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Technical Note

Comparison of measurement accuracy between two wrist goniometer systems during pronation and supination

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Abstract

Pronation and supination have been shown to affect wrist goniometer measurement accuracy. The purpose of this study was to compare differences in measurement accuracy between a commonly used biaxial, single transducer wrist goniometer (System A) and a biaxial, two-transducer wrist goniometer (System B) over a wide range of pronation and supination (P/S) positions. Eight subjects moved their wrist between −40 and 40° of flexion/extension (F/E) and −10 and 20° of radial/ulnar (R/U) deviation in four different P/S positions: 90° pronation; 45° pronation; 0° neutral and 45° supination. System A was prone to more R/U crosstalk than System B and the amount of crosstalk was dependent on the P/S position. F/E crosstalk was present with both goniometer systems and was also shown to be dependent on P/S. When moving from pronation to supination, both systems experienced a similar extension offset error; however R/U offset errors were roughly equal in magnitude but opposite in direction. The calibration position will affect wrist angle measurements and the magnitude and direction of measurement errors. To minimize offset errors, the goniometer systems should be calibrated in the P/S posture most likely to be encountered during measurement. Differences in goniometer design and application accounted for the performance differences.

Keywords: Electrogoniometers; Wrist; Pronation/supination

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1. Introduction

The position, frequency, velocity, acceleration and magnitudes of wrist movement are thought to be important factors which may play a role in the development of upper extremity musculoskeletal disorders [1–4]. Static and dynamic wrist angle measurement is also of interest in clinical settings [5,6] and in motor rehabilitation [7,8]. Therefore, collecting the static and dynamic components of wrist movements is important for characterizing wrist activity in clinical and occupational settings. There are several methods for measuring wrist movements, but electrogoniometry has often been the method of choice due to their small size, relative ease of application and ability to make ambulatory measurements. Electrogoniometers have been used to measure position [4,9–12], movement frequency [5,6,9,10,13,14] and the velocity and acceleration of movements [2,6,9,10,13]. However, despite all the advantages, electrogoniometers have been shown to be subject to position measurement errors, with these errors often being a function of wrist and forearm pronation/supination (P/S) position [13,15]. In occupational settings, wrist movement with forearm pronation and supination is common and therefore characterizing measurement errors with these types of movements are important.

The two main types of measurement errors associated with electrogoniometers are crosstalk and offset errors. Crosstalk is a phenomenon where movement in one wrist plane (e.g. flexion, extension) causes a false signal in the other wrist plane (e.g. radial/ulnar deviation). Single transducer, biaxial goniometers have been shown to experience crosstalk with simple wrist movements and forearm pronation/supination [13,15,16]. It has been hypothesized that forearm rotation causes twisting of the transducer inside the electrogoniometer and this twisting is the source of the crosstalk [13,15]. Offset errors occur

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when the goniometer's signals move away from the original zero/reference position. Offset errors often occur as a result of pronation/supination movements [15].

With the advent of electrogoniometry, two electrogoniometer systems have been commercially manufactured and made publicly available. The first goniometer system is a readily available, single transducer, biaxial goniometer. The second goniometer system, which has been used less extensively, consists of two, biaxial transducers. The main difference between these goniometer systems is their design and how they reside on the wrist. Given that there are apparent differences between the two different goniometer systems, the purpose of this study was to: (1) determine whether there were differences in measurement accuracy between the two goniometer systems over a range of flexion/extension and radial/ulnar deviation movements and (2) determine whether pronation and supination movements influenced measurement accuracy. If there are differences in measurement accuracy between goniometer systems, this may identify and lead to improvements in goniometer design and application.

2. Methods

2.1. Subjects

Five women and three men (mean age=31, range 19–54) who were free of upper extremity musculoskeletal disorders and had no prior injury to the wrist participated in this study. All subjects volunteered their time and were employees of the Department of Occupational and Environmental Medicine at the Sahlgenska University Hospital, Gothenburg, Sweden.

