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TECHNICAL NOTE

ACCURACY OF AN ELECTROMAGNETIC TRACKING DEVICE: A STUDY OF THE OPTIMAL OPERATING RANGE AND METAL INTERFERENCE

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Abstract—The positional and rotational accuracy of a direct-current magnetic tracking device commonly used in biomechanical investigations was evaluated. The effect of different metals was also studied to determine the possibility of interference induced by experimental test fixtures or orthopaedic implants within the working field. Positional and rotational data were evaluated for accuracy and resolution by comparing the device output to known motions as derived from a calibrated grid board or materials testing machine. The effect of different metals was evaluated by placing cylindrical metal samples at set locations throughout the working field and comparing the device readings before and after introducing each metal sample. Positional testing revealed an optimal operational range with the transmitter and receiver separation between 22.5 and 64.0 cm. Within this range the mean positional error was found to be 1.8% of the step size, and resolution was determined to be 0.25 mm. The mean rotational error over a 1–20° range was found to be 1.6% of the rotational increment, with a rotational resolution of 0.1°. Of the metal alloys tested only mild steel produced significant interference, which was maximum when the sample was placed adjacent to the receiver. At this location the mild steel induced a positional difference of 5.26 cm and an angular difference of 9.75°. The device was found to be insensitive to commonly used orthopaedic alloys. In this study, the electromagnetic tracking device was found to have positional and rotational errors of less than 2%, when utilized within its optimal operating range. This accuracy combined with its insensitivity to orthopaedic alloys should make it suitable for a variety of musculoskeletal research investigations.

Keywords: Electromagnetic tracking device; Accuracy; Error; Kinematics; Metal interference.

INTRODUCTION

Electromagnetic tracking devices are increasingly being used in spatial digitization and as a kinematic measuring tool. Previous investigators have focused on the accuracy of alternating-current (AC) devices (An *et al.*, 1988, 1991; McKellop *et al.*, 1993; Sidles *et al.*, 1988; Zoghi *et al.*, 1992); however, apart from manufacturers data, limited information is published on the static accuracy and effects of metal on the newer direct-current (DC) devices. In this study we evaluated Ascension Technology's 'Flock of Birds' (Burlington, VT) tracking system which measures the position and orientation of a receiver with respect to a transmitter in six degrees of freedom, using pulsed DC magnetic fields. The device was assessed for static positional and rotational accuracy and resolution. The effect of metals on the accuracy of the device was also evaluated.

METHODS

Testing was performed using the default system configuration (103 Hz, AC Wide Filter—on, DC Lowpass Filter—on) and manufacturer's software with an output positional resolution of 0.25 mm and a rotational resolution of 0.01°. Data were collected in the position and angle mode which outputs six values per sample, three positions (i.e. X, Y, Z) and three Eulerian angles (yaw, pitch and roll).

Positional accuracy was evaluated using a custom-manufactured Delrin grid board, with nominal 25 mm spacings calibrated to $\pm$ 0.005 mm by a coordinate measuring machine (DEA Swift, Livonia, MI). For six axes ($+X$, $+Y$, $-Z$, and three combinations of X, Y, Z) the receiver was advanced through 25 mm steps over a grid board range of 15–85 cm. Ten measurements were taken at each position and the mean value calculated. Error was defined as the difference between the calibrated grid spacings and the vectorial resultant between the two receiver readings. A maximum error for any single point sample was also recorded.

Positional resolution was evaluated by mounting a receiver to a 60 cm Delrin boom arm fixed to the actuator of a bi-axial Instron 8501 Servo-Hydraulic Materials Testing Machine (Canton, MA). With the initial receiver to transmitter separation at 41 cm, the boom arm was then axially translated through increments of 0.125, 0.250, 0.50, 0.750, 1.000, 1.250, 1.500, 1.750 and 2.000 mm. Ten samples were taken at each displacement, with error being calculated as the difference between the Instron actuator position from the LVDT (linear variable differential transformer, accuracy 1.0%) of the testing machine and the vectorial resultant between receiver positions. Positional resolution was defined as the minimum displacement that the device could detect.

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Rotational accuracy was evaluated by rotating the Instron boom arm through known increments using the actuator RVDT (rotational variable differential transformer, accuracy 0.75%). The average transmitter to receiver separation was maintained at 35.0 ± 1.5 cm. Angular data were averaged over ten samples at eight rotation increments (1, 2, 3, 4, 5, 10, 15 and 20°), for ten sweeps of the boom arm. Rotation matrices were reduced to an equivalent angle (screw angle) from the trace of successive rotation matrices (Goldstein, 1950). Error was defined as the difference between the Instron sweep angle and the tracking device equivalent angle.

