). Therefore, any lag effect can be considered insignificant. Manual rotation may be considered a limitation of this study. However, the displacement rate achieved was similar to that which could be attained using a mechanical system. Additionally, the slip fit of the concentric cylinders (0.025 mm clearance) restricted the relative motion to comply with the pre-defined helical pathway of the outer cylinder. Therefore, we feel that results would be similar whether the motion was achieved manually or mechanically. Digitization error was minimized by using a short stylus (30.0 mm) (Ascension Technology, 1996; Rath et al., 1996).

This study's numerical simulations extended Bottlang's (Bottlang et al., 1999) investigation, by simulating both one- and two-body motion, with error values randomly generated using a Gaussian distribution determined from the tracking system's resolution. Moreover, we induced error in all coordinates of the initial and final positions of the screw motion simultaneously, rather than individually in separate simulations. Both simulations observed large errors in SDA position and orientation for small rotations, which decrease at higher rotational magnitudes. Further, we

Table 1
Accuracy ± standard deviation for SDA parameters calculated at a 5° rotation magnitude

Test		Position (mm)	Orientation (°)	Translation (mm)	Rotation (°)
Numerical simulation	Single-body motion	2.33±1.72	0.56±0.66	0.08±0.13	0.07±0.06
	Relative body motion	3.17±2.61	0.81±0.93	0.09±0.16	0.12±0.09
Physical experimental	"Continuous" unfiltered	6.49±1.23	1.59±0.18	N/A	N/A
	"Continuous" filtered	3.31±0.21	1.04±0.03	N/A	N/A
	"Incremental"	2.80±0.25	0.60±0.02	0.06±0.00	0.09±0.01

Error ± standard deviations determined for four SDA parameters (position, orientation, translation and rotation) at a rotation of 5°, for the numerical simulations (i.e. single and relative rigid body motion) and two physical experimental tests (i.e. "continuous" and "incremental").

demonstrated single-body motion to have superior position, translation and rotation errors, but similar orientation accuracy, compared to relative body motion.

In further accordance with Bottlang, we demonstrated large errors in predicting SDA position and orientation for unfiltered physical experimental data at small rotations. They smoothed data using boxcar averaging and cubic spline interpolation, giving position and orientation errors at a 0.5° rotation for non-smoothed and smoothed data, respectively, as 17.66 and 1.34 mm, and 2.9° and 0.28°. We predicted errors of 30.10 and 3.75 mm, and 8.66° and 1.10°, prior and subsequent to data-filtering, respectively (Fig. 3). The Butterworth filter implemented in this study is equivalent to the generalized cross-validation data smoothing technique (Woltring, 1990), which has successfully diminished the small-angle noise effect (Woltring, 1990; Woltring, 1995). We showed the Butterworth filter effectively reduced SDA position and orientation errors for rotations of less than or equal to 5°, with no statistical effect at larger rotational magnitudes. Therefore, if a filter is not accessible, SDA analysis should be conducted at rotations larger than 5°. It is expected that the errors reported by Bottlang are smaller, since their data were collected at static (versus continuous) positions using a single sensor relative to a fixed source. In the current study, the physical "incremental" experiment demonstrated better accuracy compared to the physical "continuous" experiment (Table 1). Further, this study's numerical simulations demonstrated SDAs generated from single-body motion are more accurate compared to relative motion, also predicted by Woltring (Woltring et al., 1985), who indicated sensitivity to error becomes more complicated during relative rigid body motion.

Stokdijk (Stokdijk et al., 1999) also reported SDA position (5.6 mm) and orientation errors (0.25°) for the rotation of a single electromagnetic sensor about a hinge. The rotation magnitude and data-filtering technique employed was not reported.

In summary, the numerical simulations demonstrated SDA position accuracy was superior for single compared to relative body motion, whereas orientation accuracy was similar. Physical experimental tests showed the Butterworth filter improved SDA position and orientation accuracy for rotation magnitudes smaller or equal to 5°, with no effect at larger rotation magnitudes. Therefore, in the absence of a filter, SDAs should be calculated based on rotations of greater than at least 5°. Data-filtering also increased repeatability at all rotations. Additionally, this study established the ability of SDAs to accurately detect rotations about, and small translations along, the SDA. Application of SDAs should be a useful tool for describing relative motion for application where accuracy levels of approximately 3 mm and 1° are satisfactory.

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