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# Development of an in-vivo method of wrist joint motion analysis

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#### Abstract

*Background.* A clinically applicable method of plotting wrist joint motion in three-dimensions has not been described. Computer modelling has been used to improve joint arthroplasty elsewhere in the body. We aimed to develop a method of measuring, and modelling, wrist joint motion that could potentially be used to improve the kinematic performance of wrist arthroplasty designs.

*Methods.* An electromagnetic system was used to record wrist motion in three-dimensions. A small pilot study attempted to assess repeatability. A larger group of volunteers with normal wrists was also studied. An iterative computer model, using a two-axis hinge, was developed. One output from this model, the offset of the two axes of motion, is presented as an example of the possible applications of this method of analysis.

*Findings.* For any one individual, in the pilot study, the offset of the axes calculated was relatively reproducible. Between individuals the difference in the offset of the axes was more marked. In 99 normal sets of data the mean axis offset was 6.8 mm (range 28 mm to -21 mm) A positive value represented the radio-ulnar deviation axis placed distal to the flexion-extension axis.

*Interpretation.* The three-dimensional motion plots generated using this method could be used clinically to follow disease progression or recovery following surgery. The computer modelling method described has potential applications, if further refined, to wrist joint arthroplasty design.

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### 1. Introduction

In-vivo wrist joint measurement has been carried out in a number of ways previously. Methods using computerised tomography represent a considerable radiation dose and do not allow normal motion to be studied (Crisco et al., 1999). Electrogoniometers can provide information with six degrees of freedom but are cumbersome to use and difficult to fix to the subject under study (Salvia et al., 2000, Sommer and Miller, 1980). Electromagnetic measuring systems have also been previously used to study wrist joint motion. The advantages of this

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sort of system are that they do not involve radiation and only require small sensors to be fixed to the volunteer. One group used this type of device to consider the motion of each bone of the wrist in conjunction with computerised tomography scans (Bresina et al., 1986). The system was not configured for clinical use. Two further studies considered the wrist in the context of a whole arm model (Biryukova et al., 2000, Prokopenko et al., 2001). These last two studies concerned a small number of volunteers in each case (7 and 6, respectively). An incomplete range of wrist joint motion was considered, within the context of motion of the whole arm. The kinematic model was built using passively acquired data and little active wrist motion was used in the subsequently studied tasks. Forearm pronation and supination were allowed in their model even though this is known to introduce significant skin motion artifact

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(Palmer et al., 1985). In short the wrist was not the main focus of these researchers study.

Various models of wrist joint motion have previously been produced. None of these truly describes the complex interactions of the 8 bones of the wrist but a twohinge axis model can be used as a first approximation. One of the main variables in this model is the offset between the two hinge axes. An early cadaveric study found the axis for radio-ulnar deviation (RUD) was distal to that for flexion-extension (FE) by 5mm (Andrews and Youm, 1979). A later study found a mean offset of  $0.8 \,\mathrm{mm} \pm 2.8 \,\mathrm{mm}$ , i.e., the RUD axis could be proximal to that for FE (Evans et al., 1986). Another study found values of 0.3-9.6mm with the RUD axis consistently distal to that for FE (Sommer and Miller, 1980). Electromagnetic measurements have revealed offsets of 2-7mm, again with the RUD axis distal (Biryukova et al., 2000).

The aims of this study were two-fold.

Firstly we wanted to develop a simple, non-invasive tool to plot three-dimensional wrist joint motion. It was envisaged that these plots could provide readily comparable follow up data in several clinical situations such as when following the progress of patients with rheumatoid arthritis and when monitoring post-operative motion recovery.

Secondly it was perceived that a mathematical analysis of the recorded motion patterns of normal volunteers could be used to improve wrist arthroplasty design. Most modern wrist arthroplasty designs consist of an ovoid articulation that can be modelled using two-hinge axes. The optimum offset of these two axes was the main variable we decided to evaluate. We planned to study a large normal population in an effort to provide a resonable approximation of the 'best-fit' mean.

# 2. Methods

An electromagnetic system was used for in-vivo wrist joint motion measurements (Fastrak, Polhemus inc, Vermont, USA). Measurements were all made within 75 cm of the transmitter. At this range the stated static accuracy for the Fastrak system is  $0.75 \,\mathrm{mm}$  for the x, y and z co-ordinates and  $0.15^{\circ}$  for receiver orientation. No metal objects or supports were used in the vicinity of the recordings. Two mini sensors were used (each approximately 8mm in diameter). A digitizing pen was also used. This contained another sensor housed in a pen shaped casing the point of which was a known distance from the sensor inside. One sensor was attached to the subjects forearm and the other was attached to the third metacarpal head. Relative movement of these two sensors was calculated over time and this was considered to represent the overall motion of the wrist joint. Data were recorded at 6 Hz. This frequency was chosen

empirically to give good coverage of the locus of positions obtained by the third metacarpal head without undue replication and crowding of data points.

During motion recording skin motion artifact was seen to occur. This was minimised by careful choice of sensor position and firm taping of the sensors to the skin. An immobilisation rig was used to reduce forearm rotation to a minimum. Volunteers gripped a piece of wooden doweling during recording to reduce skin motion over the metacarpal heads caused by finger movement. A recording being made is shown in Fig. 1.

