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Accuracy of an electrogoniometer relative to optical motion tracking for quantifying wrist range of motion

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Abstract

Methods for capturing wrist range of motion vary in complexity, cost, and sensitivity. Measures by manual goniometer, though an inexpensive modality, provide neither dynamic nor objective motion data. Conversely, optical motion capture systems are widely used in three-dimensional scientific motion capture studies but come with setup requirements and great cost. The electrogoniometer bridges the gap between portability and objective measurement. Previous studies have not evaluated the accuracy of an electrogoniometer in tracking the combined motions of *in vivo* human wrists. Our study aims to evaluate the accuracy of a 2 degree of freedom electrogoniometer using optical motion capture as the reference for *in vivo* wrist range of motion. First, a mechanical system constructed from two plastic pipes and a universal joint mimicked a human wrist to assess the inherent accuracy of the electrogoniometer without skin-motion artifact. Simulations of radial-ulnar deviation, flexion-extension and circumduction were evaluated. Second, six subjects performed three range of motion tasks of radial-ulnar deviation, flexion-extension, and circumduction for evaluation of the *in vivo* accuracy. Bland-Altman analysis quantified the accuracy. The mechanical experiment reported greater accuracy than the *in vivo* study with mean difference values less than $\pm 1^\circ$. The *in vivo* accuracy varied across range of motion tasks, with mean differences greatest in the flexion-extension task (7.2°). Smaller mean differences values were reported in the radial-ulnar deviation task (-0.8°) and the circumduction task (1.2°). Accuracy requirements will vary depending on the research question. Task-based accuracy was reported during *in vivo* range of motion.

Keywords

measurement error; goniometer; wrist; motion analysis; kinematics

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Introduction

The wrist plays a critical role in executing movements involved in activities of daily living [1]. The wrist joint is principally a 2 degree of freedom (DoF) joint, enabling wrist flexion-extension (F/E), radial-ulnar deviation (R/U), and combinations of these two motions, such as in wrist circumduction. Joint diseases and fractures may lead to limitations of wrist range of motion (RoM) [2]. Accurately quantifying wrist RoM can aid in assessing limitations, as well as the success of therapies and surgical interventions [1,2].

There are a variety of commercially available devices and methods to measure wrist RoM, ranging from manual goniometers to electrogoniometers to optical motion capture (OMC) [3–5]. OMC is widely used in three-dimensional (3D) scientific motion capture studies [6,7]. OMC is capable of accurately capturing 3D wrist RoM without invasive procedures or exposing subjects to radiation [4,5,8,9]. However, OMC is expensive, can require extensive set-up times and typically require post-process analysis. Compared to OMC, electrogoniometers offer a method to quantify RoM that is less expensive, transportable, and straightforward to operate [10].

Mechanical experiments are commonly conducted in electrogoniometer studies to evaluate error without skin-motion artifact. Previous studies have evaluated the mechanical accuracy of electrogoniometers using protractor [10,11] and plurimeter measurements [12] as the reference. *In vitro* testing of wrist electrogoniometers typically use fluoroscopy as a reference [5]. The *in vivo* accuracy of electrogoniometers has been evaluated with a manual goniometer [13,14], protractor measurements [15], and two-dimensional video analysis [16]. These methods were limited to measuring planar angles and most protocols were limited to uniplanar wrist movements that did not assess combined wrist motion. OMC has been used to validate electrogoniometer accuracy for measuring RoM in the knee [10], however, unlike the knee joint, the wrist joint is principally a 2 DoF joint.

Our study aims (1) to evaluate the accuracy of a 2 DoF electrogoniometer using OMC as the reference standard in an idealized mechanical system and (2) to evaluate the accuracy of the electrogoniometer using OMC as the reference standard for *in vivo* wrist RoM across a combination of different directions of motion.

Materials and Methods

Overview

The electrogoniometer (model W75; Biometric Ltd., Newport, UK) (1000Hz) consisted of two end blocks connected by a protective spring, housing a composite wire that contained a series of strain gauges mounted around the circumference of the wire. The manufacturer specifies an accuracy of $\pm 3^\circ$ over a range of $\pm 150^\circ$.

