FEASIBILITY AND RELIABILITY OF A WEB-BASED SMARTPHONE APPLICATION FOR MEASUREMENTS OF JOINT POSITION

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ABSTRACT

Objectives: Joint angle measurement is generally performed using a simple goniometer. With today's smartphones possessing the ability to measure angles, this technology can be used to measure joint angles. Although studies have evaluated smartphone applications for this purpose, they lack consistency and homogeneity. The objective of this study is to analyse the reliability and accuracy of three smartphone IMU-based applications for goniometric measurements using three different industry standards as external controls.

Methods: In the first two phases of the study, measurements taken between 90°-165° (simulating knee extension) using three smartphone applications were analysed against the three industry standards. In the third phase, the smartphone's raw data was analysed against a digital inclinometer across the X, Y and Z axes individually.

Results & Conclusion: Results obtained from the three phases of experiments in this study indicate a high degree of reliability and validity of the applications compared to the industry standards, with any deviations deemed not clinically significant indicating that the technology can be used in a clinical setting. However, further clinical research focussed on joint motions with greater than a single degree of freedom is required before the use of such an application in clinical practice.

KEYWORDS: Goniometry; Goniometer; Measurement; Joint angle; Smartphone application; Joint position; Range of Motion; Proprioception; Accelerometer.

INTRODUCTION

Joint angle measurement is a fundamental part of functional assessments in diagnosis and rehabilitation, being routinely used by doctors, as well as physical and occupational therapists to quantify baseline range of movements or their limitations, plan interventions and subsequently analyse the efficacy of their interventions by serial measurements (1)(2). Joint position sense or joint angle reproduction testing using joint angle measurement is also used to analyse proprioceptive performance which can be reduced in pathologies such as stroke, peripheral nervous disorders, degenerative diseases of joints like osteoarthritis, or aging (3)(4)(5)(6)(7)(8).

The measurement of joint angle for these purposes is commonly performed in a clinical setting by using a manual goniometer, digital inclinometer or isokinetic dynamometer (4)(9)(10)(11)(12). It is generally accepted that individuals with proprioceptive deficit are prone to greater magnitudes of joint position or angle error (3)(4)(5)(6)(8). These methods often provide tactical, visual or auditory cues that have a confounding effect on the measurement and therefore need to be eliminated during testing. However, despite the widespread use of joint position testing, the reliability and validity of these methods have rarely been evaluated against different controls in research (13)(14).

The use of a simple goniometer is considered the industry standard for clinical use to measure joint angle, due to its small size, low cost, availability, usability and prevalence in literature (13). However, the greatest limitation with a manual goniometer is the intra- and inter-rater variability. Studies have also reported variable reliability using a simple or universal goniometer, with change in direction of motion (13)(14)(15). As such, an isokinetic dynamometer is often used due to increased reliability and is commonly used for laboratory studies. However, the use of an isokinetic dynamometer in clinical scenarios, is limited due to the cost and large size of the equipment (15)(16).

Technological advancement has always been a significant propeller for the improvements seen in medical practice. Although smartphones have become a very integral part of our lives, their use in everyday clinical setting has been limited. Today's smartphones possess a camera, 3-dimensional accelerometer, magnetometer, gyroscope and an Inertial Motion Unit (IMU), whose potential has not been completely harvested to improve clinical practice (17)(18)(19). IMUs in smartphones are present as a chip, gathering data from the accelerometer, gyroscope and magnetometer to measure velocities and orientation (19).

With this potential, several researches have examined the utility of smartphone based JPR measurements. Studies by Ferriero et al. and Jeon et al. analysed the reliability and validity of a photography based 'DrGoniometer' smartphone application as an alternative for a simple manual goniometer (20)(21). Both studies suggested good inter-rater and intra-rater reliability and validity of the smartphone application (20)(21). The 'DrGoniometer' application was also evaluated by Mitchell et al. and Otter et al. (22)(23) who acceded that smartphone based goniometric measurements could prove to be a viable alternative in clinical practice for joint angle measurement. However, Mitchell et al. concluded that an inclinometer-based 'GetMyROM' application was superior to the photography-based 'DrGoniometer' application. Ockendon and Gilbert tested a novel accelerometer-based application against a simple goniometer among healthy volunteers to measure knee joint angle. The study reported excellent reliability of the application and recommended its use in clinical settings (24).