The anatomical axes of each volunteer's wrist were visually aligned with the axes of the measuring system at the start of each recording. The right wrist was measured in each case. The x-axis was parallel to the floor. The forearm was pronated and then aligned so that an imaginary line passing between the radius and ulna, just proximal to the wrist, was also parallel to the floor. On occasion this necessitated wedging of the immobilisation rig as shown in Fig. 1. In order to try and improve the accuracy of this stage of the alignment process the chosen lateral mid-points of the radius and ulna were marked with a pen. These pen marks were then touched with the digitizing pen and the z-axis readings for the radius and ulna were compared. The wedging of the rig was then adjusted until the z-axis readings were different by 2mm or less. The y-axis was aligned along the length of the forearm through the 3rd metacarpal. The z-axis passed vertically upwards from the volar surface of the wrist to the dorsal surface.

Once aligned in the rig with the sensors in place two further digitizing pen readings were made. These recorded the position of the mid-axial tip of the distal part of the 3rd metacarpal head and the tip of the distal radial styloid laterally. These points allowed the



Fig. 1. Test rig during Fastrak recording. The grey cube to the right of the picture is the Fastrak transmitter that also defines the global axes of motion.

subsequent motion of the sensors to be related back to the individuals bony anatomy.

Once these procedures had been followed a supporting tray, built into the rig, was removed and motion recording began. The volunteers were instructed to imagine tracing two diagrams with their 3rd metacarpal head. These diagrams are shown in Fig. 2. Decreasing circumduction loops were followed smoothly by flexion/extension arcs moving from maximal ulnar to maximal radial deviation. A slow steady speed was encouraged and recording was continuous over the two patterns so that one set of data was generated. These patterns were chosen to ensure that not only were the extremes of motion captured but that all points between were covered. One practice was followed by two repetitions of the motion pattern, both of which were recorded. The entire process took approximately 10min of the volunteers' time.

A visual print out of the whole of an individual's recording was made using the SWORDS constraint modelling system (Kenney et al., 1997). Programs were written by one of us (DS) to subtract any forearm sensor motion from that of the metacarpal sensor for each recorded data point. A three-dimensional plot of the sequential positions of the 3rd metacarpal sensor were then displayed on the screen relative to a 'fixed' forearm sensor and the x, y and z axes. These plots could be viewed from any orientation on the computer screen.

A mathematical analysis of the data was carried by two of us (GM and DS). Firstly each data set was reduced to 50 points. This was achieved by calculating the distance between each point and its nearest neighbour and then eliminating those that were closer than a threshold distance. The threshold was varied until 50 points, spread over the entire locus, were obtained. The processed motion pattern was next compared to a similar pattern generated by a computer model of the wrist. The computer model was created using a C++ program in conjunction with the SWORDS modeller. The model represented the wrist using a simplified two-hinge model with five variable parameters (Fig. 3). The two axes of motion were mutually perpendicular and this arrangement was not variable in this model. Baseline figures were given to the computer wrist model in order to allow 'movement' of the 3rd metacarpal head marker as rotation around the flexion/extension and radio/ulnar deviation axes was simulated. A pattern generated in this way was then compared to an individuals recording. The sum of the squared distance from each experimental point to its closest computer-generated match gave the 'cost' of the joint configuration under consideration. This process was repeated to minimise the 'cost' by adjusting the five configuration parameters. The axis configuration resulting in the lowest 'cost' in each individual was noted. Analysis of all data sets was performed concurrently with no user intervention.

A pilot study of four normal volunteers was carried out to assess the repeatability of the motion measuring technique. Two sets of recordings were made as described. The volunteer was then removed from the device completely and the whole process repeated. Each of the resultant four sets of data from each volunteer was then compared visually via the SWORDS program. The axis offset values  $(l_1)$  of the best-fit computer-generated wrist model were also compared.

A larger population study was then undertaken. In this study 108 volunteers were recruited from within the University to have their wrist joint motion measured. The only exclusion criterion was a known wrist joint abnormality. Information was recorded, anonymously, regarding each person's age and hand dominance.



Fig. 2. Diagrams followed during motion recording. The two motions followed one another to generate one set of data.



Fig. 3. Diagram of computer model. The five variables are marked  $b_x$ ,  $b_y$ ,  $b_z$ ,  $l_1$  and  $l_2$ .

## 3. Results

A typical visual print out from the SWORDS program analysis of the in-vivo data from one individual in the pilot study is shown in Fig. 4. The volunteer could be seen to be broadly following the guides depicted in Fig. 2 whilst these recordings were made. Continuous data acquisition resulted in some sections of the locus being covered several times so obscuring the original guiding pattern. The aim was to achieve coverage of the whole locus reasonably evenly. Three views of the image are presented but the data can be rotated within the programme to be seen from any angle.

Two stages of the iterative mathematical analysis are shown in Fig. 5. This depicts the data reduced to a set of 50 points with the computer model superimposed.

