Development and validation of an electrogoniometric wrist alignment device

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Abstract: This paper reports the development of an instrumented flexible electrogoniometric hand posture corrective device designed specifically for monitoring and controlling the range of motion (ROM) at the hand and wrist. The device, known as the wrist alignment device (WAD), consists of flexible electrogoniometers attached to a Lycra® glove and a control box housing the WAD circuitry. The WAD controls the wrist ROM within set limits by means of presetting the joint angle ranges prior to commencing measurements, thereby preventing or reducing extreme wrist ulnar deviation, wrist hyperflexion, and wrist hyperextension. Additionally, the device consists of a window comparator, which allows the joint movement always to remain within the set limits. Where the subject's wrist ROM is outside the presettings, a piezo-buzzer is triggered which alerts the subject to reduce the ROM, thereby ensuring that the joint angles are always kept within the preset angle range. All instrumentation associated with the development of the device underwent calibration. As a device, it has widespread applications within the office and clinical environment. Preliminary results indicate that reliable measurements based on ROM settings can be obtained when using the WAD.

Keywords: flexible electrogoniometer, electrogoniometric glove, wrist alignment device

1 INTRODUCTION

An electrogoniometer is one of the most useful methods for measuring and recording joint motion [**1**, **2**]. Predominantly this instrumented device measures joint angle using an electronic potentiometer connected to a metal link whereby each link is strapped to a limb segment such that, when the limb moves, the potentiometer rotates and generates a signal which is then recorded [**1**–**3**]. In particular, they are useful measurement devices for assessing and determining the functional outcome of joint stability. Electrogoniometers have widespread applications in ergonomics [**4**–**6**], orthopaedics [**7**–**11**], rehabilitation [**3**, **11**–**14**], and research [**7**, **15**–**18**]. It is common practice to place electrogoniometers directly onto the skin adjacent to the joint of interest. Additionally, electrogoniometers can be stitched into a fabric material or held together by Velcro material. An example of such an application is instrumented gloves [**18**, **19**]. Although flexible electrogoniometers have been incorporated into gloves as a means to monitor hand joint motion, the range of motion (ROM) of the hand joint can be better controlled with emphasis on subject specificity, thus allowing the subject to control his or her hand movement within a set range of motion. Previous studies have developed gloves to monitor hand and wrist motion [**10**, **18**–**20**], but none of these gloves has been used specifically to control joint ROM.

Movements involving the hand, wrist, and forearm are known contributors of increased carpal tunnel pressure (CTP). Basic research studies have provided information about increased pressure within the carpal tunnel leading to carpal tunnel syndrome (CTS) [**21**, **22**]. These studies have found that CTS patients have higher CTPs when compared with healthy individuals [**5**, **21**, **23**–**28**]. Within the occupational setting, epidemiological studies have shown that wrist joint posture and motion are related to an increased incidence of CTS [**29**], which is also linked to elevated pressure changes within the

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carpal tunnel. Previous studies have demonstrated that deviation of the wrist and forearm from the neutral position, by flexion–extension [**23**, **30**] or radio–ulnar deviation [**30**, **31**], can contribute to increased CTP. Wrist extension to 40° can increase the tunnel pressures by 40 mmHg [**30**, **31**]. It has also been shown that wrist extension consistently produces higher CTP than wrist flexion [**31**]. Additionally, finger flexion [**32**] and finger extension [**31**, **33**] have both been found to increase CTP, with the mid-range (neutral) motion posture eliciting the lowest CTP [**5**, **33**]. Also, straight fingers produce significantly higher pressures than 45° and 90° metacarpophalangeal joint flexion angles in extended wrist postures. This may be due to the distal muscle movement encroaching into the carpal tunnel space [**31**]. While there is evidence of CTP being lowest when the wrist is at a neutral position, wrist postures outside the functional neutral are still adopted predominantly among keyboard and mouse operators.

Therefore, the purpose of this paper was to develop an instrumented flexible electrogoniometric hand posture corrective device to provide feedback and to control hand and wrist joint ROM within preset limits.

2 METHOD

2.1 Design and development

The design and development stage incorporates flexible electrogoniometry integrated into a flexible electrogoniometric glove (FEG) that is linked to the WAD. The stages of development and implementation are described in terms of the components.