2.2. Equipment

Two wrist goniometer systems were evaluated; these goniometer systems have been described in detail in a previous paper [16]. The first system, designated as System A, consisted of a single-transducer, biaxial goniometer (Model X 65; Biometrics; Gwent, UK) connected to an 8-bit data logger (Model DL 1001; Biometrics; Gwent, UK). The second, System B, consisted of a two-transducer, biaxial goniometer connected to a 12-bit logger (WristSystem; Greenleaf Medical; Palo Alto, CA). Fig. 1 shows how both systems resided on the wrist. Both systems used the same sensing element manufactured by Biometrics Ltd. The sensing element consisted of a 0.3 mm diameter steel beam (flexible wire) with four small resistive wires symmetrically mounted along the full length of the beam. The manufacturer cites a measurement range of ±150° with less than ±5° of cross-talk.

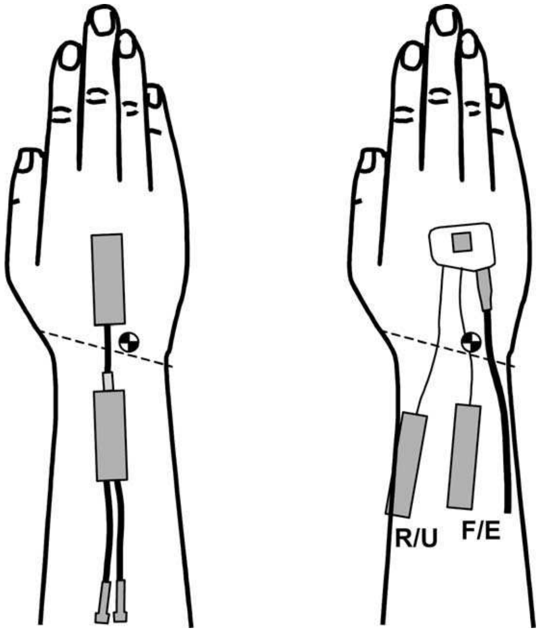

Fig. 1. Wrist goniometers shown mounted on a wrist: System A (left) and System B (right). To facilitate comparisons between how the systems reside on the wrist, System B is shown without the fingerless glove. The dashed line and the circle represent the anatomical flexion/extension axis and radial/ulnar deviation centres of movement, respectively [17–19].

Goniometer System A was attached to the subjects' right wrist using the methods prescribed by [15]. System B was secured to the subject's wrist using a lycra fingerless glove. The glove was attached by sliding the glove and goniometer over the subject's hand and securing with three velcro straps. To ensure that the glove was securely attached to the hand but loose enough around the wrist to allow the glove to rotate over the skin, the experimenter put one finger under the glove and tightened the straps over his finger.

With System A, since both endblocks were rigidly secured to the hand and forearm with double-sided tape, any rotation between the two endblocks, which may occur during pronation/supination movements, may twist the sensing beam and potentially result in measurement errors. With System B, the distal endblock was secured to the back of the hand, but the proximal endblock contained a circular channel. This circular channel allowed the terminal portion of the transducer to freely slide and rotate within the proximal endblock. Thus, any rotation between the two endblocks which may occur during pronation/supination should not be transmitted to the beam, and thereby reduce measurement errors. In addition, unlike System A, System B's fingerless glove system allowed the proximal endblock to freely slide over the skin of the forearm; this prevented any translational movement between the endblocks during pronation/supination.

A tiltable, adjustable-height table (Part 50642, Förbandsmaterial AB; Partille, Sweden) combined with a calibration fixture (Greenleaf Medical; Palo Alto, CA) was used to repeatedly position each subject's forearm and wrist in known pronation/supination (P/S), flexion/extension (F/E) and radial/ulnar (R/U) angles (Fig. 2). The calibration fixture and tiltable table were positioned to allow wrist movement in one plane (the F/E or R/U plane) while simultaneously restricting motion in the other plane.

2.3. Calibration

The goniometers were calibrated with the subject's wrist in 90° pronation in the calibration fixture. Neutral wrist postures were defined and measured using the methods prescribed by the American Academy of Orthopaedic Surgeons [20]. System A was calibrated by putting the subject's wrist in a neutral F/E and R/U position and offsetting/recording the zero positions by pushing a button on the goniometer's logger. Using a manual goniometer, System B was calibrated by putting the wrist in five different calibration positions (Table 1) and storing each position in the loggers' memory. As a result of these calibration procedures, System A had a universal gain, which was the same for all subjects, and System B had a gain specific to each subject and used a linear algorithm to account and correct for crosstalk [16,21].

