original article

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Wrist electrogoniometry: are current mathematical correction procedures effective in reducing crosstalk in functional assessment?

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ABSTRACT | **Background:** The recording of human movement is an essential requirement for biomechanical, clinical, and occupational analysis, allowing assessment of postural variation, occupational risks, and preventive programs in physical therapy and rehabilitation. The flexible electrogoniometer (EGM), considered a reliable and accurate device, is used for dynamic recordings of different joints. Despite these advantages, the EGM is susceptible to measurement errors, known as crosstalk. There are two known types of crosstalk: crosstalk due to sensor rotation and inherent crosstalk. Correction procedures have been proposed to correct these errors; however no study has used both procedures in clinical measures for wrist movements with the aim to optimize the correction. **Objective:** To evaluate the effects of mathematical correction procedures on: 1) crosstalk due to forearm rotation, 2) inherent sensor crosstalk; and 3) the combination of these two procedures. **Method:** 43 healthy subjects had their maximum range of motion of wrist flexion/extension and ulnar/radials deviation recorded by EGM. The results were analyzed descriptively, and procedures were compared by differences. **Results:** There was no significant difference in measurements before and after the application of correction procedures ($P \leq 0.05$). Furthermore, the differences between the correction procedures were less than 5° in most cases, having little impact on the measurements. **Conclusions:** Considering the time-consuming data analysis, the specific technical knowledge involved, and the inefficient results, the correction procedures are not recommended for wrist recordings by EGM.

Keywords: reproducibility of results; physical therapy; health evaluation.

HOW TO CITE THIS ARTICLE

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Introduction

The recording of human movement is fundamental to biomechanical, clinical and occupational studies as it allows the identification of movement variations, postural risk factors in the workplace, and the evaluation of the effectiveness of preventive and rehabilitation programs[1,2]. Postures and wrist movements have been identified as important risk factors in the development of work-related upper limb musculoskeletal disorders[3,4].

Angle measurements of wrist movement are also important in clinical evaluations[5] and in rehabilitation[6] to analyze normal and altered movement, as well as evaluating the effect of physical therapy. As such, reliable and valid measurements of wrist range of motion (ROM) are essential both in clinical practice and in the occupational context.

The flexible electrogoniometer (EGM) is considered a useful piece of equipment in the functional evaluation of different joints[7-9]. It has the advantage of being light, portable, easy to operate, and relatively inexpensive[10-13], and it can be applied in occupational[2] and clinical environments[14-17]. Other advantages are: the recording is not influenced by other devices or energy sources, large quantities of data can be recorded, and long duration recordings can be made[13,18].

Despite these advantages, the electrogoniometer is susceptible to errors due to crosstalk[7,16], considered the main source of error in this equipment. Crosstalk occurs when movements performed exclusively in one plane are captured, as a false recording, in the plane orthogonal to the one where the movement occurs. This phenomenon takes place in the wrist joint, for example, when ulnar/radial deviations are recorded during the performance of pure movements of flexion/extension and vice-versa[19]. According to Hansson et al.[1,2] and Buchholz and Wellman[20], the crosstalk in the electrogoniometric recording of the

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wrist occurs due to the rotation of the forearm, as part of this movement is transferred to the wrist sensors.

Different measurement results between identical sensors were also identified as significant sources of error in electrogoniometric recordings[21,22]. This type of error, known as inherent error, occurs even in the absence of spring torsion and is possibly due to the way the sensitive elements ("strain gauges") are housed inside the device's sensitive unit. This error generally increases with the ROM increasing and with the use of the sensor[21,22].

Previous studies have suggested procedures for the correction of errors arising from crosstalk due to sensor rotation[7,20] and for differences between identical sensors[22]. In both cases, there was a reduction in errors. However, Hansson et al.[7] concluded that the application of error correction procedures due to sensor rotation hampers the analysis of data and do not have a great impact on the measurements obtained, with an average reduction of 0.7° for the flexion-extension movement and 1.6° for the deviation measured in ROM of 150° and 58°, respectively. In contrast, Sato, Coury, and Hansson[22], when applying a correction algorithm to evaluate the crosstalk inherent to laboratory measurements in a prototype, found a considerable reduction in error, with an average of 3.7° and a maximum of 10°. The authors suggest that other studies should evaluate the compensation effect of the crosstalk inherent to clinical and functional situations. The study carried out by Sato, Coury and Hansson[22] is recent and was the first to identify and apply correction procedures for inherent crosstalk. These types of errors and their respective correction procedures are currently known and reported in the relevant literature. Nevertheless, despite the fact that these types of errors are already recognized, there are no studies available in the literature combining both procedures to optimize correction.