Together, the data from these studies suggest that a smartphone application can indeed be a valid alternative to a standard manual goniometer and an isokinetic dynamometer, however, there are some inconsistencies in the study designs and outcomes. Although most studies report superior or similar outcomes to a simple goniometer, the necessary controls and the smartphone applications used in these studies, vary. Most studies compared the measurements of photography-based and accelerometer/gyroscope-based applications against a simple or universal goniometer, which have inherent issues. To date, an isokinetic dynamometer has not been used to compare static angle measurements despite its superior reliability to a simple goniometer (15)(16). Besides, the studies have not evaluated the raw data collected from a smartphone against a simple goniometer or an isokinetic dynamometer and rely on data from third party applications which process and present the data to the observer.

The objective of this study was to analyse the reliability and accuracy smartphone-based goniometric measurements, by comparing the results from three applications against various external controls. Although this study did not aim to measure dynamic angular movements, an isokinetic dynamometer was used as the main control for static angle measurements during testing as it has already been demonstrated to have superior reliability compared to a simple hand-held manual goniometer (15)(16). A manual goniometer along with a digital inclinometer were also used as external controls to be compared with three different iPhone® (Apple Inc., Cupertino, CA) applications to used measure angles.

MATERIALS AND METHODS

The study aimed to analyse the reliability and validity of a smartphone-based measurement technique against the industry standards which are the simple goniometer (produced by Workzone Digital Angle Level, UK) and a Biodex System 4 Pro isokinetic dynamometer (Biodex Medical Systems, Shirley, New York, USA). The isokinetic dynamometer was used as an external control to simulate knee extension (angles between 90-165) for the first and second phases of experiments, while a digital inclinometer (developed by Snowspring, USA) was used to assess the accuracy of the smartphone measurements across the X, Y and Z planes in a second independent experiment (10° intervals from 0-80° across all axes).

(FIGURE 1)

Descriptive statistics (Means, Standard Deviations and Coefficient of Variance) of the measurements at different angles corresponding to knee extension were performed to analyse the spread and variance of the measurements through the different observations. Further statistical analysis using Pearson correlation, one-way ANOVA, independent t-tests and Bland-Altman comparisons were done to analyse the data collected through different methods of measurement and to study significant differences. Statistical significance was set at $p < 0.05$.

The following applications were used for this study:

(1) **Measure application** (built-into the iPhone): The application only measures change across the Z axis and hence for this study, the iPhone was positioned in such a way that the change in joint angles during movement was around the Z axis (Apple Support, 2019).

(2) **PT Goniometer** application (Available to download for free from the iPhone App Store): In this application the axes of movement can be predefined prior to measurements. However, the application does not display the changes across different axes.

(3) **A novel web-application**: https://manak.github.io/web-goniometer/. For this study, a custom web-application was built that would track the current orientation of the device in 3D space (rotation around the X, Y and Z axes) in degrees. The first tap on the screen would record the device's position as the zero value (original starting orientation). Every subsequent tap would record the orientation at the time of tap, and the change in orientation from the original zero value. Once completed, a double tap of the screen will show all the values that were recorded along with the raw data captured by the smartphone. To access the data from the IMU of the device, the device orientation events as specified in the W3C Device Orientation Specification were used (17). By building a web-based application, it eliminated the need to develop multiple native applications for different devices to test the accuracy of their respective IMUs. In this study, we used an iPhone® X, although any modern smartphone that contains an IMU and runs a recent operating system (iOS 4.2+, Android with Chrome 59) will be able to use the web application described.

TESTING METHODS

Phase One: For the first phase of experiments, the isokinetic dynamometer was set to 90° according to the simple goniometer. Five measures were taken at 90°, 105°, 120°, 135°, 150° and 165° each (total of thirty measures), corresponding to the simple goniometer and the values on two iPhone® X applications (Measure and PT Goniometer) and the isokinetic dynamometer and digital inclinometer were recorded. These measurement angles were chosen due to their clinical relevance to knee extension. The measurements were repeated five times after bringing the simple goniometer back to 90° to assess reliability. All measurements were taken on the same day by the same tester. The data collected from the Measure application had to be standardised for statistical analysis.

Phase Two: During the second phase of experiments, the reliability of the custom-built web-application was assessed with the isokinetic dynamometer used as the main control. The measurements of the second phase were five measures taken at 90°, 105°, 120°, 135°, 150° and 165° each similar to the first phase of study (total of 30 measures). The web-application was set to 0° with the initial tap and the measurements taken therefore had to be standardised to match with that of the dynamometer for statistical analysis.