Table 1
Calibration positions for System B, flexion and radial deviation are indicated by negative angles

Position	Flexion/extension	Radial/ulnar deviation
1	0	0
2	40	0
3	−40	0
4	0	−10
5	0	20

2.4. Wrist posture measurement methods

Pronation, supination, R/U and F/E angles were defined and measured according to clinically accepted standards [20]. Negative angles were used to denote flexion and radial deviation. The calibration fixture was securely attached to the tiltable table and this apparatus was used to position the forearm and wrist in different P/S and wrist angle combinations. The subject's chair was adjusted so their feet rested flat on the floor and the

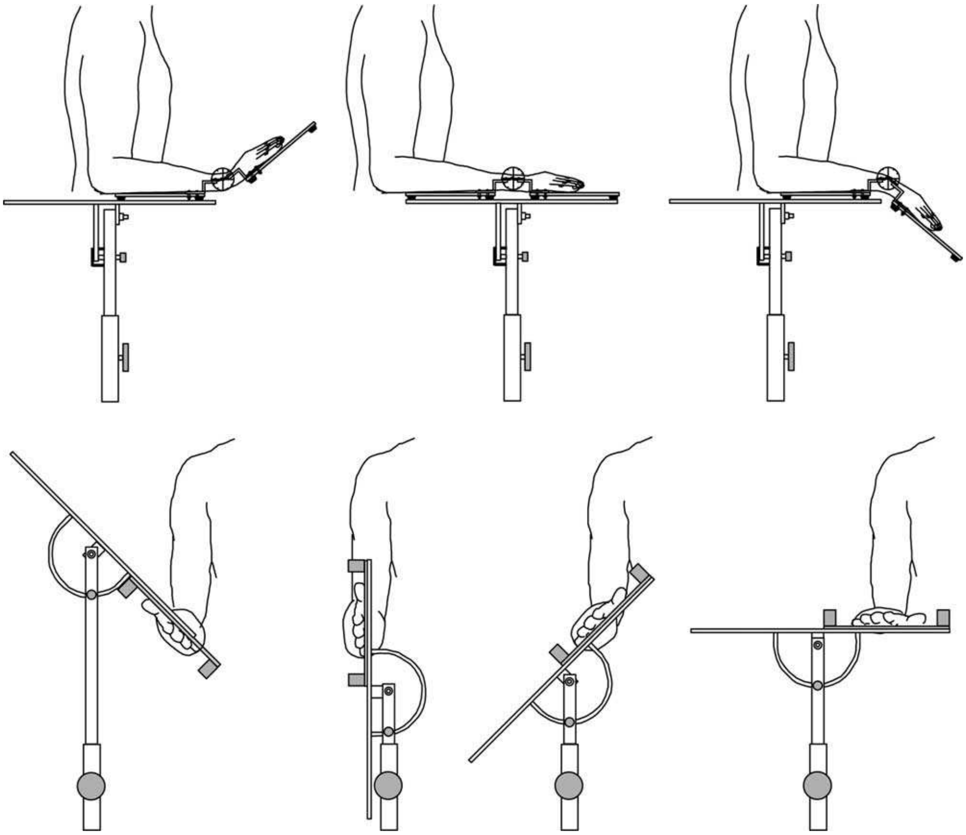

Fig. 2. The calibration fixture attached to the tiltable table demonstrating how the system was used. Top row shows how the system was used to position in flexion and extension, R/U movements were performed in the neutral (middle) position. Bottom row from left to right shows how the system was used to position the wrist and forearm in 45° supination, 0° neutral, 45° pronation and 90° pronation, respectively.

wrist positioning apparatus was adjusted so the subject's arm was resting comfortably at their side, forming a 90° angle at the elbow. Manual goniometry was used to define the various wrist angles for each subject. To ensure the repeatable repositioning of the subject's hand in the apparatus throughout the experiment, outlines of the hand were traced on the base of the calibration fixture for the various R/U positions and the analogue F/E scale settings on calibration fixture were noted for each F/E position.