Considering that these two error types are sources of significant imprecision, that the correction procedure proposed by Sato, Coury, and Hansson[22] has yet to be tested in a functional situation, and that the combination of these two correction procedures could optimize the correction of the errors described, not yet reported in the available literature, the objective of this study was to compare the effect of currently employed correction procedures for: 1) compensation for crosstalk due to forearm rotation for wrist flexion/extension and ulnar/radial deviation; 2) compensation for the error inherent to the sensors; and 3) joint compensation of these two errors by combining both correction procedures in functional situations.

Method

Subjects

The 43 subjects included in the study were university students with the following characteristics: right-handed individuals, 23 women and 20 men with a mean age of 22±3.2 and 23±2.9 years, mean height of 161±7.3 and 170±4.0 cm, and mean body mass of 58±8.7 and 74±10.7 kg, respectively. All subjects agreed to participate and signed an informed consent agreement. We excluded individuals with evident upper limb ROM restrictions, prior upper limb injury or chronic pain at the time of collection, obesity (body mass index>30 kg/m²) and height over 1.80 m. Individuals of both sexes were selected as it is recognized that men and women display differences in maximum wrist ROM[23].

The number of participants was established by sample calculation using the software program ENE (version 2.0, Glaxo Smithkline, Department of Biometrics, Madrid, Spain). To achieve this, a difference of 5° between corrections[24] was considered significant, and the significance level was set at 5%. The test power was 90%. Results indicated a sample size of 19 individuals per sex. The study was approved by the Ethics Committee of Universidade Federal de São Carlos (UFSCar), São Carlos, SP, Brazil (CAAE Protocol 0054.0.135.000-07).

Equipment

The following equipment was used: biaxial sensors (model XM65) and uniaxial sensors (model Z110; Biometrics Ltd, Gwent, UK); universal goniometer; data acquisition unit (DataLog, Biometrics Ltd, Gwent, UK); connection cables; vest with support for DataLog; elastic straps and other materials. The sensors used in this study had already been used in previous studies with an average of 1,000 incursions performed. According to the manufacturer, these sensors have a working life of 2,000 incursions[25].

Procedures

Initially, information was obtained relating to age, weight, and height. Next, the individual performed wrist flexor and extensor stretching for 30 seconds to reduce possible muscle tensions and allow freer movements. After the sensors were fixed (as described below), the individuals performed flexion/extension movements and ulnar/radial deviation of the wrist to familiarize themselves with the movement and speed to be performed. Next, the subject was asked to perform three repetitions for each movement (flexion/ extension, ulnar/radial deviation), with the forearm in maximum pronation. The pronation position was chosen as it is the reference for the wrist measurement movement, measured by means of goniometry[24,26]. The forearm rotation movement was controlled so as not to interfere with the measurements of the other movements. The order for movement performance was drawn at random. The individuals were instructed to achieve maximum ROM during their attempts.

Reference position and sensors attachment

The sensors were attached on a universal goniometer aligned on a table (Figure 1a). This position was considered the device's mechanical reference and was recorded for one minute. The mean value in degrees recorded by the sensor in this period was subtracted from subsequent recordings, including the crosstalk correction procedure. The sensors were then positioned on a precision device, developed by Sato, Coury, and Hansson[22], with precision of 1°, and moved through a ROM of 100° in both planes of movement for one minute resulting in an average of 14 cycles for each recording. The mean movement speed was not measured, however, based on the data on duration, number of cycles recorded, and the ROM reached, it may be estimated that the mean speed was low (approximately 15°/s). This record was used to derive the crosstalk inherent to the sensor and apply the correction procedure for this error.

