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Technical Note

Calibration of the "Flock of Birds" electromagnetic tracking device and its application in shoulder motion studies

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Abstract

In this paper the applicability in terms of measurement accuracy of the "Flock of Birds" six D.O.F. electromagnetic tracking device in shoulder research is investigated. Position measurements in a workspace of approximately 1 m^3 were performed using a stylus. The andom error at the stylustip appeared to be 1.86, 1.98 and 2.54 mm for *x*-, *y*- and *z*-coordinate, respectively. The error caused by distortion of the magnetic field by metal in the concrete of especially the floor was 20.8, 22.2 and 20.4 mm for the *x*-, *y*- and *z*-coordinate, respectively. Calibration and leaving out the measurements closests to the floor lowered this error to 2.07, 2.38 and 2.35 mm. Orientation errors of the shoulder bones evolving from the measurement inaccuracy were estimated from repeated measurements of shoulder bony landmarks of ten subjects by means of the stylus. These errors were generally below 2°. This is lower than found for the same measurements using a spatial linkage digitizer. It is concluded that the "Flock of Birds" is a useful tool for shoulder kinematic studies. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Electromagnetic tracking device; Calibration; Shoulder; Kinematics

1. Introduction

Van der Helm and Pronk (1995) described a palpation technique to obtain 3D positions of bony landmarks of the shoulder. The main advantage of this technique is that scapula orientations can be measured quite easily. Furthermore, bone- referenced local coordinate systems (LCS) can be constructed (Van der Helm and Pronk, 1995; Van der Helm, 1997). So far, the bony landmark position recordings were performed using a spatial linkage digitizer (Pronk and Van der Helm, 1989), having the disadvantage that every bony landmark had to be measured separately. Using a six degree-of-freedom (D.O.F.) tracking device would make measurements faster by measuring both the position and the orientation of multiple receivers simultaneously. Construction of referenced LCS is then still possible using a stylus: a receiver mounted on a pointer. Little is known about the accuracy of the tracking devices and their susceptibility to metal distortion. An et al. (1988) investigated the usefulness of the Polhemus AC tracking device. Milne et al. (1996) investigated the accuracy and susceptibility to metal distortion of the "Flock of Birds" (F.O.B) DC electromagnetic tracking device. It was concluded from both studies that with the tracking devices sufficient accuracy could be gained, providing there was no metal nearby. However, the issue of calibration is not dealt with and the accuracy of the combination of tracking device and stylus has not been investigated. The goal of this study was to investigate the accuracy of measurements performed with a stylus in workspace large enough to perform position measurements of both the right and the left shoulder. A calibration procedure is carried out. Finally, the accuracy of palpation measurements using the FOB is estimated from in vivo recordings of 3D shoulder positions.