Four different pronation and supination positions were tested: palm down, 90° pronation (90 P); 45° pronation (45 P); palm vertical, 0° neutral (0 N) and 45° supination (45 S). In each P/S position, subjects moved from 40° of flexion to 40° of extension in 20° increments while in 0° of R/U deviation and from 10° of radial deviation to 20° of ulnar deviation in 10° increments while in 0° of F/E (eight positions). Each position was held for 5 s and the data were sampled from the goniometers at 20 Hz and stored in the loggers' memory. The aggregate of these eight different positions will be referred to as identity movements. With the four P/S positions, a total of 32 different wrist positions were measured.

After the experiment the data were transferred to the hard disk of a computer for subsequent analysis. The wrist angles used to position the wrist in the calibration fixture were considered the "Gold Standard" and the wrist angles measured by the goniometers the independent variable. The order that the goniometer systems were tested was randomised across subjects. With each goniometer, the P/S positions were also randomised.

2.5. Data analysis

The wrist angles were calculated using an interactive data analysis program (Goniometer Analysis System, Version 1.0; Ergonomic and Research Consulting, Inc.; Seattle, WA). The software presented the goniometer data to the user in a graph, and using two interactive cursors, the user could select the time window of goniometer data to be analysed and summary measures (mean and standard deviation) were calculated and saved to a data file for subsequent analysis. For each of the 32 wrist positions, wrist angles were calculated by taking a 1 s average in the middle for each 5 s wrist position measurement. With the summary data from the eight subjects, the group mean and range of the angles were calculated. In addition, the measurement errors in F/E and R/U deviation, relative to the Gold Standard (calibration apparatus settings), were also calculated. Finally, over the 80° of movement in F/E and the 30° of movement in R/U deviation, the range of movement (ROM) and crosstalk values were calculated for each subject. Given the small sample size, the fact that there are no non-parametric tests that can calculate both *p*-values and interactions on repeated measures, and the apparent normal distribution of the data (no outliers), repeated measures analysis of variance methods were used to determine whether there were significant differences between goniometer systems, pronation/supination positions or any significant goniometer system by position interactions.

3. Results

3.1. Wrist position measurements and measurement errors

Fig. 3 and Table 2 show the effects of pronation and supination on the two goniometer systems. The bold black identity lines in the figure indicate the actual movements performed. Departures from these identity lines indicate measurement errors.

3.1.1. Radial/ulnar crosstalk

When the wrist was moved from flexion to extension, indicated by the vertical identity lines in Fig. 3, there should have been no change in the radial/ulnar component of the wrist angle. Departure from the vertical identity line indicates the presence of R/U crosstalk. As shown in Fig. 3 and Table 2, System A was prone to more R/U crosstalk than System B. With System A, the R/U crosstalk was largest in 90 P, lowest in 0 N and increased, but in the opposite direction, in 45 S. With System B, the R/U crosstalk was relatively constant over the various pronation/supination positions.

3.1.2. Flexion/extension crosstalk

When the wrist was moved radially to ulnarly, there should have been no change in the F/E component of the wrist angle; the actual R/U movements of the wrist are indicated by the bold horizontal identity lines in Fig. 3. Departure from the bold identity lines indicates the presence of F/E crosstalk. As shown in Table 2, F/E crosstalk was present with both goniometer systems. The F/E crosstalk tended to be parabolic with System A and was greatest in 90 P, decreased in 45 P and 0 N and increased but in the opposite direction in 45 S. With System B, the F/E crosstalk gradually increased from 90 P to 45 S.