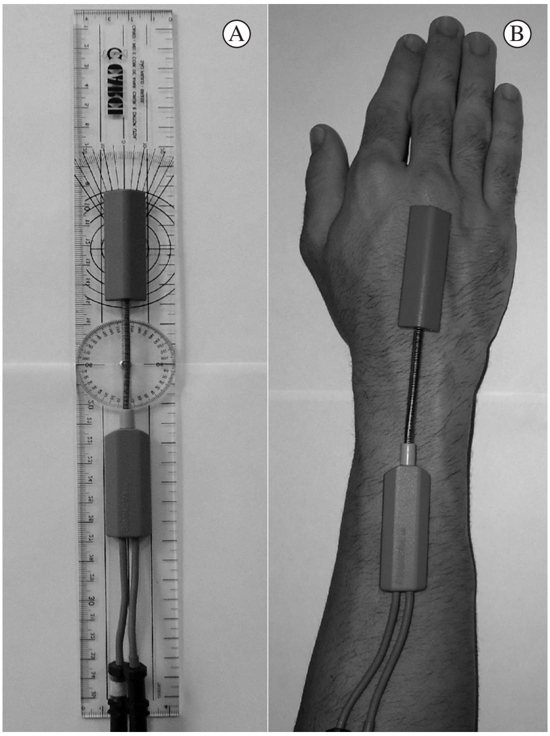

Figure 1. Mechanical reference position of the sensor (A) and fixing the sensor to the subject's wrist (B).

After recording the reference position, sensor XM65 was placed on the participant's right wrist using two-sided tape (Figure 1b). The enblocks, fixed and telescopic, were positioned so that the center of the spring coincided with the center of the wrist joint (approximate axel of the movement). The electrogoniometer was coupled to the wrist joint at maximum flexion. The telescopic enblock was attached to the third metacarpal bone, and the fixed, on the medium line of the forearm (line traced between the lateral epicondyle of the humerus and the medium point between the ulna head and the styloid process of the radium). The torsiometer was coupled to the forearm in the supine position, with the elbow at 90°. The telescopic enblock was attached to distal radius, and the fixed endblock, close to the medial epicondyle of the humerus.

Procedures for data correction

Error correction of sensor XM65 due to forearm rotation

Data was collected using the software program DataLog PC (version 3.0, 2002), with sample frequency of 100 Hz. After data collection, the files were exported in text format for processing in a routine specifically developed in Matlab (version 7.0.1, MathWorks Inc., Natick, MA, USA). Raw data from the electrogoniometer were exported in ASCII format, converted into angles using an equation supplied by the manufacturer and filtered with second-order Butterworth low-pass filter, with cutoff frequency of 2 Hz determined by residual analysis[27] and zero-phase lag. The raw data were the mean values of the three attempts made by individuals for each movement. The values obtained in the three attempts were compared in order to verify their reproducibility. Reproducibility between attempts was calculated by means of two-way mixed Interclass Correlation Coefficient (ICC) with absolute agreement and single measures[28] and through the standard error of measurement (SEM). The results of this comparison of good agreement between the attempts with ICC and SEM, respectively, for the flexion movement were 0.95 (IC 0.92-0.97) and 2.0; for the extension 0.94 (IC 0.90-0.97) and 2.3; for the ulnar deviation 0.94 (IC 0.90-0.97) and 1.7; and for the radial deviation movement 0.90 (IC 0.84-0.94) and 1.8.

The crosstalk correction due to sensor rotation was based on the algorithm proposed by Hansson et al.[7], the only one currently available in literature and which consists in the principle of rotating a vector on a θ angle in a generic plane (Figure 2). This algorithm was based on the data collected in a prototype developed by Hansson et al.[7] and, therefore, is not influenced by the subjects' measurements.

To perform this correction, we considered $\{\vec{i},\vec{j}\}$ an orthogonal base. The vector (x,y) forms an angle φ with the vector $\vec{i}$. Rotating the vector (x,y) at a θ angle, anti-clockwise, the (x',y') coordinates are obtained. As such: $\begin{cases} x = r\ \cos\varphi \\ y = r\ sen\varphi \end{cases}$ $\begin{cases} x' = r\ \cos\ (\varphi+\theta) \\ y' = r\ sen\ (\varphi+\theta) \end{cases}$

where $r = \|(x,y)\| = \sqrt{x^2+y^2}$.