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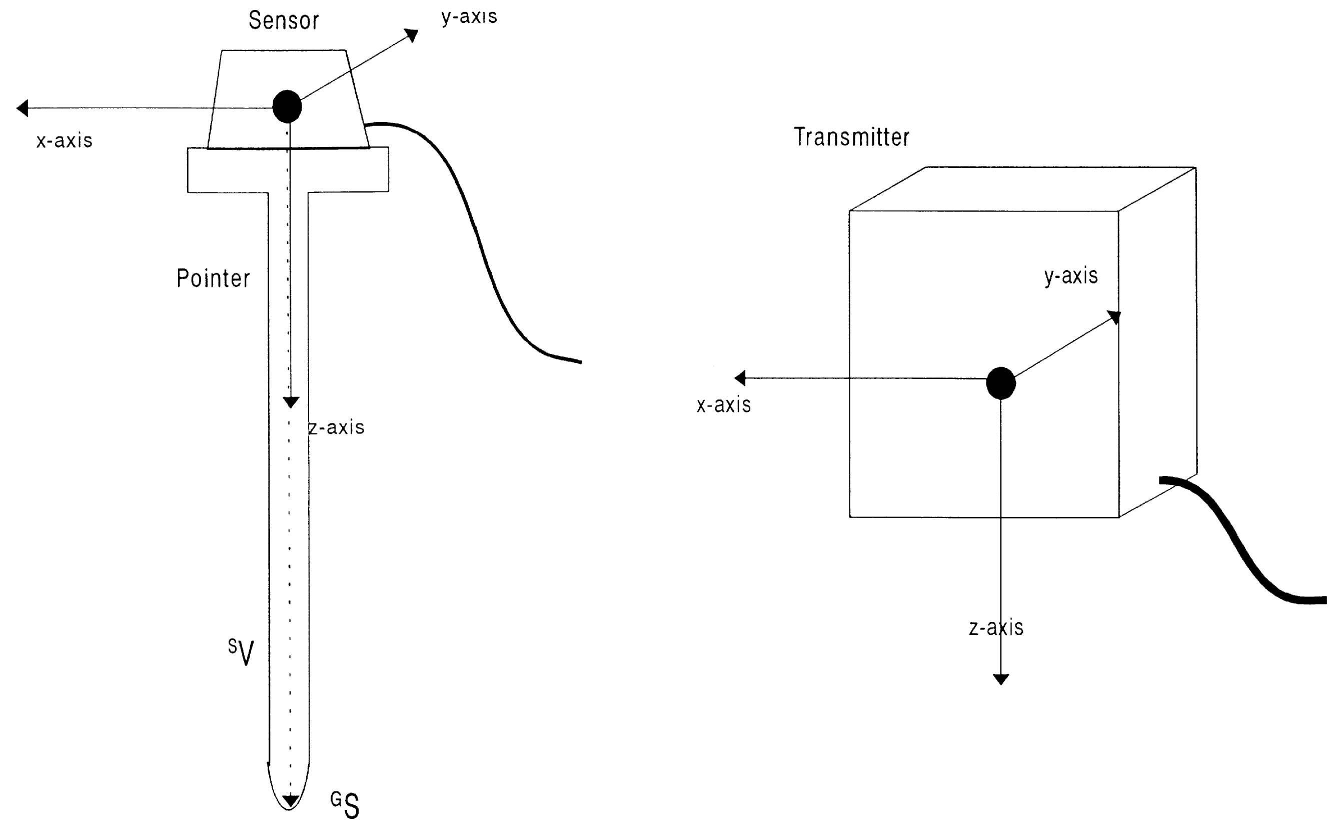

Fig. 1. The stylus: a receiver mounted on a pointer of about 65 mm length. Shown in the figure are the vectors according to Eqs. (2) and (3).

2. Methods

2.1. Measurement system

A "Flock of Birds" system consisting of an extended range transmitter and four wired receivers was used (Ascension Technology. Inc., Burlington, VT, USA). All settings were in the default mode (103 Hz, AC wide filter on, DC low pass filter on). The system specifications regarding measurement accuracy are 7.62 mm and 0.5° RMSE for position and orientation respectively. According to the manufacturer the optimal working range of the system is 8"–96" (0.203–2.44 m) in each direction. A pointer with a tip diameter of approximately 1 mm was attached to a receiver. The position vector $[x; y; z]$ of the stylus tip with respect to the origin of the local coordinate system of the receiver was approximately [0; 0; 65] mm (Fig. 1).

2.2. Stylus tip calibration

A wooden calibration box was constructed as an open frame in which 160 small holes were drilled. The holes were positioned horizontally in a space of 1 m × 1 m × 1 m in three levels separated by open spaces of 0.45 m. The box was placed in the measurement field at a minimal height of 1.00 m above the floor and 0.50 m away from the transmitter which itself was placed halfway the vertical height of the calibration box, 1.50 m above the floor. The 3D positions of the bottom of the holes (hereafter called data points) were measured by means of a spatial linkage digitizer with an accuracy of 0.1 mm RMSE. The stylus tip was then placed in each hole and slowly rotated around its endpoint while orientation and position of the stylus receiver were recorded. In this way, about 150 observations per data point were obtained. At every data point, the vector ${}^{S}\mathbf{V}_s$ between the receiver's center and the stylus tip was estimated by minimizing using a Gauss–Newton approach (Ljung, 1987):