Rotational resolution was evaluated by rotating the boom arm assembly through increments of 0.1° from 0.1 to 0.8°. Ten samples were taken at each rotation increment comparing the tracking device equivalent angle to the Instron RVDT. The rotational resolution was defined as the minimum rotation the device could sense.

Interference of five cylindrical metal samples was evaluated for different placements within the working field. The 12 mm diameter by 125 mm long samples were chosen to represent the shape, volume, and materials of upper-extremity orthopaedic implants. The metals tested were aluminium (6061), cobalt chrome alloy (Co–Cr–Mo), mild steel (1018), stainless steel (316 L) and a titanium alloy (Ti–4Al–6V). Initial background readings were taken with the transmitter and receiver secured 45 cm apart. Measurements were then repeated with each metal sample placed on end, at ten sites in proximity to the transmitter or receiver. Interference was defined as the difference between the mean metal reading and the initial background reading taken before placing the metal *in situ*. For comparative purposes, the X, Y, Z positional data were reduced to a resultant vector length. The three angles were also combined to one equivalent angle of rotation. The interference resultants from all five materials were compared using a one-way analysis of variance and a Student–Newman–Keuls multiple comparison procedure.

RESULTS

An optimal operational zone of minimal positional error was found to be within a transmitter to receiver separation range of 22.5–64.0 cm (Fig. 1). Within this zone the ten-sample mean error was -0.50 mm for all six axes tested. The maximum single sample error within this zone was -1.00 mm. The positional error in the centre of this optimum zone (44.5 cm separation) was found to increase proportionally with the measured distance. Over increments of 2.5–15.2 cm the mean error was found to be 1.8% of the step size (Fig. 2). For smaller step increments the device was found to be sensitive enough to repeatably measure position changes of 0.25 mm.

Rotational error increased proportionally with the receiver rotation angle. Over the 1–20° range, the mean error was found to be 1.6% of the rotational increment (Fig. 3). The tracking device was found to repeatably sense rotations as small as 0.1°, between adjacent arc rotations. The rotational error was also found to be minimal within a receiver separation range of 22.5–64 cm (data not shown).

Of the metals tested only mild steel produced significant interference of the measured position and rotation ($p < 0.001$). Maximum interference occurred when the offending metal was placed adjacent to the receiver on a line collinear with the center of the transmitter and receiver. At this location the mild steel induced a positional difference of 5.26 cm (Fig. 4) and an angular difference of 9.75°.

DISCUSSION

In this study, the 'Flock of Birds' electromagnetic tracking device was found to have positional and rotational errors of less than 2%, when utilized within its optimal operating range of 22.5–64.0 cm. The device is sensitive enough to read positional and rotational changes of 0.25 mm and 0.1°, respectively. These values are equal to or slightly better than the manufacturer's technical literature which suggests accuracies of 2.5 mm RMS and 0.5° RMS averaged over the translational range, and resolutions of 0.75 mm and 0.10° at 30.5 cm. These results are comparable to previous investigations on AC tracking devices, which reported accuracies in the range of 0.3–0.9 mm, 0.3–1°, and an optimal separation of 10–70 cm (An *et al.*, 1988, 1991; McKellop *et al.*, 1993; Sidles *et al.*, 1988; Zoghi *et al.*, 1992).

We evaluated accuracy on a relative basis from two sequential positions and orientations in space, which is similar to how the

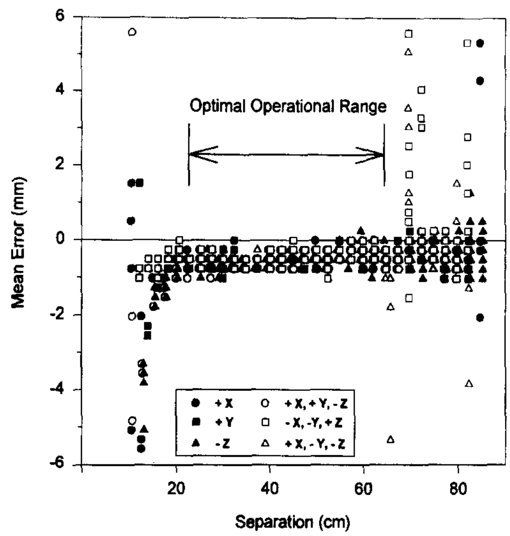

Fig. 1. The mean position error for 25 mm steps, over the working range of the device ($n = 10$). The six symbols represent the directions of travel, i.e. $+X$, $+Y$, $-Z$, $+X+Y-Z$, $-X-Y+Z$ and $+X-Y-Z$. An optimum operational range was defined as the transmitter–receiver separation over which each of the six axes exhibited a mean error of less than ± 0.5 mm.