2.1.1 Flexible electrogoniometer

Flexible electrogoniometers were chosen because of their pliability and cost effectiveness. These electrogoniometers were developed by Nicol and colleagues at the Bioengineering Unit of Strathclyde University [**3**] and were incorporated into the wrist alignment device (WAD). The flexible electrogoniometer consisted of a flexible steel strip that was strain gauged such that the output (angle) was independent of the shape of the strip within the plane of measurement. Additionally, the output was linearly proportional to the angle subtended by one end relative to the other end. Errors due to effects from polycentric joints and linear skin movements were avoided. Details of the instrumentation are described by Nicol [**3**] and Rand [**18**, **34**].

Four flexible electrogoniometers were connected to an 8-bit data logger (Biomedical Monitoring Ltd, Glasgow, UK) and data were collected at a sampling rate of 50 Hz (Fig. 1). Two flexible electrogoniometers recorded movements during wrist flexion–extension and wrist radio–ulnar deviation for both the left and right hands respectively. The data logger stored the wrist joint motions, which were then downloaded and saved to a file. The data logger was calibrated by the manufacturers. Data were processed using a Matlab (The MathWorks, Inc.) program written by the authors. Prior to collecting data, each flexible electrogoniometer was calibrated using an instrumented protractor designed to measure joint angle movement both statically and dynamically. Using the instrumented protractor ensured that the values obtained were accurate to within $\pm 1°$. Linear variation and repeatability tests were exempted from this section, as the instrumented

Fig. 1 (a) Flexible electrogoniometers, (b) data logger

protractor has already been proven to be a reliable calibration technique [**35**, **36**].

2.1.2 *Flexible electrogoniometric glove (FEG)*

The custom-made FEG was constructed from Lycra® (Fig. 2). Provisions were made on the dorsal side of the glove for the flexible electrogoniometers to measure the following hand movements during static postures and dynamic manipulative tasks:

(a) flexion and extension of the index finger metacarpophalangeal (MCP) joint;
(b) flexion and extension of the middle finger MCP joint;
(c) wrist flexion and extension;
(d) wrist radial and ulnar deviation.

The flexible electrogoniometers were fastened to the glove by way of inserting them through general-purpose tubing located in the provisions stitched onto the dorsal surface of the glove of the finger and wrist joints. The general-purpose tubing was a polyurethane tube (RS Components Ltd, Corby, Northants, UK) with internal and outer dimensions of 2.5 and 4 mm respectively. Each finger and wrist electrogoniometer provision consisted of two subdivisions – provision A and provision B.

Before any measurement commenced, the FEG was calibrated such that every joint angle could be reconstructed from the electronic signal. With regards to this paper, only wrist flexion–extension and radio–ulnar deviation joint movements are reported. The FEG was produced as a one-size-fits-all glove where flexible electrogoniometers were fastened into their various provisions. This ensured that subjects with small, medium, and large hands experienced a comfortable fit. The calibration of the glove involved the use of wooden blocks cut to known angles (0, 10, 20, 30, 45, 60, and 80°). With the glove on, the palmar side of the hand was placed on the wooden block for flexion measurements and the dorsal side of the hand for extension measurements. With the hand placed in the neutral position (0° flexion–extension and 0° radio–ulnar deviation), all settings were zeroed prior to performing the calibration. For every angle measurement obtained, the hand was returned to the neutral position to ensure that the original settings were still the same, thus reducing any anatomic variability that could have arisen. During the FEG calibration, each set of angles was measured 3 times, as the palmar and dorsal aspects of the wrist joint conformed to the wooden block. All other flexible electrogoniometers attached to the glove showed similar R^2 values ($\geqslant 0.998$) for all wrist flexible electrogoniometers.

2.1.3 *Design of wrist alignment device (WAD)*

The wrist alignment device (WAD) was developed primarily to reduce extreme wrist ulnar deviation, wrist hyperflexion, and wrist hyperextension (Fig. 3(a)). As a device it can control the wrist ROM within