Phase Three: The third phase of experiments was done to assess the accuracy of the web-application across the X, Y and Z axes individually using a digital inclinometer as control. For this phase, the iPhone® was mounted on a commercially available gimbal with measurements taken at 10° intervals (total of 27 measures).

STATISTICAL ANALYSIS

Descriptive statistical analysis of means, standard deviations and coefficients of variance were calculated using Microsoft Excel 2019. Further statistical analysis was performed using GraphPad Prism 8 (GraphPad Software Inc., San Diego, California, USA).

RESULTS

Phase 1 (Described in Table 1): Descriptive statistical analysis of the various external controls against the simple goniometer, showed standard deviations and coefficient of variance of less than 1 for both external controls (isokinetic dynamometer and digital inclinometer), suggesting good reliability of the external controls and prompted their use as primary controls in the second and third phases of experiments. The two iPhone applications analysed in this phase (Measure and PT Goniometer) had standard deviations and coefficient of variance less also than 1, suggesting a high degree of reliability and precision. One-way ANOVA indicated no significant difference between the methods of measurement (p = 0.96, while Pearson correlation analysis suggested significant correlation among the methods (r=1; 99% confidence with p = <0.001) i.e., the values obtained from the different methods of measurements demonstrate significant correlation with each other.

(TABLE 1)

Phase 2: Standard deviation and coefficient of variance obtained were < 0.5 for the measurements on the web-application against the isokinetic dynamometer. Independent t-test generated a p-value of 0.99, demonstrating no significant difference, with the Bland-Altman plots indicating differences of <1° between the two methods of measurement. These data together demonstrate the high degree of reliability and validity of the web-based measurement of angle, closely aligned to measurements obtained on the isokinetic dynamometer.

(TABLE 2)

Phase 3: To assess the reliability of measurement in X, Y and Z planes of the web-based application, measurements were taken against the digital inclinometer. Independent t-test analysis suggested no significant difference between the web-application and the digital inclinometer ($p = 0.99$). Bland-Altman analysis showed differences of <1° between the two methods. These data confirm the reliability of the web-based application in all three planes, accounting for angle differences during multi-plane movement.

DISCUSSION

The first phase of experiments was conducted to analyse the reliability, accuracy and precision of the measurements obtained from the various controls and the two iPhone® applications – Measure and PT Goniometer; precision indicating the accuracy of the measurement with repetition and reliability indicating the accuracy of serial measurements at the various angles used in the study. A simple goniometer was used as the primary control for this phase, due to the common use in clinical settings. This facilitated the analysis of the validity and reliability in measurements between the simple goniometer and the two other external controls used – an isokinetic dynamometer and digital inclinometer. The use of a simple goniometer is the industry standard for goniometric measurements, despite a few studies suggesting superior reliability of an isokinetic dynamometer (15)(16). Isokinetic dynamometers have found little use in a clinical setting, possibly due to their large size and expensive initial costs. However, there still remains a paucity of studies comparing the reliabilities of a simple goniometer and an isokinetic dynamometer for static angle measurements (15)(16). Currently, studies analysing the reliability of digital inclinometers against a simple goniometer have presented contradictory results. Some studies suggest that digital inclinometers are a reliable alternative to simple goniometers for joint angle measurements, while others recommend cautious use of digital inclinometers for goniometric measurements, while carefully adhering to measurement protocols as significant difference exists between the two devices (25)(26)(27)(28). Therefore, the reliability statistics performed between the different controls used in this study can help add to the existing literature in these areas, demonstrating measurement parity.

The Measure application was chosen for this study because it is built-in to every iPhone® and uses the smartphone's inbuilt gyroscope and accelerometer data for angular measurements. The Measure application has only been analysed in a few studies for reliability for goniometric measurement, despite the availability and unlimited access. The other application used in the study was the 'PT Goniometer' application. Although several studies have been performed on various goniometric applications, most of the applications analysed in research are available at a cost from the Apple App Store. The 'PT Goniometer' was chosen as the second application to be analysed, as currently there are no studies evaluating its reliability and it is available to download for free.

A total of 30 measurements were taken in Phase 1 using the various modes of measurements at angles between 90-165°, at 15° intervals. Studies assessing the reliability and validity of smartphone-based applications for goniometric measurements usually perform between 20-

40 measurements (18)(29)(18)(30)(31)(32). Results obtained from the first phase was dissected, so that each of the different methods of measurements can be analysed for measurements of reliability and accuracy against the simple goniometer. The accuracy of each measurement method was variable at different angles of measurements, with greater differences seen at higher angles of extension. The data comparing the simple goniometer against the isokinetic dynamometer and digital inclinometer, suggests that they can be used interchangeably (Table 1). This also prompted the use of the isokinetic dynamometer and digital inclinometer as control measures in phase two and three of the study, respectively.