3.1.3. Offset errors

In Fig. 3, the horizontal and vertical distances from the origin of the identity lines to the intersection point of the goniometry data represent F/E and R/U offset errors. These offset errors are summarized in Table 2. Depending on the pronation/supination position, both goniometer systems tended to overestimate the amount of extension. In general, System B was prone to greater F/E offset errors but followed the same trends as System A. R/U offset errors were roughly equal but opposite in

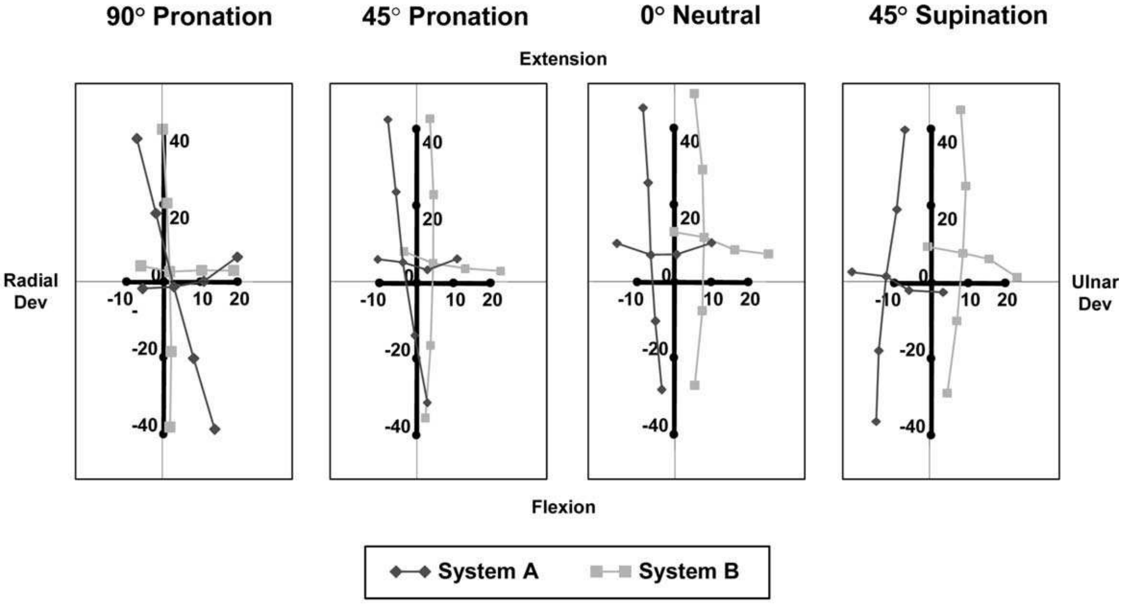

Fig. 3. The effects of pronation and supination on measurement accuracy. The bold black identity lines indicate the actual movements according to the “Gold Standard”; the dark grey lines with the diamonds, the angle measurements from System A; and the light grey lines with squares, the angle measurements from System B. The data shown from System A and B are group means from the eight subjects.

Table 2

Crosstalk, offset errors and range of movement (ROM), grouped by goniometer system, over the pronation/supination positions tested. Direction of movement was from 40° flexion to 40° extension and 10° radial deviation to 20° ulnar deviation (n=8). Negative radial/ulnar (R/U) crosstalk and offset error values indicate a false radial deviation signal. Negative flexion/extension (F/E) crosstalk and offset error values indicate a false flexion signal. The p-values under systems and positions indicate the differences between goniometer systems and pronation/supination positions. The interaction p-values indicate performance differences between the goniometer systems across the range of pronation/supination positions tested

	System A				System B				*p*-values		
	90 P	45 P	0 N	45 S	90 P	45 P	0 N	45 S	Systems	Positions	Interactions
R/U Crosstalk (movement, −40 to 40°)	−21.0	−11.4	−4.9	7.9	−2.8	0.2	−0.2	5.0	0.03	<0.01	<0.01
F/E Crosstalk (movement, −10 to 20°)	8.6	0.9	1.2	−8.1	−0.8	−5.5	−7.2	−9.2	0.01	<0.01	0.10
F/E offset error	−0.9	6.3	8.7	1.5	3.1	6.0	13.0	8.5	<0.01	<0.01	0.01
R/U offset error	2.7	−3.0	−5.1	−11.6	1.6	3.8	8.1	9.0	<0.01	0.04	<0.01
F/E ROM (80°)	76.0	73.8	73.8	76.0	77.8	78.1	76.5	73.9	0.52	0.36	0.24
R/U ROM (30°)	25.6	26.8	25.3	24.4	25.1	28.4	25.2	24.0	0.58	0.31	0.25

direction between the two goniometer systems, gradually increasing from a minimum in the calibration posture, 90 P, to maximum in 45 S. As can be seen in Fig. 3, offset errors were minimal in the 90 P position, the position the goniometers were calibrated/zeroed in, and in general increased the further the P/S position was away from the calibration position. For both systems, F/E offset errors were at a maximum in 0 N and R/U offset errors maximal in 45 S.