Two experiments were completed. The first experiment assessed the mechanical accuracy of the electrogoniometer using a mechanical set-up constructed from two PVC pipes (representing the forearm and hand) connected by a universal joint (Figure1). This mechanical experiment was designed to assess the inherent accuracy of the

electrogoniometer in tracking coupled motions. The second experiment assessed the *in vivo* accuracy of the electrogoniometer in six healthy volunteers (age: mean 25.3y (SD 2.9y), 3 males, 6 right hands) after informed consent with our institutions IRB approval.

Mechanical Experiment

The electrogoniometer was mounted to the mechanical system with the distal end block attached to the hand pipe and the proximal end block attached to the forearm pipe using double-sided tape (Figure 1). The centre axes of both end blocks were aligned axially with a visual inspection.

A capture volume was set up with four passive OMC cameras (Oqus 5-series, Qualisys, Gothenburg, Sweden) (100Hz). Independently adhered reflective spheres were attached to the forearm pipe (n=4, 6.4mm dia.) and hand pipe (n=4, 6.4mm dia.). Anatomical markers (n=3, 6.4 mm dia.) were attached on each side of the universal joint to simulate the radial styloid and ulnar styloid. A marker at the distal tip of the hand pipe simulated the distal end of the MC3 (Figure 1). The resolution of the experimental setup was 0.2mm (calculated using the average of differences of marker-to-marker distances) [17].

Three RoM tasks were simulated with the universal joint in the mechanical experiment. A tabletop vice grip secured the forearm pipe in a vertical position, allowing the hand pipe to manoeuvre freely. The neutral pose consisted of the forearm pipe and hand pipe held vertically, visually aligning the centre axis of the pipes (Figure 1). A volunteer manually manipulated the mechanical joint to simulate motion in two orthogonal directions of F/E and R/U, and circumduction. Each RoM task was synchronously recorded by both systems for 10 seconds. A total of nine 10 second measurements were taken, three for each RoM task.

In Vivo Experiment

The distal end block of the electrogoniometer was attached to the dorsal surface of the third metacarpal (MC3) using double-sided tape. While fully flexing the wrist, the electrogoniometer was extended to its maximum length and the proximal end block adhered to the dorsal surface of the right forearm, visually aligning the centre axis of the forearm (equidistant from the radial styloid and ulnar styloid) with the distal end block.

Six passive OMC cameras (200Hz) were set up for the *in vivo* experiment. Independently adhered reflective spheres were attached to the skin with double-sided adhesives to the proximal forearm (n=4, 6.4mm dia.), distal forearm (n=4, 6.4mm dia.), and the dorsal surface of hand (n=4, 6.4mm dia.) (Figure 2). Anatomical markers (n=5, 6.4mm dia.) were attached to the end of the MC3, radial styloid, ulnar styloid, lateral epicondyle and medial epicondyle. An orthogonal coordinate system was defined at the neutral positions. Calculation of Euler angles with XYZ order quantified the radial-ulnar component (X-axis) and flexion-extension component (Y-axis) of the motions.

Three RoM tasks (R/U, F/E and circumduction) were completed by each subject. The neutral pose was captured when the subjects had their forearm in 90° pronation and palm flat on a table. The electrogoniometer and OMC systems were both zeroed with the subject in the neutral pose. During the R/U task, subjects slightly elevated their hand and forearm off

the table and continuously performed the R/U motions (Figure 2a). Before capturing the F/E motions the subject adjusted their forearm to 0° pronation, from this position the F/E motion was continuously performed (Figure 2b). Lastly, the subjects returned to the neutral position and elevated the forearm off the table. The elbow remained resting on the table and the opposite hand was used to support the forearm and the circumduction motion was continuously performed (Figure 2c). Subjects were instructed to focus on wrist RoM during the trials and limit forearm movement. Three 20 second measurements of dynamic movements per subject were recorded by both systems simultaneously, one for each RoM task.