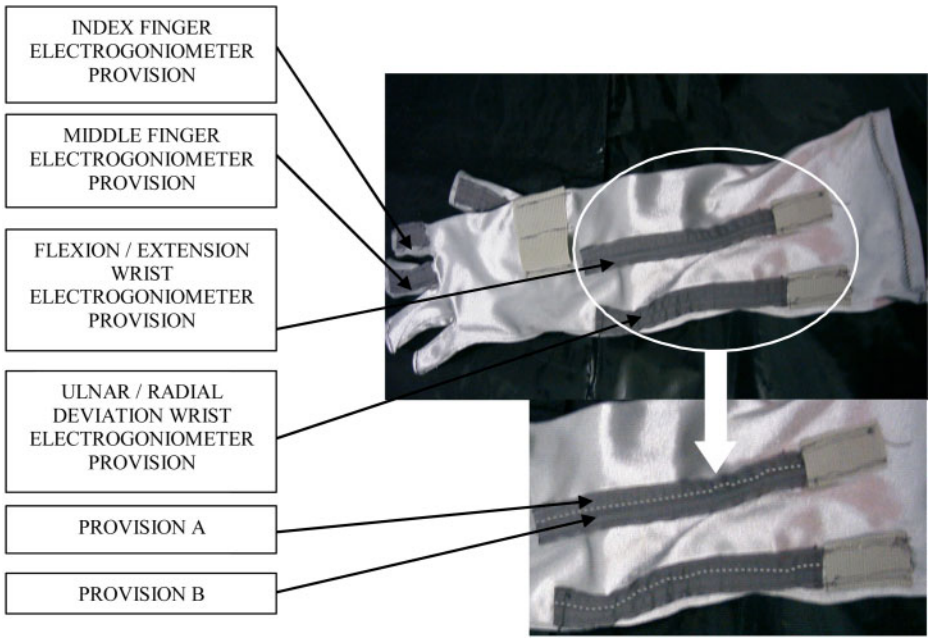

Fig. 2 Glove design (dorsal side)