3.1.4. *Range of movement measurements*

As shown in Table 2, both systems tended to underestimate F/E ROM, and to a greater extent, R/U ROM movements over the various pronation/supination positions tested.

4. Discussion

4.1. *Effects of pronation/supination on goniometer measurement accuracy*

The main finding of this study is that forearm pronation/supination will affect wrist angle measurement accuracy as well as the magnitude and direction of measurement errors. In general, with pronation and supination, both goniometer systems were prone to both R/U and F/E offset errors. These offset errors tended to increase as the wrist and forearm moved away from the P/S position the goniometers were calibrated/zeroed in. Therefore, to reduce measurement errors, it is critical that the goniometer is calibrated/zeroed in the P/S posture most likely to be encountered during measurement. System B was prone to less R/U crosstalk compared to System A, this is most likely due to differences in transducer design. There were both similarities and differences in measurement accuracy and error patterns between goniometer systems, the combination of these similarities and differences may lead to improvements in goniometer design and application.

4.1.1. Crosstalk errors

Both goniometer systems were subject to crosstalk measurement errors with the errors being a function of P/S position. These crosstalk errors will also effect angular velocity and acceleration measurements. Crosstalk will cause the velocity and acceleration to be underestimated in one plane of movement and overestimated in the other plane. These errors will be dependant on the goniometer system and will increase as the amount of crosstalk increases. System A was prone to more R/U crosstalk compared to System B. F/E crosstalk was present with both goniometer systems and was also shown to vary with P/S position. There may be two sources of crosstalk: (1) intrinsic crosstalk associated with the design, application and twisting of the goniometer transducer when on the wrist [13], and (2) extrinsic crosstalk associated with the anatomy and complex movement of the wrist joint [16]. Our results indicated that twisting of the goniometer transducer is a source for R/U crosstalk with System A. Fig. 4 shows the results from the four pronation/supination positions, grouped by goniometer, superimposed over one another and aligned to the origin. With System A, there was a synchronous clockwise shift in both the F/E and R/U movements going from 90 P to 45 S. We feel this shift in the signal was due to the known rotation of the endblocks that occurs with pronation and supination [13]. However, with System B, there was very little shift in the F/E movements and a slight clockwise shift in the R/U movements. We feel this difference between the goniometer systems can be attributed to two major design differences. First, unlike System A, the proximal ends of System B’s transducers floated freely within its proximal endblocks; this allowed the end blocks to twist/rotate without imparting any twist on the transducers. Second, unlike System A, which was taped to the subject, System B’s transducers were mounted in a fingerless glove system that allowed the transducers to freely move over the skin of the forearm. However, based on the present study, it is not possible to determine the relative importance of each of these design features.

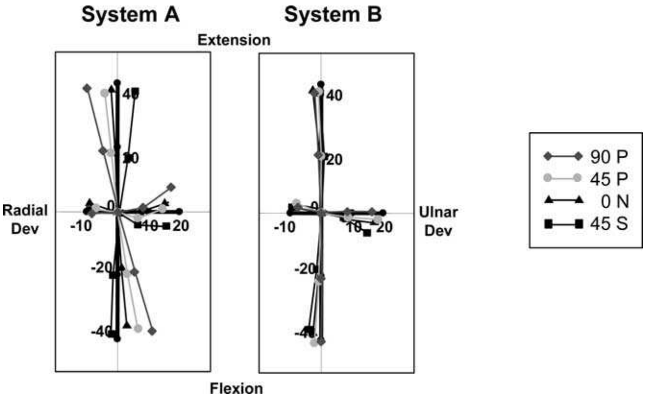

Fig. 4. The effects of pronation and supination on F/E and R/U crosstalk grouped by goniometer system. Offset errors in the various pronation and supination positions have been corrected for, so the origins in each P/S position are aligned (n=8).