$$J = \sum_{i=1}^{n} e_i^2, \tag{1}$$

where

$$\mathbf{e} = -\,{}^{G}\mathbf{S} + ({}^{G}\mathbf{O}_S + \mathrm{R}(\alpha, \beta, \gamma)^{T} \cdot {}^{S}\mathbf{V}_S), \tag{2}$$

or

$$\begin{bmatrix} e_x \\ e_y \\ e_z \end{bmatrix} = -\begin{bmatrix} s_x \\ s_y \\ s_z \end{bmatrix} + \left(\begin{bmatrix} o_{sx} \\ o_{sy} \\ o_{sz} \end{bmatrix} + (R_x(\alpha_S) \cdot R_y(\beta_S) \cdot R_z(\gamma_S))^{T} \times \begin{bmatrix} v_{sx} \\ v_{sy} \\ v_{sz} \end{bmatrix} \right) \tag{3}$$

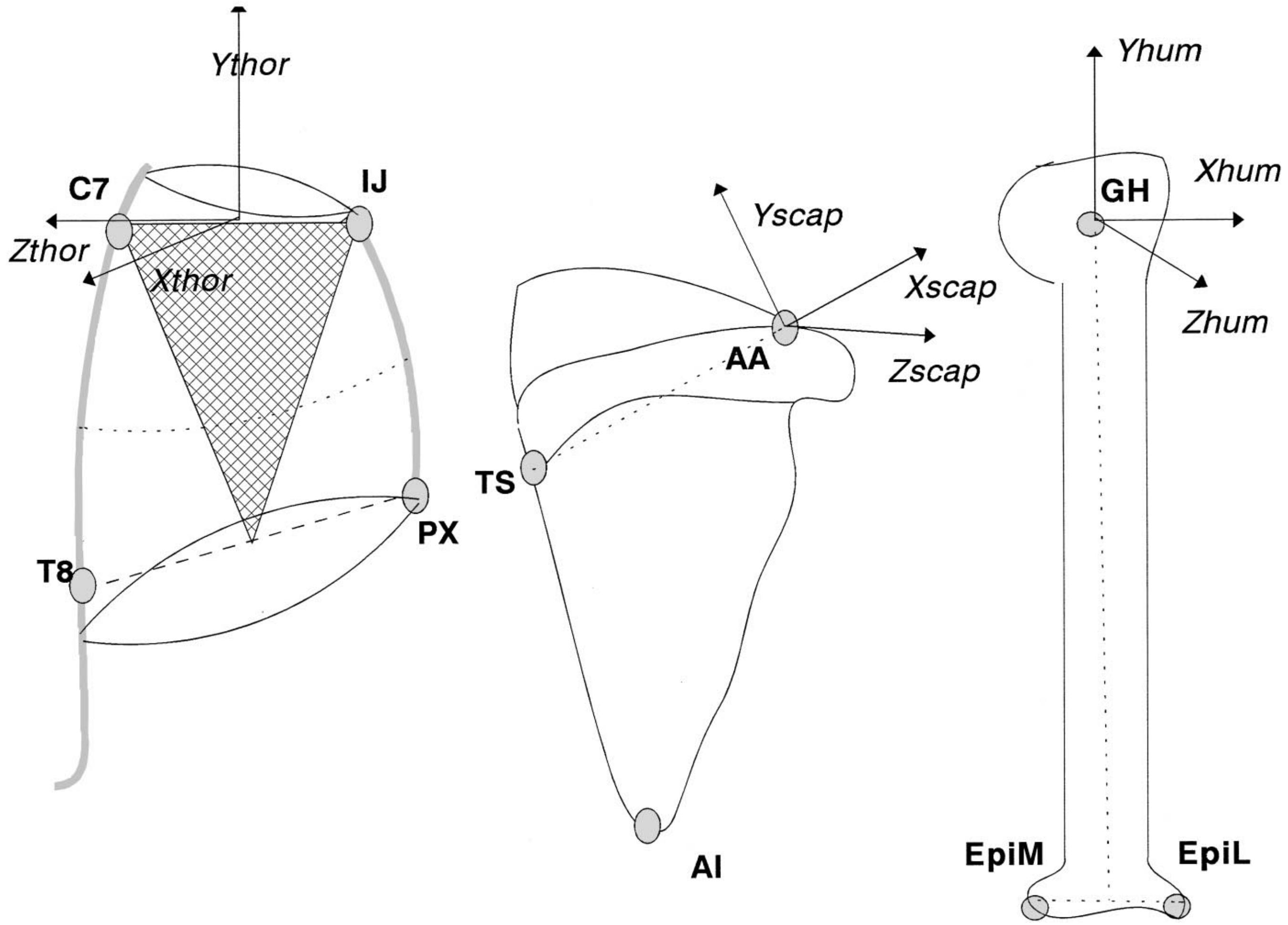

Fig. 2. a graphical representation of the coordinate systems used in this study.