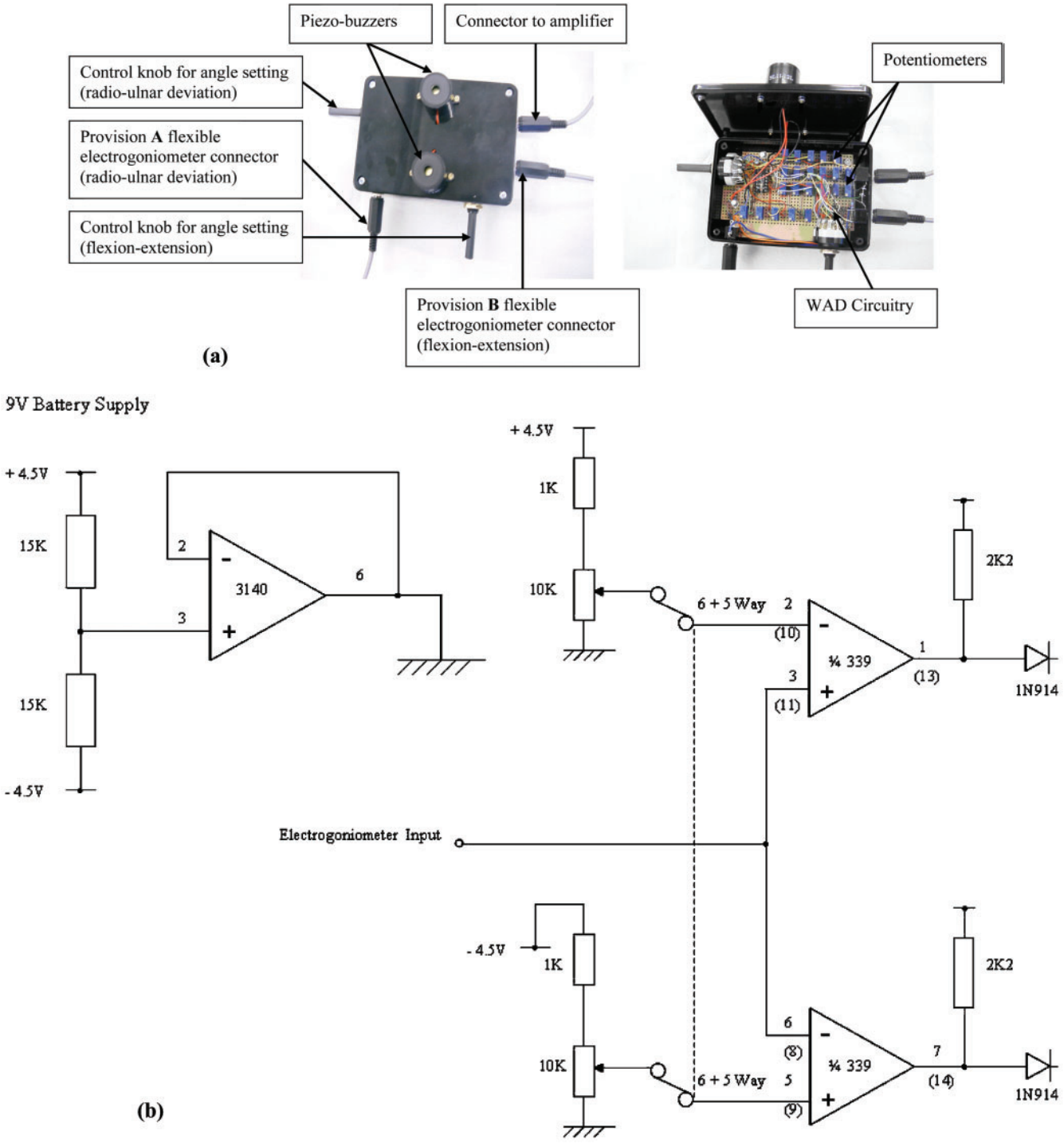

Fig. 3 (a) WAD control box; (b) WAD circuit diagram using a 339 Quad Comparator

set limits by means of presetting the joint angle ranges prior to commencing measurements. The device consists of a window comparator, which allows the joint movement always to remain within the set limits (Fig. 3(b)). Where the subject's wrist ROM is outside the presettings, a piezo-buzzer (RS Components Ltd, Corby, Northants, UK) alerts the subject to reduce the ROM, thereby ensuring that the joint angles are always kept within the preset angle range. As indicated in Fig. 2, each electrogoniometric provision on the FEG consisted of split provisions, provision A and provision B, for measuring wrist flexion–extension and wrist radio–ulnar deviation. The flexible electrogoniometers were connected to the WAD and data logger. Specifically, one flexible electrogoniometer was inserted into

provision A to monitor the ROM via the use of the WAD, while the second flexible electrogoniometer was inserted into provision B to collect the ROM data. Calibrations were performed on each component to ensure data validity and reliability in the ROMs obtained.

2.2 FEG and WAD validation

The FEG was validated by measuring the consistency of measurement and accuracy of the wrist flexible electrogoniometers. This was investigated by comparing the flexible electrogoniometric measurements from the instrumented protractor with the wrist joint angular measurements obtained from the FEG. The WAD validation process simply relied on the calibration of the flexible electrogoniometers which were subsequently integrated into the FEG. Specifically, the WAD calibration was performed 3 times to ensure the potentiometers did not need retuning. Also, within the WAD, the settings were capable of being readjusted to monitor higher wrist joint angle ranges. The WAD was tested on five subjects, with results reported in Fig. 4 and Tables 2 and 3 respectively.