Therefore,

$$x' = r\left[\cos\varphi\cdot\cos\theta - sen\varphi\cdot sen\theta\right] = $$
$$= \left(r\ \cos\varphi\right)\cdot\cos\theta - \left(r\ sen\varphi\right)\cdot sen\theta, \text{ thus}$$

$$x' = x\ \cos\theta - y\ sen\theta.$$

Similarly,

$$y' = r\left[sen\varphi\cdot\cos\theta + \cos\varphi\cdot sen\theta\right] = $$
$$= \left(r\ sen\varphi\right)\cdot\cos\theta + \left(r\ \cos\varphi\right)\cdot sen\theta, \text{ and}$$

$$y' = y\ \cos\theta + x\ sen\theta.$$

Correction of error inherent to sensor XM65

The correction of the inherent error was performed in accordance with Sato, Coury, and Hansson[22]. According to these authors, the reproducibility of the inherent error is consistent in consecutive measurements even after intense sensor use, staying below 10° (data estimated from graphs). To perform this correction, we used the recording obtained in the previously described prototype[22]. The X-Y graphs of the filtered data constitute the sensor's inherent error (Figure 3). The data were organized in a increasing order and divided into 5° intervals, from the minimum value to the maximum value recorded in the prototype. For the samples of each interval, the mean of the flexion/extension and ulnar radial deviation angles was calculated, generating a matrix of 40 elements. Based on this matrix, an 8-degree polynomial was set. These parameters were chosen from the residual analysis through the least squares criterion. The wrist movement data were then corrected according to the derived polynomial so that for each sample of flexion/extension and ulnar/radial deviation a polynomial value was calculated and subtracted from the flexion/extension and deviation values recorded.

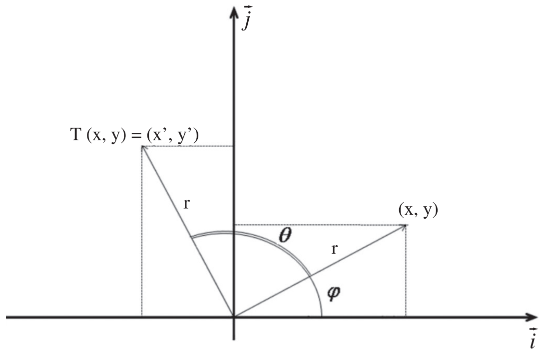

Figure 2. Principle used to rotate a vector at an angle θ in a generic plane.

Data analysis

Results were submitted to normality and homogeneity tests. As the assumptions were not met, non-parametric tests were used. To evaluate the differences between corrections, the Kruskal-Wallis statistical test was applied with the Mann-Whitney post hoc and Bonferroni's adjustment ($P \leq 0.008$). The root mean square (RMS) was calculated to identify the difference between the corrections (intercorrection variability). The RMS value describes differences between measurements disregarding the sign of this difference (for more or for less). The dependent variables of this study are the raw and corrected angle values. For statistical analysis, the significance level of 5% ($P \leq 0.05$) was considered; in the cases where it was necessary to apply non-parametric tests of multiple comparisons (post hoc), Bonferroni's adjustment was applied (adjustment = α/number of comparisons). Thus, the significance level considered was $P \leq 0.008$.

Results

Figure 4 shows the ROM for the raw data, data corrected for inherent crosstalk due to forearm rotation, data corrected for inherent crosstalk, and data corrected for the combination of the two correction procedures. The upper part of Figure 4 shows the results obtained for the flexion/extension movement (a) and the influence of these movements on the respective orthogonal planes, generating false recordings, such as ulnar/radial deviation movements (b), when effectively no movement was performed on that plane. In the lower part of the figure, the inverse situation is illustrated: ulnar/radial deviations (c)