s_x, s_y, s_z are the coordinates of the global position of the stylus endpoint $^{G}\mathbf{S}$ (estimated); o_{sx}, o_{sy}, o_{sz} are the coordinates of the position vector $^{G}\mathbf{O}_s$ of the stylus receiver (output FOB); α_s, β_s, γ_s are the Euler angles describing the orientation of the stylus receiver (output FOB); R is the rotation matrix describing the rotation of the receiver's local coordinate system (LCS) with respect to the (global) transmitter coordinate system (GCS); v_{sx}, v_{sy}, v_{sz} are the coordinates of the vector $^{S}\mathbf{V}_s$ (estimated). Note: the superscript G in front of the vector means orientation in the GCS, whereas the superscript S means orientation in the local (= receiver) coordinate system.

$^{S}\mathbf{V}_s$ and $^{G}\mathbf{S}$ were estimated simultaneously at every data point. The mean value of $^{S}\mathbf{V}_s$ over all data points was used for further calculations.

2.3. Calibration of the workspace using the stylus

A second set of measurements was performed in the same way as the first set. Using the estimated $^{S}\mathbf{V}_s$, the global positions of the calibration box data points $^{G}\mathbf{Q}$ were calculated for each observation by:

$$\begin{bmatrix} q_x \\ q_y \\ q_z \end{bmatrix} = \begin{bmatrix} o_{sx} \\ o_{sy} \\ o_{sz} \end{bmatrix} + (R_x(\alpha_s)\cdot R_y(\beta_s)\cdot R_z(\gamma_s))^{T}\cdot \begin{bmatrix} v_{sx} \\ v_{sy} \\ v_{sz} \end{bmatrix}. \tag{4}$$

The data points of the calibration box, measured by the palpator, $^{G}\mathbf{P}$, were oriented in the GCS of the FOB using an algorithm according to Veldpaus et al. (1988). Linear regression was used to estimate the parameters of a function which minimised:

$$e = {}^{G}\underline{\mathbf{Q}} - {}^{G}\underline{\mathbf{P}}. \tag{5}$$

Both the orientation angles and the position coordinates in linear, quadratic and cross-term form were used as regressors.

2.4. In vivo error estimation

Repeated measurements were performed on the right shoulders of 10 healthy volunteers. Subjects were in

Table 1
Bony landmarks, local coordinate system definitions and rotation sequences used to calculate bone orientations expressed in Cardan angles

Thorax	
Coordinate system: origin ^{G}**IJ** ^GY_t:{^{G}**IJ** + ^{G}**C7**)/2 − (^{G}**PX** + ^{G}**T8**)/2}/‖(^{G}**IJ** + ^{G}**C7**)/2 − (^{G}**PX** + ^{G}**T8**)/2‖	Bony landmarks
$^G\mathbf{X}_t$: perpendicular to the plane through ^{G}**IJ**,^{G}**C7** and (^{G}**PX** + ^{G}**T8**)/2	**PX** Processus xyphoideus
^GZ_t: perpendicular to $^G\mathbf{Y}_t$ and $^G\mathbf{X}_t$	**IJ** Incisura jugularis
Rotation sequence: $X\ Y'\ Z''$	**C7** 7th Cervical vertebra
	T8 8th Thoracal vertebra
Scapula	
coordinate system: origin ^{G}**AA**	Bony landmarks
$^G\mathbf{X}_s$: (^{G}**AA** − ^{G}**TS**)/‖(^{G}**AA** − ^{G}**TS**)‖	**AA** Angulus acromialis
$^G\mathbf{Z}_s$: perpendicular to (^{G}**AI** − ^{G}**AA**) and $^G\mathbf{X}_s$, pointing backwards	**TS** Trigonum Spinae
$^G\mathbf{X}_s$: perpendicular to $^G\mathbf{X}_s$ and $^G\mathbf{Z}_s$	**AI** Angulus Inferior
Rotat ion sequence: $Y\ Z'\ X''$	
Humerus	
Coordinate system: origin ^{G}**GH**	Bony landmarks
$^G\mathbf{Y}_h$: {^GGH − (^GEM + ^GEL)/2}/‖{^{G}**GH** − (^{G}**EM** + ^{G}**EL**)/2}‖	**EL** Epicondylus Lateralis
^GZ_h: perpendicular to $^G\mathbf{Y}_h$ and (^{G}**EL**-^{G}**EM**). pointing backwards	**EM** Epicondylus Medialis
$^G\mathbf{X}_h$: perpendicular to $^G\mathbf{Y}_h$ and $^G\mathbf{Z}_h$	**GH** Glenohumeral joint rotation
Rotation sequence: $Y\ Z'\ Y''$	center[a]