During the first phase of the experiments and a pilot of the methodology, it was found that measurements taken beyond a single degree of freedom (i.e. beyond one plane of motion) caused inherent issues with the recording of data. Such difficulties are similar to those reported by clinicians, who suggest that the measurements are not reliable and representative of the change in angle. This prompted the development of a web-application that could provide the unaltered raw data obtained from the IMU of the iPhone®, in all three axes. All of the applications that have been evaluated in literature only display the angular changes in a single axis (18)(28)(29)(30)(31)(32). This web-application was designed to display the raw as well as processed data of all three axes of rotation. The web-application thereby developed had three main advantages:

(i) A web-application is easier and quicker to develop compared to a smartphone-based application.

(ii) The web-application could be run on any modern smartphone that contains an IMU and a recent operating system (iOS 4.2+, Android with Chrome 59).

(iii) The raw data generated could facilitate the analysis of the reliability, accuracy and precision of a smartphone's IMU data for the purposes of joint angle measurement.

The second phase of experiments were performed similar to phase 1. The web-application demonstrated significant correlation with the isokinetic dynamometer and only had small differences of less than 1°, compared to the Bland-Altman analysis of the 'Measure' and 'PT Goniometer' applications which showed much larger deviations, although the differences may not be clinically relevant (33)(34). It can therefore be deduced that the web-application demonstrates a high degree of reliability and validity across a range of angles.

Statistical analysis of the third phase of experiments demonstrated excellent reliability and validity of measurements from the web-application when compared against the digital inclinometer, throughput all three axes (independent t-test, $p = 0.99$). Correlation analysis suggested a high degree of correlation of the measurements of the web-application and the digital inclinometer ($r = 1$ with 99% confidence, $p < 0.001$), while Bland-Altman analysis showed differences ranging between 0 and ± 0.75° between the two methods of measurement. Therefore, it can be concluded that the data derived from the IMU using the web-application is extremely accurate, reliable and valid across the three planes of motion. This accuracy of the IMU can be applied to measure complex movements that involve more than one plane of motion and thus demonstrate more clinical relevance than previously published methods.

Results obtained from the three phases of experiments in this study indicate a high degree of precision and accuracy of the applications evaluated in this study, compared to the industry standards of simple goniometer, isokinetic dynamometer and digital inclinometer for the measurement of joint angles. The deviations of measurements from the mean (SD) and the control measures observed on the various applications analysed, are not clinically significant (33)(34). The absence of significant differences between the methods of measurement and the clinically insignificant deviations, suggest that smartphone IMU-based applications are reliable, accurate and precise for goniometric measurements. This is in agreement with other studies that have analysed smartphone-based goniometric applications, indicating that a smartphone IMU-based device can be used for the measurement of joint angles in a clinical setting as an alternative to a simple goniometer.

CONCLUSION

Although the ROM measurements obtained on the various applications were comparably reliable to those of the simple goniometer, isokinetic dynamometer and digital inclinometer, the 'PT Goniometer' and 'Measure' applications had their limitations. Based on the results obtained in this study, it can be concluded that the data derived from the IMU demonstrates a high degree of intra-tester reliability, accuracy and precision compared to the industry standard simple goniometer, as well as the other external controls used in this study. Therefore, a smartphone IMU-based application can be a reasonable alternative to a simple goniometer in a clinical setting for ROM measurements. Moreover, the use of such an application requires minimum training, making it easy to use. However, the use of such an application cannot be recommended for clinical practice until further research is carried out to assess the reliability and validity of the application in different joints, across different planes of movement among subjects with various joint pathologies.

FIGURES AND TABLES

Simple Goniometer		90°	105°	120°	135°	150°	165°
Isokinetic Dynamometer (Control)	Mean	91	105.6	120	134	148	162
	SD	0	0.5	0	0	0	0
	CV	0	0.5	0	0	0	0
Digital Inclinometer (Control)	Mean	90.24	105.44	120.59	136.75	151.77	166.72
	SD	0.08	0.05	0.04	0.08	0.04	0.08
	CV	0.09	0.05	0.03	0.06	0.03	0.05
Measure Application	Mean	90.4	105.8	120.8	136.8	153	-
	SD	0.5	0.4	0.4	0.4	0	-
	CV	0.6	0.4	0.4	0.3	0	-
PT Goniometer Application	Mean	91	105.8	121	136.8	153	168.8
	SD	0	0.4	0	0.4	0	0.4
	CV	0	0.4	0	0.3	0	0.3

Table 1: Descriptive statistics from the first phase of experiments.