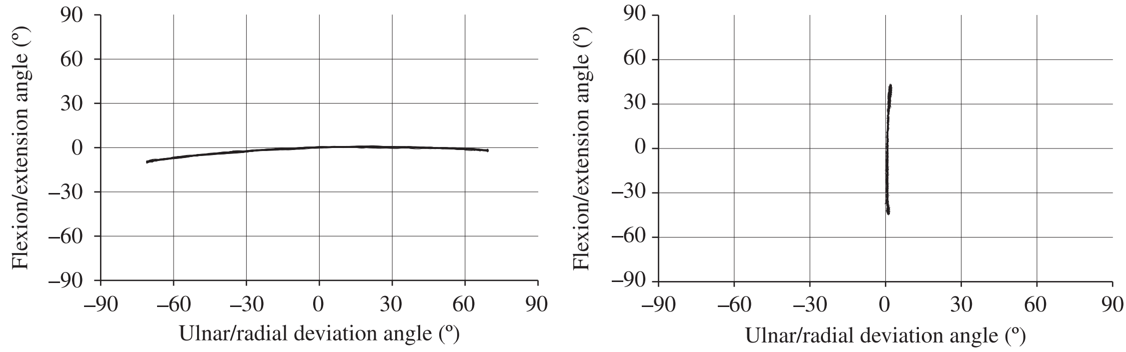

Figure 3. Inherent error of sensor.