Finally, System B used an algorithm to “electronically align” the goniometers during the calibration procedure to correct for crosstalk. We feel this algorithm played a minor role in reducing crosstalk but has been shown to reduce between subject variability [16]. The algorithm was derived in the calibration position and could propagate errors in the other P/S positions. This was not the case, as shown in Fig. 4: the F/E identity movements did not shift/rotate with P/S, but the R/U identity movements did. This shift/rotation of the R/U movements could be the result of a propagation of errors from the electronic alignment algorithm or due to a mechanical artefact from P/S. Further work has to be done to identify the importance of the alignment algorithm.

4.1.2. Offset errors

Both goniometer systems were subject to offset errors, with the errors being a function of P/S position. F/E offset errors were similar between the goniometer systems in both magnitude and direction. These errors may be due to changes in the cross-sectional shape of the forearm that occur with P/S. However, R/U offset errors were roughly equal in magnitude but opposite in direction. The R/U transducer on System B was more radially situated compared to System A. This indicates that a more intermediate placement of the R/U transducer may be optimal for reducing R/U offset errors. Finally, it is worth noting that offset errors will affect position data, but other measurements like velocities, acceleration and mean power frequency measurements should be less affected as long as the wrist’s P/S position is not changing.

4.1.3. Range of movement measurements

Both systems underestimated ROM in both F/E and R/U. Possible sources for the measurement error included the equipment and/or methods used. One major difference between the goniometer systems was that System A had a fixed gain for measuring F/E and R/U, whereas System B had gains specific to each subject, which were derived from the calibration procedure. It would be reasonable to expect that System B may be more accurate for measuring the ROMs due to the subject specific gains. Although not presented in this paper, System B did have less spread in the data as measured by the standard deviation and group maximum and minimum ROM values. However, since both systems yielded similar mean ROM measures, we feel the ROM underestimation may be primarily due to the methods used. The underestimation in F/E and R/U deviation ROM can be explained by the fact that when the subjects were moving in F/E and R/U deviation, it was very easy for subjects to subtlety and slightly move the distal part of the forearm in the same direction of the movement, resulting in an underestimation of the ROM.

4.1.4. Effect of calibration position

The P/S position in which the goniometers were calibrated influenced the offset errors. When the goniometers were calibrated in 90 P, the offset errors were minimal in 90 P and maximal in 0 N for F/E and maximal in 45 S for R/U deviation. However, if the goniometers were calibrated in 0 N, the opposite would be the case. These results indicate that offset errors are a function of P/S position and will be affected by the calibration position. To reduce offset errors, goniometers should not be calibrated in one P/S posture when it is known that they will be used in another P/S posture. If it is anticipated that goniometers will have to be used over a wide range of P/S positions, offset errors can be reduced by calibrating the goniometers in the P/S position most likely to be encountered or in a mid-range P/S position. This way, offset errors can be reduced or cancel one another out.

4.2. Implications

Goniometer crosstalk has been identified by others as an important and substantial source of measurement error [13,15,16]. Other researchers have postulated that crosstalk could be a result of twisting of the goniometer transducer [13]. Our results confirm this finding and demonstrate that the crosstalk can be substantially reduced with changes in goniometer design.

System A is readily available whereas System B is not at present. Most work in goniometry has been performed with System A. Based on our results, with respect to crosstalk, it appears the transducer placement for System A can be optimised for one pronation/supination position, but not a range of P/S positions.

A fair amount of work has been put into developing mathematical algorithms to correct for the errors in the goniometer signal with System A [13,15,22]. System B demonstrated that the need for some mathematical corrections can be eliminated through enhancements in goniometer design.

Offset errors were present in both systems and were dependant on P/S position. If a device was developed to accurately measure P/S position, these measurements could be used to correct the offset errors. One way to do so would be to build a transducer that is both a goniometer and a torsiometer, that way, in conjunction with a calibration routine (putting the forearm in various P/S positions), the torsiometer signal could be used as input to correct offset errors in the goniometer signal.

In summary, by comparing the two goniometer systems, important differences have been identified. Some of these differences may be used to help direct future studies to further the understanding of goniometry and ultimately lead to improvements in goniometer design, use and application.

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