Data Collection and Synchronization

For both experiments, the 3D positions of markers were triangulated with Qualisys Track Manager (Qualisys, Gothenburg, Sweden) and exported to Visual 3D (C-Motion Inc., Germantown, MD). A 10Hz low-pass filter was applied to the 3D data.

The DataLITE management software (10.05, Biometric Ltd., Newport, UK) recorded the electrogoniometer output and quantified the radial-ulnar and flexion-extension components of the RoM tasks.

An active low transistor-transistor logic (TTL) pulse which was sent to both systems at the start of each capture allowed for post-processing synchronization. The biaxial angles from DataLITE and Euler angles from Visual3D were exported to MATLAB (R2017a, The MathWorks Inc., Natick, MA) for synchronization and analysis.

Statistical Analysis

Bland-Altman analysis was used to quantify the bias between systems as the mean difference (MD) of OMC minus electrogoniometer and the variation about the MD with 95% limits of agreement (LoA) [18].

The *in vivo* data was imported into SAS version 9.4 (SAS Institute Inc., Cary, NC) to test for variation by task and component of measurement. A generalized estimating equation (GEE) was used to model the bias as a function of subject within RoM task and direction of measurement. The within-subject correlation was modelled using heterogeneous compound symmetry. The maximum-likelihood estimators were adjusted for possible model misspecification using classical sandwich estimators. Post hoc pairwise comparisons between tasks and between task and direction of measurement combinations were conducted via orthogonal contrasts. The Holm test was used for multiple comparisons to maintain a 2-tailed familywise alpha at 0.05.

Results

Bland-Altman analysis of mechanical experiment data reported the bias of all RoM tasks to be less than 1° and the largest LoA to be (−2.6°— 4.5°) (Table 1). The bias was within the manufacture accuracy specification of ±3°.

In the *in vivo* experiment, bias values varied across RoM task with the largest bias of approximately 7° for the radial-ulnar component of the F/E task (Table 2). The GEE found a statistically significant interaction between RoM task and component of measurement ($P=0.0002$). In post hoc tests, the bias was shown to be significantly underestimated (positive bias) in the radial-ulnar component of the F/E RoM task compared to the radial-ulnar components R/U and circumduction tasks ($P<0.05$). Within F/E RoM task, bias differed significantly between component of measurement, with the flexion-extension component overestimating (negative bias) and the radial-ulnar component underestimating (positive bias) ($P=0.0073$) (Figure 3).

Discussion

This study aimed to evaluate the accuracy of a 2 DoF electrogoniometer during *in vivo* wrist RoM using OMC as the reference standard. The *in vivo* experiment resulted in the largest bias in both components of the F/E RoM task. The accuracy varied based on task and component of measurement. The mechanical experiment confirmed an agreement between the two systems with no skin-motion artefacts or natural motion present.

Previous mechanical experiments have compared electrogoniometer to protractor measurements and plurimeter measurements. Perriman et al. reported a maximum difference of 1.5° referencing a plurimeter [12]. Similarly, Ojima et al. reported a mean error of 2.1° referencing a protractor measurement jig [1]. Despite the technology differences, these previous studies are in agreement with our findings.

Previous studies have reported inaccuracy of electrogoniometers for measuring *in vivo* wrist range of motion. Investigators have reported substantial MD values above 9° referencing manual goniometry [13] and protractor [15] measurements. These larger biases may be due to different experimental protocols, reference standards, and/or an older electrogoniometer model that they used. Electrogoniometer models incorporating shorter strain gauge length to minimize torsion have since been released [13]. Buchholz and Wellman reported forearm rotation as the major source of error in their experiment [15]. Johnson et al. demonstrated that forearm position decreased accuracy when the forearm was fixed in a position that was different than the position the electrogoniometer was zeroed to [14]. In our study, the R/U task presented the lowest errors and was completed in the same forearm and hand position both systems were zeroed to, suggesting that forearm positioning may have been a factor in accuracy.