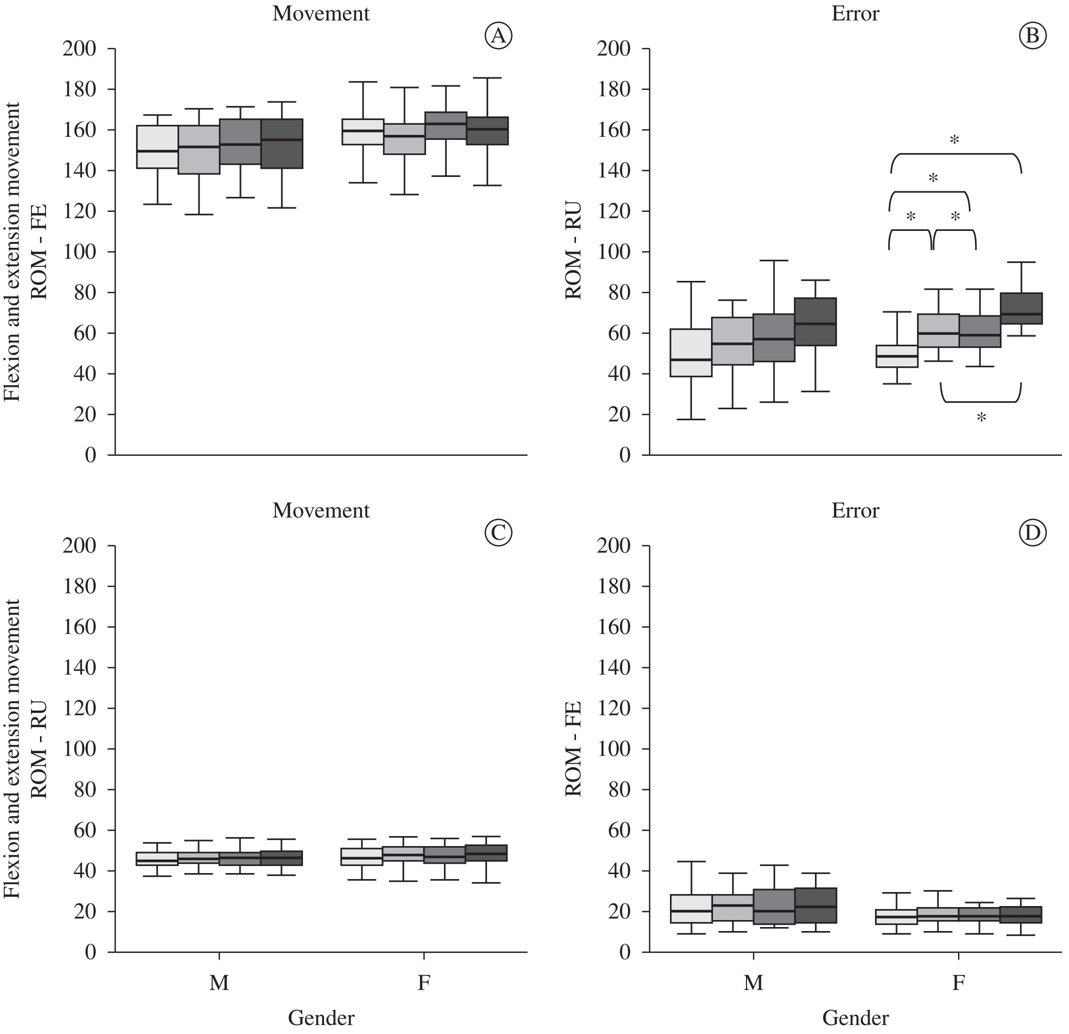

Figure 4. Flexion/extension angles (A and D) and radial/ulnar deviation angles (B and C) for: raw data = □; data correction to subtraction of crosstalk due to the rotation = ▨; data correction to subtraction of inherent crosstalk = ▩ and; data correction through the combination of both procedures = ■, for each gender. Statistically significant differences were noted between the corrections (*).

occurring in the frontal plane and false recordings (d) occurring in the orthogonal (sagittal) plane for each type of correction performed.

For the flexion/extension movement, there was no significant difference in the ROM between the raw and corrected data. For this movement's errors, recorded on the deviation plane, there was a significant difference for the female sex only, where the error range increased, instead of decreasing, for all correction procedures. The mean values obtained on the error plane, for both genders, was 50.1° for raw data, 58.7° for data corrected by crosstalk, 60.3° corrected by inherent crosstalk and 68.7° for data corrected by crosstalk and inherent crosstalk. For the deviation movement, the mean value on the error plane was 24.3° for raw data, 24.5° for data corrected by crosstalk, 25.7° for data corrected by inherent crosstalk and 25.0° for data corrected by crosstalk and inherent crosstalk.

For the ulnar/radial deviation movement, there was no significant difference between the raw and corrected data. Similarly, there was no significant difference between the error data, recorded on the sagittal plane, for all the correction procedures applied.

Table 1 shows the RMS values for the differences between the raw and corrected data for the flexion/extension and ulnar/radial deviation movements by gender and correction type.

The results indicate that, in general, the correction procedures generate little impact on the measurements, since the differences were lower than 5° in the majority of cases, with few exceptions. A more expressive case occurred for the error recorded in deviation during the flexion/extension movements, when the correction procedure for the crosstalk errors due to rotation and inherent crosstalk significantly increased the error ranges instead of reducing them.

Table 1. RMS values of differences between raw and correct data for each wrist movement by gender. Significant differences between gender (*).

Correction procedures	Male	Female
Flexion/extension movement		
Movement		
raw – crosstalk	1.1±0.6	1.8±0.8
raw – inherent error	2.8±0.5	3.1±0.5
raw (crosstalk+ inherent)	2.7±0.8	2.4±0.9
Error		
raw – crosstalk	3.3±1.8	5.1±2.2*
raw – inherent error	3.6±0.6	3.8±0.6*
raw – (crosstalk+ inherent)	5.9±2.7	8.3±2.9*
Deviation movement		
Movement		
raw – crosstalk	1.5±0.9	2.5±1.2
raw – inherent error	2.9±0.4	3.6±1.3
raw – (crosstalk+ inherent)	2.9±1.1	2.3±0.9
Error		
raw – *crosstalk*	1.0±0.9	1.0±0.7
raw – inherent error	1.6±0.4	1.3±0.4
raw – (crosstalk+ inherent)	2.3±1.3	2.0±0.8

Discussion

The correction results by crosstalk due to forearm rotation and inherent error did not significantly alter the values of recorded movements. Records of corrected movement were similar to records without corrections both on the same movement plane and on the orthogonal plane (error). For the flexion/extension movement in the female group, the correction procedures caused a statistically significant increase in error, indicating that the correction made the record more imprecise.

Correction procedures for crosstalk due to rotation were also applied by Hansson et al.[7] for the wrist joint in a prototype and in a functional situation. These authors found a slight error reduction for the flexion/extension movement (mean of 1.7°) and ulnar/radial deviation (2.5°). A possible explanation for the different results reported by those authors and the present study may be the sensor model used. Hansson et al.[7] used the XM110 model, and the present study used the XM65. However Foltran et al.[23] did not find a significant difference between the recordings of these sensors and that, for individuals up to 1.80 m tall, the XM65 sensor would be recommended because it causes less spring bulging during wrist extension.