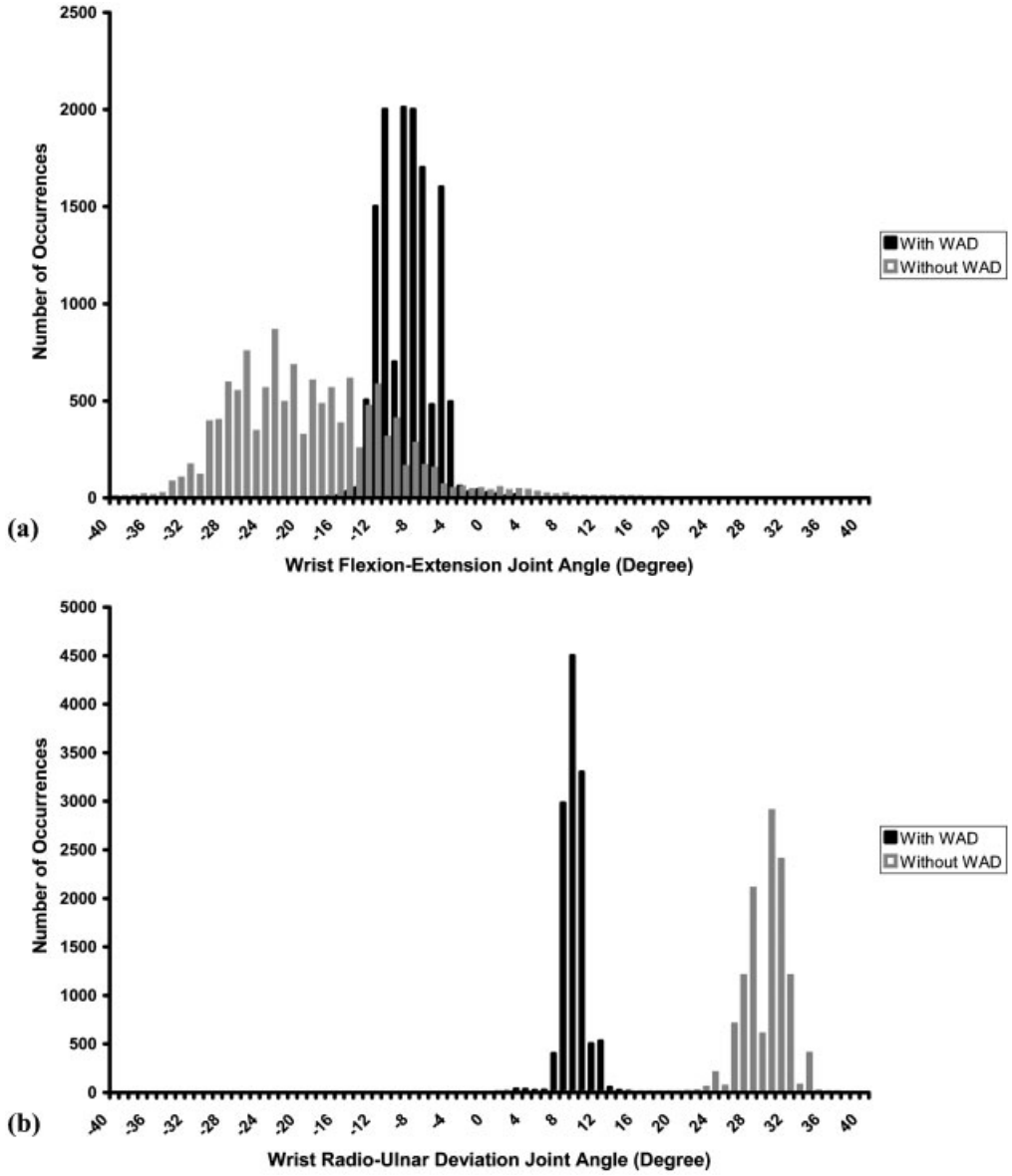

Fig. 4 Illustration of data spread during a numeric typing exercise using the dominant hand of subject A_m: (a) wrist flexion–extension; (b) wrist radio–ulnar deviation. The negative angles represent extension (and radial deviation) while the positive angles represent flexion (and ulnar deviation)

3 RESULTS

The calibration charts showed that R^2 values ranged from 0.9987 to 0.9998 for the wrist flexible electrogoniometers. From the calibration charts, the equation of the line for each flexible electrogoniometer was not identical, and so these values were incorporated into the Matlab program as a means to identify each flexible electrogoniometer. The size of variability between the flexible electrogoniometers for each angle was small (less than 2°).

3.1 Consistency of measurement

The consistency of measurement of the FEG was tested. This was determined by using the neutral angle (0°) as the reference point. Ten subjects performed two routines each, comprising complete wrist flexion–extension and wrist radio–ulnar deviation with the aim of determining whether the wrist returned to the reference position after the test. The routines were repeated 10 times, as the coefficient of variation was determined to ascertain how repeatable and reproducible the measurements were. The FEG was found to produce consistent readings as the subjects performed the repetitive wrist flexion–extension and wrist radio–ulnar deviation tasks. The coefficient of variation was found to be 0.01 per cent, which is negligible.

3.2 Accuracy of measurement

The accuracy was determined by comparing the calibration readings of the instrumented protractor and wooden block (FEG) with threshold settings on the WAD for each measured joint angle. Angular readings obtained from the wooden block (FEG) and instrumented protractor were measured against known angle threshold settings. For both calibrations the same flexible electrogoniometer was connected to the WAD. Table 1 shows the flexion calibration readings from 0 to 60° for the wrist flexible electrogoniometer (L2) using the instrumented protractor and FEG wooden blocks as the outcome measurements were confirmed by the buzzer sound. The results from both calibrations show very little difference, primarily because the flexible electrogoniometers were always reset to neutral prior to taking joint angular measurements. Both calibration methods triggered the buzzer at the preset angles.