Researchers have reported accuracy of electrogoniometers for measuring wrist range of motion. Rawes et al. reported electrogoniometer accuracy as a standard deviation of 3° [19]. However, accuracy is only reported in terms of standard deviations and the methods for reference measurements appear to have been manually defined, raising potential concerns about the robustness of the validation [19]. Ojima et al. describe the need to fix forearm supination and pronation after discrepancies in measurements during preliminary experiments but the data is not reported [1].

There were limitations to this study. The proper positioning of the electrogoniometer occupied ideal space for OMC marker placement on the dorsal surface of the MC3 and forearm. These locations are likely less susceptible to soft tissue artefact and are ideal for marker placement. Both systems were subject to skin-motion artefacts associated with *in vivo* motion capture [9]. Systems like biplanar videography can address these concerns by quantifying the true bone movements [20,21].

Although electrogoniometers are easy to use, they have some limitations. The strain gauge connecting the two end blocks of the electrogoniometer is susceptible to over-compression and torsion per the electrogoniometer user manual, which may have led to errors. To account for the potential electrogoniometer over compression, subjects performed each RoM task before taking measurements. Pegs were placed on the table to prevent the subject from entering a position that visually over compressed the electrogoniometer. This presents a concern that a natural full range of motion may lead to inaccuracy of the electrogoniometer. Different sizes of the electrogoniometer may address concerns of over-compression during *in vivo* RoM. Additionally, the electrogoniometer is not capable of quantifying supination and pronation.

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Figure 1.

The orientation of the electrogoniometer and reflective markers for the mechanical experiment. Two PVC pipes connected by a universal joint simulated the hand and forearm.

Figure 2.

(a) Top view of the forearm and hand position for radial-ulnar deviation (R/U) *in vivo* range of motion (RoM) task. (b) depicts the side view of the forearm and hand position for flexion-extension (F/E) task *in vivo* RoM task. (c) depicts the side view of the forearm and hand position for circumduction *in vivo* RoM task.

Figure 3.

Estimated mean bias and limit of agreement for each task by component of measurement (radial-ulnar and flexion-extension) based on the model output. The intervals are overlaid on the mean bias points for the individual subjects ($n=6$) for each task and direction. The three range of motion (ROM) tasks were flexion-extension (F/E), radial-ulnar deviation (R/U) and circumduction (Circ). P -values for pairwise comparisons are adjusted using the Holm test in order to maintain a family-wise P -value < 0.05 .

Table 1.

Mechanical accuracy of the electrogoniometer compared to the reference standard optical motion capture (OMC). Mean differences (MD) and limits of agreement (LoA) from Bland-Altman analysis are grouped by component of measurement (radial-ulnar and flexion-extension) and range of motion (RoM) tasks.

RoM tasks	Radial(−) Ulnar(+) Deviation (degrees)		Flexion(+) Extension(−) (degrees)	
	MD	LoA	MD	LoA
Circumduction	−0.2	−1.9 — 1.5	0.7	−0.8 — 2.3
Flexion-Extension	1.0	−2.6 — 4.5	0.3	−1.3 — 1.8
Radial-Ulnar Deviation	−0.2	−2.0 — 1.5	0.2	−3.5 — 3.8

Table 2.

In vivo accuracy of the electrogoniometer compared to the reference standard optical motion capture (OMC). Mean differences (MD) and limits of agreement (LoA) from Bland-Altman analysis are grouped by component of measurement (radial-ulnar and flexion-extension) and range of motion (RoM) tasks.

RoM tasks	Radial(–) Ulnar(+)	Deviation	Flexion(+) Extension(–)	
	MD	LoA	MD	LoA
Circumduction (degrees)	1.2	–9.2 — 11.5	–0.9	–9.7 — 7.9
Flexion Extension (degrees)	7.2	–0.9 — 15.2	–5.2	–14.3 — 4.0
Radial Ulnar Deviation (degrees)	–0.8	–4.1 — 2.5	0.8	–3.5 — 5.1