Buchholz and Wellman[20] also applied correction procedures for crosstalk due to rotation and found a mean reduction in errors of 7.1°±5.1° to 4.7°±3.8° in the flexion/extension movements and of 10.5°±8.8° to 4.7°±5.2° in the ulnar/radial deviations. The authors reported a significant difference only for the flexion/extension movement. A possible explication for the divergence in results may be in the number of individuals evaluated. Buchholz and Wellman[20] evaluated only four individuals, reducing the inter-individual variability. The authors also evaluated the passive ROM of the wrist fixed in maximum pronation and supination on a platform coupled to a protractor, making the movements more standardized and less functional, when compared to the active movements performed by individuals on this study.

The results found with the correction of inherent error resulted in less impact on the range measurements of this study. Sato, Coury, and Hansson[22] applied correction procedures to the inherent crosstalk in records obtained from a prototype and found a significant reduction in error after the application of this procedure. However, the assessed ROM (200° for flexion/extension) was greater than the wrist ROM recorded in the present study (150° for flexion/extension). Additionally, this correction method depends on the error inherent to the sensor. When the sensor is not used often and its sensitive elements are well aligned within the spring, the recording error is small, hence the correction effect is negligible. In the present study, it is clear that these two factors influenced the result, given that the sensor's inherent error was small in the ROM tested (Figure 3).

Despite the simultaneous application of two correction procedures, the results did not change significantly. A possible explanation could be the ROM achieved during the performance of wrist movements (approximately 150° for the flexion/extension movement and 40° for the deviation movement), which are lower than those tested by Hansson et al.[7] (180° and 90° respectively) and Sato, Coury, and Hansson[22] (200° and 60° respectively, in the prototype).

The crosstalk due to rotation and the inherent crosstalk are two important sources of error in the recording of movements, and the correction of data summing up these sources of error had not been previously investigated. In this study, the combination of correction procedures was applied to reduce measurement errors, since, when applied separately with the aid of prototypes, these procedures showed positive results in previous studies[7,22]. Therefore, with the combination of corrections for these two sources of errors, a significant improvement in data corrections was expected, but results did not confirm this hypothesis. This may have occurred because better correction results are found for greater ranges[22], around 180°, measured in prototypes and, therefore, greater than the data collected in active ROM by this study (around 150°). The electrogoniometer error is directly linked to the degree of spring torsion and, during greater ROM, we find greater degrees of spring torsion. Thus, better correction results are expected in the greater ROM. Furthermore, for functional data, small modifications in ROM, such as 6° found by Buchholz and Wellman[20], had little impact on the correction of data[7].

It is also worth noting the complexity of recording wrist movements, both because of the number of bones in this region and the freedom of movement of this joint complex[29]. Therefore, the combination of movements in this joint can influence the measurement errors[30], among other aspects, because extension is associated with the radial deviation[31], and the individual has difficulty separating these movements when performing an activity that is both functional and isolated[32].

Other sources of error and variation can occur concomitantly, such as skin movement[33], interindividual variation[34] related to the characteristics of each participant, i.e. bone structure, fat, muscle, skin flexibility, which can contribute towards the different ranges of rotation between the sensor enblocks[20].

Limitations

The present study tested only two of the correction procedures currently available. However, there may be other procedures that were not mentioned in the reviewed literature or new methods may be proposed in the future, which could lead to more satisfactory results than those produced here. In contrast, it is important to recognize that these correction methods have been used in recent publications[35], which also used procedures similar to those used by our group.

Conclusions

There was no significant error reduction for the majority of the recordings after the application of both isolated and combined correction procedures. Considering that the calculations involve an operational burden as they increase complexity and data processing time and that the results had little impact on the measurements, it is not recommended to apply these procedures in the correction of wrist movements. Thus, manufacturers should work to enhance electrogoniometric sensors to reduce the probability of distortion of sensitive elements and springs, leading to crosstalk. Similarly, the positioning of the sensors in a standardized manner and the careful handling of equipment will possibly result in the improvement of data quality and will contribute to the physical therapist's decision making on preventive and rehabilitation programs.

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