(SD = Standard Deviation; CV = Coefficient of Variance)

	90°	105°	120°	135°	150°	165°
Mean	90.1551	105.1242	120.5673	135.1524	149.9121	164.7645
SD	0.3519	0.3384	0.2462	0.3243	0.3224	0.3506
CV	0.3903	0.3219	0.2042	0.2399	0.2150	0.2128

Table 2: Descriptive statistics from the second phase of experiments.

(SD = Standard Deviation; CV = Coefficient of Variance)

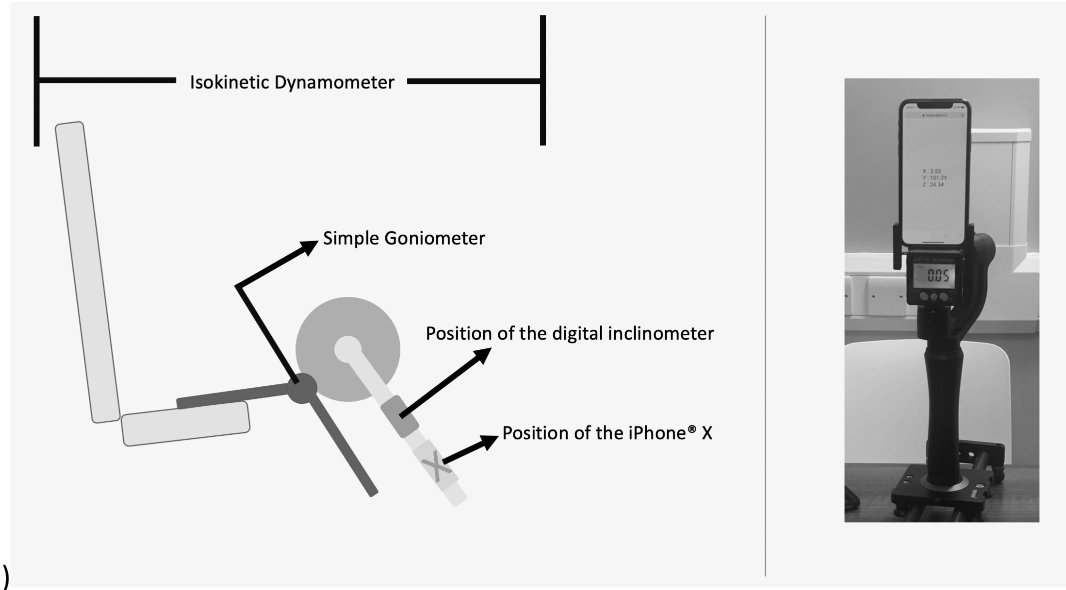
(a)  (b)

Fig. 1: Experimental Setup for (a) Phase 1 and 2; (b) Phase 3

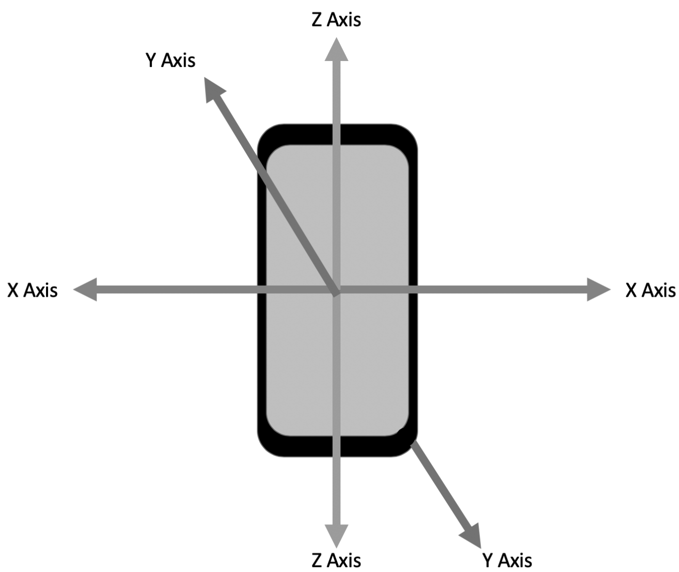


Fig. 2: Axis orientation of a smartphone.

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