[a] Not a true bony landmark, but estimated from regression equations according to Meskers et al. (1998b).

a seated position on a wooden platform about 1 m above the floor with the arm hanging aside the body. Receivers were attached to thorax and upper arm according to Meskers et al. (1998a). Twelve shoulder bony landmarks were located by manual palpation (Table 1) and their 3D position was subsequently recorded using the stylus. These measurements were repeated 5 times. Each subject then performed a arm elevation in small steps of 18° in the frontal plane. Bony landmark positions were expressed in the LCS of the receivers on thorax and upper arm, allowing recalculation of their global position in every position of the arm or thorax once the global position and orientation of the sensor is known (Meskers et al., 1998a). In every arm position, LCS on each shoulder bone were constructed and their orientations with respect to the thorax LCS were expressed in Cardan angles (Table 1). Scapula orientation measurements were performed using a scapula-locator: a three pin device to be adjusted manually over the scapula (Johnson et al., 1993; Meskers et al., 1998a). The average standard deviation of the bone orientations over the total of arm positions was calculated from the standard deviation evolving from the repeated palpation measurements in the resting position.

3. Results

Table 2 gives an overview of the errors from the different calibration procedures. The random error at the stylus tip was calculated as the mean of the variability of the repeated measurements at each data point. This error was not influenced by distance of data points to the floor. The RMSE calculated over the total workspace was unacceptably high, justifying the calibration procedure. Calibration successfully lowered the RMSE. Leaving out the data points closests to the floor further lowered the RMSE. Table 2 also gives the estimated in vivo orientation errors of the bones evolving from palpation inaccuracies, together with the errors evolving from similar measurements by Groot (1998) using a palpator.

4. Discussion

Two problems affect measurements using the FOB. Firstly, a stylus will cause stylus length-dependent amplification of the measurement inaccuracy. These inaccuracies are of random nature and their influence will be diminished by performing repeated measurements. Secondly, distortions of the magnetic measurement field causes fixed errors. From the initial RMSE it is clear that a calibration procedure is necessary to get accurate results. When the data points closest to the floor were left out, the RMSE became distinctively smaller, resulting in an RMSE of 2.07, 2.38 and 2.35 mm. It is clear that the steel reinforced concrete floor causes substantial distortions in the magnetic field even if the measurements were performed a least 1 m above the floor. The RMSE after the calibration procedure was such that the remaining positional and rotational errors were small. The reproducibility of the system, thus the random error, is less affected by the distance to the floor. This can give the false impression that the system is accurate.