3.3 WAD test

For the WAD test the joint angle limits were set at 15° for wrist flexion–extension and wrist radio–ulnar deviation respectively. The reason for choosing these angle ranges was to ensure the wrist joint posture conformed to the office workstation standards. From the literature, current workstation guidelines for keyboard slope are based on the assumption that the wrist joint angles during typing coincide with the keyboard slope. The American National Standard for Human Factor Engineering of Visual Display Terminal Workstations (ANSI/HFS) Standard No. 100-1988:37 states that:

> Wrist extension beyond 15° can increase histological pressure inside the carpal tunnel of the wrist, which is associated with carpal tunnel syndrome. Accordingly, it is recommended that keyboard slopes be minimized and limited to the range 0° to 15°.

Figure 4 presents graphs showing the data spread of the ROM at the wrist with and without using the WAD. Using subject A_m as the model, subjects performed a 10 min numeric data entry typing task, where the set limits were set to the 15° mark to control extreme wrist ulnar deviation, hyperextension, and hyperflexion.

Typing without the aid of the WAD shows the wrist to be more prone to hyperextension and extreme ulnar deviation. However, using the WAD, the results from Fig. 4 indicate that the wrist joint angles for both wrist flexion–extension and radio–ulnar deviation are well within the set limits.

Table 1 Analogue/digital calibration readings using the L2 flexible electrogoniometer

Angle (deg)	Instrumented protractor reading	Mean (FEG) calibration reading after 10 tests	SD (FEG) after 10 tests	WAD buzzer confirmation (yes or no)
0	128	128.5	1.29	Yes
10	134	134.25	1.71	Yes
20	143	143.75	1.71	Yes
30	152	153.5	1.29	Yes
45	165	166.5	1.29	Yes
60	177	176.75	1.26	Yes

L2 represents the flexible electrogoniometer name.

Although some of the joint angles appear to be out of their set limits, this was expected given that the subject is required to correct the hand and wrist posture when the buzzer is triggered, which is only when the hand is on the 15° mark or outside the 15° range.

A further office activity WAD test was performed by five subjects using both left and right hands respectively. The office activity performed combined both keyboard (typing) and mouse (clicking/dragging and scrolling) activities, each of the three tasks lasting 10 min. The result summaries (Tables 2 and 3) provide a confirmation of the mean joint angles falling within the 15° set limits. The mean ± SD joint angles for the right-hand flexion (extension), right-hand radio (ulnar) deviation, left-hand flexion (extension), and left-hand radio (ulnar) deviation were 5.0 ± 2.0° (7.8 ± 2.0°), 5.0 ± 2.9° (6.0 ± 1°), 5.0 ± 3.0° (8.2 ± 1.0°), and 4.6 ± 3.2° (4.2 ± 2.0°) respectively. Some subjects produced maximum flexion–extension and maximum radio–ulnar deviation joint angles outside the 15° set limits. The subjects corrected their wrist posture as soon as the piezo-buzzer was triggered.

4 DISCUSSION

The WAD has proven to be a useful device that can control a set ROM. This device ensures that the wrist and forearm are always maintained within a neutral position. The preliminary results indicate that reliable measurements based on ROM settings can be obtained when using the WAD. Both calibration methods, when used in conjunction with the WAD, triggered the piezo-buzzer at all angle settings. This confirmed the accuracy of the device. Furthermore, the reliability of the device was validated by performing tests to ascertain whether consistent measurements were obtainable. The results show that repeatable and reproducible joint angle measurements can be obtained, as reflected by the 0.01 per cent coefficient of variation. While flexible electrogoniometers have been incorporated into gloves as a means to monitor hand joint motion, the ROM of the hand joint can be better controlled with emphasis on subject specificity, thus allowing the subject to control his or her hand movement within a set range of motion. Also, previous studies have developed gloves to monitor hand and wrist motion [**10**, **18**–**20**], but none of these gloves has been used specifically to control joint ROM.

As a device it has widespread applications ranging from office activities to clinical applications. With regards to office activities, the WAD will be a useful device to monitor and control wrist ROM during the performance of office-related activities such as typing, mouse clicking and dragging, and mouse scrolling. The outcome of the WAD test showed that extreme wrist ulnar deviation and wrist hyperextension during typing was considerably reduced as the wrist maintained a neutral position. Within the

Table 2 Result summary of wrist flexion–extension joint angles for the combined repetitive office activity WAD test

	Wrist left-hand range of motion				Wrist right-hand range of motion			
Subjects	Mean flexion	Mean extension	Maximum flexion	Maximum extension	Mean flexion	Mean extension	Maximum flexion	Maximum extension
A	3	9	5	20	2	7	6	20
B	6	8	17	20	6	8	19	20
C	4	9	6	18	4	10	15	20
D	9	8	19	19	6	8	17	16
E	3	7	10	20	7	6	17	19

All mean values have been rounded to the nearest whole number.