The results from the pilot study for the axis offset are shown in Table 1. A considerable spread of results is seen.

For repeated recordings without reapplying the rig the difference in axis offset varied from 1.4 to 4.9 mm with one outlying value of 23.9 mm.

The average of the two recordings made without the rig being removed was calculated and these values were then compared between rig applications. The differences for each individual with separate rig applications varied between 0.25 and 6.25 mm.

The average value for all the recordings for each individual was calculated. When these values were compared between individuals the differences observed were greater, varying from -5.4 to 10.5 mm.

In the larger population study a full analysis of the data was possible in 99 cases (32 female and 67 male). Nine cases were excluded mainly due to aberrant data point recordings in the in-vivo data sets. The mean age

of volunteers was 29 years (range 18–63). 93% (92 of 99) were right handed.

The computer-generated best-fit axes showed considerable variation between individuals. Overall the mean position of the radio-ulnar deviation axis was 6.8 mm distal to the flexion-extension axis (SD 9.8 mm, range 21.0 mm proximal to 28.2 mm distal). The distribution of this offset is shown in Fig. 6.

# 4. Discussion

One of the aims of this study was to develop a simple, non-invasive tool to plot three-dimensional wrist joint motion in a way that would allow individual patterns to be compared visually over time. We feel we have achieved this with the adapted Fastrak system. Our method of data acquisition is non-invasive and not time-consuming. In addition it does not expose the volunteer to radiation. A visual inspection of the threedimensional patterns of movement is possible following simple computerised analysis. Even in normal volunteers these recorded patterns can be seen to vary from person to person.

Our second aim was to develop a computer programme capable of reproducing the motion patterns we had measured as closely as possible using a simplified geometric model. Our results so far have gone some way towards achieving this aim. The pooled model results of a group of individuals with normal wrists could ultimately present optimum geometric parameters for a wrist replacement design. Implanted correctly these replacements should most closely reproduce normal wrist kinematics, within the limits of the simple model chosen. We accept that the model we chose does not completely



Fig. 4. One motion recording, Volunteer A: (a) AP view from proximal to distal along y-axis; (b) Lateral view from ulnar to radial along x-axis; (c) Superior view from dorsal to volar along z-axis.



Fig. 5. Process of computer optimisation: (•) experimental data point; (+) computer model data point; (a) 0 iterations, cost 23.24; (b) 20 iterations, cost 0.73.

Table 1 Pilot group results

Volunteer	Rig application	Recording number	$l_1 \text{ (mm)}$
A	1	1	2.4
		2	7.1
	2	1	7.8
		2	6.1
В	1	1	11.7
		2	8.1
	2	1	10.1
		2	11.9
С	1	1	11.0
		2	12.4
	2	1	15.8
		2	-8.1
D	1	1	-10.5
		2	-6.5
	2	1	0.2
		2	-4.7

describe wrist kinematics. It has been known for some time that some rotation occurs around the y-axis in the normal wrist (Palmer et al., 1985). The two axes of rotation do not appear to be mutually perpendicular (Sommer and Miller, 1980) and translation may occur along the axes, not just rotation (Salvia et al., 2000). We have chosen a model we knew to be a simplification both as a reasonable starting point and as a practical approach; any replacement, to be manufactured in a cost-effective way, would have to be something of a simplification.

We have focussed on the model results relating to the offset of the two chosen axes. This could easily be incorporated into a wrist replacement design and has been found by others to be the parameter that most affects the performance of this type of model (Sommer and Miller, 1980). Our modelling process was similar to that of Sommer and Miller but was simplified by the use of the computer and an electromagnetic measuring system rather than an instrumented spatial linkage to acquire data. Our model did not allow the orientation of the two axes to vary but could be modified to do this.

Our pilot study was small and each volunteer underwent a very limited number of recordings. A wide range of computer generated axes offsets were obtained in this group but values for one individual were largely similar whilst values for separate individuals were usually different. We suspected that the large range of results we observed was related more to inadequacies with our measuring system rather than with our computer model.



Fig. 6. Frequency distribution of computer model axis offset results  $(l_1)$  from population study.

Reproducible alignment with the global axes, accurate referencing to bony anatomy and skin motion artifact were the main areas of concern. It is pertinent to ask whether the variation in results we observed in the pilot study group were too wide to be acceptable. Perhaps the flaws in the system made it invalid for the purpose we proposed? With the limited amount of time left in which to complete this preliminary study we chose to apply the method as it stood to a larger group of individuals. This was in the belief that increased numbers would result in a closer approximation of the true population mean if the method was at all valid. The mean value we found for the offset of the two axes in the larger population study was similar to that found by other researchers using different methods of wrist joint motion analysis. This gave us some encouragement that the method holds some promise. Further studies to tighten up the measuring system and thoroughly validate its reproducibility would be necessary to realise this promise.

This paper presents the preliminary results of a new approach to rational wrist replacement design. As it stands our method of plotting wrist motion could be suitable for clinical recordings, made to allow relatively gross visual comparisons over time. We feel the computer modelling method we describe has potential but has some way to go before the results obtained could confidently be used to improve wrist replacement design.

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