The variance of the position of the bony landmarks will be partially random, viz., palpation error and stylus endpoint inaccuracies, and partially fixed, viz., magnetic field distortions. The random factor can be diminished by

Table 2
Estimated and measured errors (mm) from the calibration measurements and the in vivo shoulder position measurements using the spatial linkage digitizer (= palpator), according to Groot (1998) and the FOB

Procedure			x	y	z
Stylustip					
Random error stylustip whole workspace (mm)			1.86	1.98	2.58
Random error stylustip without ground level (mm)			1.58	2.07	2.64
Workspace					
Before calibration error whole workspace (mm)			20.8	22.2	20.4
After calibration error whole workspace (mm)			3.24	5.64	2.73
Before calibration error without ground level (mm)			14.4	12.3	14.0
After calibration error without ground level (mm)			2.07	2.38	2.35
Bone	Rotation	Palpation error palpator (°)	Palpation error FOB (°)		
Thorax	X (backward rotation)	1.07	0.57		
	Y' (torsion)	2.65	0.62		
	Z'' (latero-rotation)	0.78	0.71		
Scapula	Y (protraction)	2.31	2.05		
	Z' (latero-rotation)	1.38	1.87		
	Y'' (spinal tilt)	2.27	1.40		
Humerus	Y (elevation plane)	4.58	2.41		
	Z' (elevation angle)	2.66	1.12		
	Y'' (axial rotation)	6.31	5.07		

performing repeated measurements. The effect of inaccuracies of the measurements of the bony landmarks at the onset of the experiment will result in fixed errors in the assessment of bone rotations. These errors will cause an offset and will add to the inter-individual variance. Eventually, the estimated orientation errors of the bone orientations evolving from inaccuracies of palpation were lower than found by Groot (1998) who used a far more accurate measuring device (RMSE 0.1 mm). Using the FOB, palpation is necessary only once to establish the orientations of the bony landmarks in the local coordinate systems of the receivers on the shoulder bones. Thereby variability caused by repeated measurements of the bony landmarks in every arm position as it is necessary using the palpator is eliminated. Furthermore, the FOB palpation measurements can be performed when the subject is in a resting position. Bony landmarks are then easy and well palpable without muscles sliding over.

It should be noted that the present study did not include receiver-bone relative motions. This issue is adressed more extensively in Meskers et al. (1998a).

References

An, K.N., Jacobsen, M.C., Berglund, L.J., Chao, E.Y.S., 1988. Application of a magnetic tracking device to kinesiologic studies. Journal of Biomechanics 21, 613–620.

de Groot, J.H., 1998. The reproducibility of the shoulder kinematics measured by means of the palpation method. Clinical Biomechanics, In press.

Van der Helm, F.C.T., Pronk, G.M., 1995. Three dimensional recording and description of motions of the shoulder mechanism. Journal of Biomechanical Engineering 177, 27–40.

Van der Helm, F.C.T., 1997. A standardized protocol for motion recordings of the shoulder. In: Veeger, H.E.J., Van der Helm, F.C.T., Rozing, P.M., (Eds.), Proc 1st Conf Int Shoulder Group. Shaker Publishing Ltd., Maastricht, Netherlands, pp. 8–12.

Johnson, G.R., Stuart, P.R., Mitchell, S., 1993. A method for the measurement of three dimensional scapular movement. Clinical Biomechanics, 8, 269–273.

Ljung, L., 1987. System Identification: Theory for the User. Prentice-Hall, Englewood Cliffs, NJ.

Meskers, C.G.M., Vermeulen, H.M., De Groot, J.H., Van der Helm, F.C.T., Rozing, P.M., 1998. 3D shoulder position measurements using a six degrees of freedom electromagnetic tracking device. Clinical Biomechanics 13, 280–292.

Meskers, C.G.M., Van der Helm, F.C.T., Rozendaal, L.A., Rozing P.M., 1998. In vivo estimation of the glenohumeral joint rotation center from scapular bony landmarks by linear regression. Journal of Biomechanics 31, 93–96.

Milne, A.D., Chess, D.G., Johnson, J.A., King, G.J.W., 1996. Accuracy of an electro magnetic tracking device: a study of the optimal operating range and metal interference. Journal of Biomechanics. 29, 791–793.

Pronk, G.M., Van der Helm, F.C.T., 1989. The palpator, an instrument for measuring the three dimensional positions of bony landmarks in a fast and easy way. Journal of Medical Engineering Technology 15, 15–20.

Veldpaus, F.E., Woltring H.J., Dortmans, L.J.M.G., 1988. A least squares algorithm for equiform transformation from spatial marker coordinates. Journal of Biomechanics 21, 45–54.