Table 3 Result summary of wrist radio–ulnar deviation joint angles for the combined repetitive office activity WAD test

	Wrist left-hand range of motion				Wrist right-hand range of motion			
Subjects	Mean UD	Mean RD	Maximum UD	Maximum RD	Mean UD	Mean RD	Maximum UD	Maximum RD
A	2	8	5	17	6	2	15	4
B	6	4	13	7	5	2	20	11
C	6	3	17	8	6	5	15	18
D	3	2	13	4	6	5	14	13
E	4	2	13	5	7	2	20	5

All mean values have been rounded to the nearest whole number. RD – radial deviation; UD – ulnar deviation.

office environment, the WAD potentially could be beneficial to typists, secretaries, data entry operators, graphic designers, and frequent keyboard and mouse users, as highly repetitive, forceful, and precarious positioning of the hand and wrist can be managed by ensuring that the wrist ROM is well within a comfortable range suggested by ANSI/HFS that does not increase the pressure within the carpal tunnel. Although previous studies have provided evidence of musculoskeletal disorders resulting from excessive keyboard use [**4**, **6**] and mouse usage [**4**, **31**, **37**, **38**], the WAD may be a useful tool to help alleviate and possibly reduce the potential for an increase in carpal tunnel pressure during keyboard and mouse operations. From a clinical perspective, the use of the WAD has strong benefits in hand and wrist rehabilitation. For instance, the WAD can be used by clinicians to monitor the fracture recovery process of a patient's wrist or hand during rehabilitation. The rehabilitation sessions (at home or in the clinic) would help promote joint mobility but within a controlled preset ROM. Using the WAD, clinicians will be able to control and monitor the wrist ROM by gradually rehabilitating patients who have dislocated or fractured their wrists, particularly in patients who have suffered from a Colles' fracture or a Smith's fracture. Additionally, as a clinical device it is capable of being used by lower limb fracture patients who want to control and maintain a set ROM for their lower limb during the fracture recovery process (this will entail using a longer flexible electrogoniometer). Should the lower limb be subjected to larger joint angle ranges beyond the set range, an alarm is triggered which alerts the patient immediately to reduce the joint ROM. As a device it would cost more than a plastic goniometer but less than a portable motion analysis system. Also, the device is cost effective as all components and accessories can be obtained locally. Anyone who does occupationally related activities that entail predisposing the wrist to hyperflexion, hyperextension, extreme ulnar deviation, and extreme radial deviation could use the WAD. They will find the device does not affect performance or physically restrict ROM – rather it improves performance by way of reducing the potential for pressure increments during the performance of a hand-related task. In cases where hands need to be immersed in liquid, the FEG need not be worn; instead the flexible electrogoniometers can be taped directly onto the skin covering the joint areas of interest. Rehabilitation training could range from days to weeks depending on the individual, where the purpose of the training would be to ensure that the joint position remains as close as possible to the neutral position during the performance of the activity in question and after the WAD has been removed. When compared with an instrumented splint or hand-held plastic goniometer, the WAD is better because it is comfortably designed with an audio feedback mechanism. With respect to the one-size-fits-all glove during the WAD test, no subject showed any signs of discomfort. In fact, they all adapted and showed signs of improvement in their hand and wrist movement while performing the repetitive tasks. This was assessed and judged by the number of times the subjects had to realign their wrists after the buzzer was triggered. Wireless flexible electrogoniometry would be the next step forward.

Overall, the WAD will be a valuable device to clinicians and office workers in the future, as preliminary tests have demonstrated that using the WAD considerably reduces the wrist ROM, but more clinical and office activity tests will need to be performed.

5 CONCLUSIONS

A useful device has been developed that has potential to control wrist ROM. Moreover, the device will be beneficial both to office workers as a means to help reduce hyperextension and extreme ulnar deviation during keyboard and mouse operations, as well as to clinicians when monitoring and controlling wrist ROM of patients undergoing rehabilitation after wrist fracture.

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