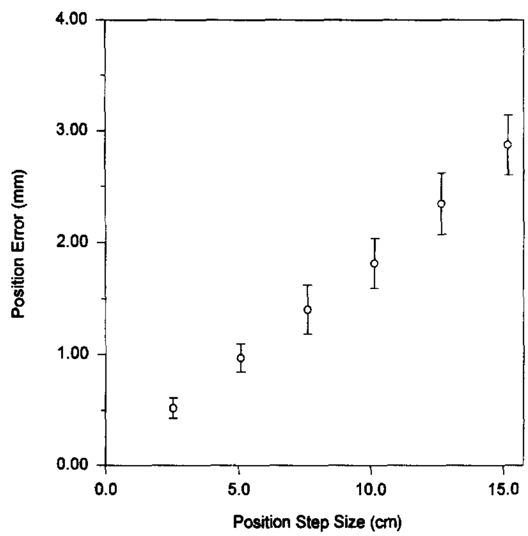

Fig. 2. The mean and standard deviation of positional error for steps of 2.5–15.2 cm along all six axes ($n = 10$). The mean error was found to be 1.8% of the step size. Measurements were taken near the centre of the previously defined optimal operational range.

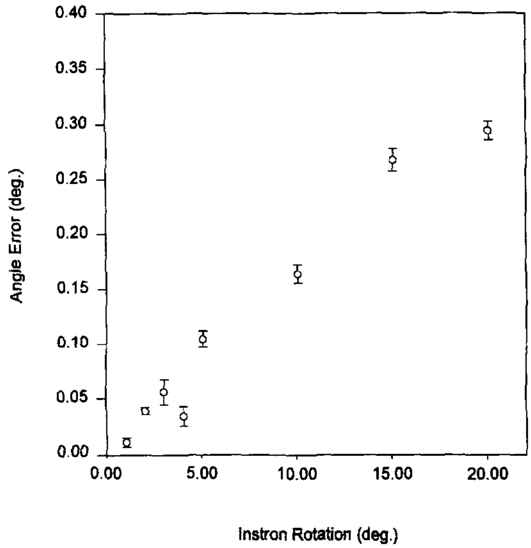

Fig. 3. The mean and standard deviation of rotational error for arcs of 1–20° ($n = 10$). Within this range the mean error was found to be 1.6% of the rotation increment. The measurements were taken near the centre of the previously defined optimal operational range.

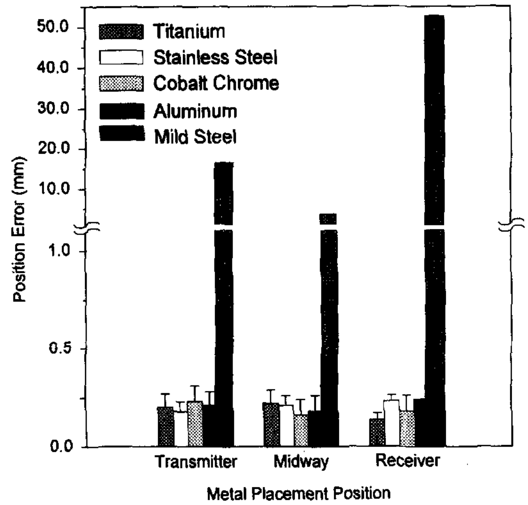

Fig. 4. Effects of different metal cylinders, when placed at three positions on a line collinear with the centre of the transmitter and receiver. The placement positions shown are: transmitter (6 mm from the edge), midway between the transmitter and receiver (230 mm away from each), and receiver (6 mm from the edge). Mild steel placed adjacent to the receiver generated the largest interference on the positional and rotational data. Only mild steel exhibited a significant difference ($p < 0.001$).

device is used in biomechanical investigations. This configuration will usually permit the receivers to operate within the optimal operating range throughout an experiment. However, in extended range applications multiple transmitters and receivers may be required to operate within the accuracy envelope.

It has been suggested that DC tracking devices have a reduced sensitivity to metal interference relative to AC devices; however, the effect of metals on DC devices has not been previously reported in the literature. This investigation demonstrates that the 'Flock of Birds' is insensitive to surgical alloys of a shape and volume commonly used in upper-extremity orthopaedic implants. In theory, the deleterious effects of mild steel may be reduced by altering the sampling frequency, but for accuracy-sensitive applications mild steel within the working field should be avoided with this device. Overall, the device's accuracy and insensitivity to surgical alloys should make this a useful tool for a variety of musculoskeletal research investigations.

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