



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

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Objective: Measurement of joint angles is usually performed using a simple goniometer, which can often be time-consuming and inaccurate, however smartphones can measure angles, this technology could be used to measure joint position. Studies of smartphone applications for this purpose lack consistency and homogeneity. The aim of the current study is to analyse the reliability and accuracy of 3 inertial motion unit-based smartphone applications for goniometric measurement, using 3 different industry standards as external controls.

Methods: In the first 2 phases of the study, measurements of angles between 90° and 165° (simulating knee extension) using 3 smartphone applications were analysed against the 3 industry standards. In the third phase, the smartphone's raw data was individually analysed against a digital inclinometer across the x, y and z axes.

Results and conclusion: Results from the 3 phases of this study indicate a high degree of reliability and validity of the applications compared with the industry standards, with no clinically significant deviations. Thus, this technology could be used in a clinical setting. However, further clinical research, focussing on joint motions with greater than a single degree of freedom, is required before the use of such applications for joint position measurement in clinical practice.

Key words: goniometry; goniometer; measurement; joint angle; smartphone application; joint position; range of motion; proprioception; accelerometer.

Accepted Nov 30, 2020; Epub ahead of print Dec 18, 2020

J Rehabil Med 2021; 53: jrm00188

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Joint angle measurement is a fundamental part of functional assessment in diagnosis and rehabilitation, it is routinely used by doctors, physical and occupational therapists to quantify baseline range of movement or their limitations, to plan interventions and subsequently to analyse the efficacy of interventions by use of 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 (e.g. in osteoarthritis or ageing) (3–8).

LAY ABSTRACT

The range of movement of various joints in the human body is regularly measured in a clinical setting, using a traditional angle measurement device (a goniometer), during functional assessments by doctors and physical and occupational therapists. However, such measurements can often be time-consuming and inaccurate. This study analysed the accuracy of smartphone apps for measuring joint angles compared with a goniometer. The results show that smartphone apps could be a good alternative for measuring joint angles.

The measurement of joint angle for these purposes is commonly performed in a clinical setting, using a manual goniometer, digital inclinometer or isokinetic dynamometer (4, 9–12). It is generally accepted that individuals with proprioceptive deficit are prone to greater magnitudes of joint position or angle error (3–5, 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 (13–15). 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 driver of improvements in medical practice. Although smartphones have become an integral part of our lives, their use in the everyday clinical setting is limited. Today's smartphones have a camera, 3-dimensional accelerometer, magnetometer, gyroscope and an inertial motion unit (IMU), whose potential has not been fully used to improve clinical practice (17–19). IMUs in smartphones are present as a chip, gathering data from the accelerometer, gyroscope and magnetometer to measure velocities and orientation (19).

To explore their potential, several researchers have examined the utility of smartphone-based Joint Position Reproduction measurements. Studies by Ferriero et al. and Jeon et al. analysed the reliability and validity of a photography-based DrGoniometer smartphone application (app) (designed by CDM s.r.l., Milano, Italy) as an alternative to a simple manual goniometer (20, 21). Both studies suggested good inter- and intra-rater reliability and validity of the smartphone app (20, 21). The DrGoniometer app was also evaluated by Mitchell et al. and Otter et al. (22, 23), who agreed that smartphone-based goniometric measurements could prove a viable alternative in clinical practice for joint angle measurement. However, Mitchell et al. concluded that an inclinometer-based GetMyROM app (designed by Interactive Medical Productions, LLC, Hampton, New Hampshire, USA) was superior to the photography-based DrGoniometer app. Ockendon & Gilbert tested a novel accelerometer-based app (24) against a simple goniometer among healthy volunteers to measure knee joint angle. The study reported excellent reliability of the app and recommended its use in clinical settings (24).

Together, the data from these studies suggest that a smartphone app could 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 apps used in these studies, vary. Most studies compared the measurements of photography-based and accelerometer/gyroscope-based apps against a simple or universal goniometer, both of 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). In addition, the studies have not evaluated raw data collected from a smartphone against a simple goniometer or an isokinetic dynamometer; instead they rely on data from third-party apps, which process and present the data to the observer.

The objective of this study was to analyse the reliability and accuracy of smartphone-based goniometric measurements, by comparing the results from 3 apps 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 with 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 3 different iPhone® (Apple Inc., Cupertino, CA, USA) apps used to measure angles.

MATERIAL AND METHODS

This study analysed 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° and 165°) for the first and second phases of the study, 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° to 80° across all axes).

Descriptive statistics (means, standard deviation (SD) 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's correlation, 1-way analysis of variance (ANOVA), independent *t*-tests and Bland–Altman comparisons, was performed 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 apps were used in this study:

- *Measure app (built-into the iPhone)*. This app 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, available from: <https://apps.apple.com/gb/app/measure/id1383426740>).
- *PT Goniometer app (available for free download from iPhone® App Store)*. In this app the axes of movement can be predefined prior to taking measurements. However, the app does not display the changes across different axes.
- *A novel web app (<https://manak.github.io/web-goniometer/>)*. For this study, a custom web app was built by the authors of the study 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

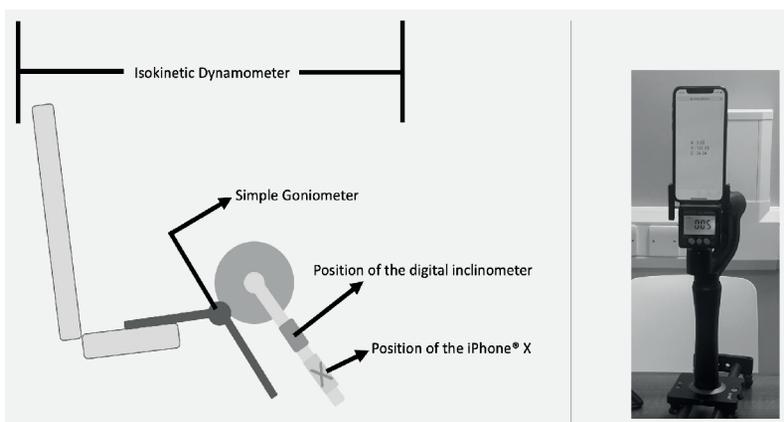


Fig. 1. Experimental setup for (a) Phases One and Two; (b) Phase Three.

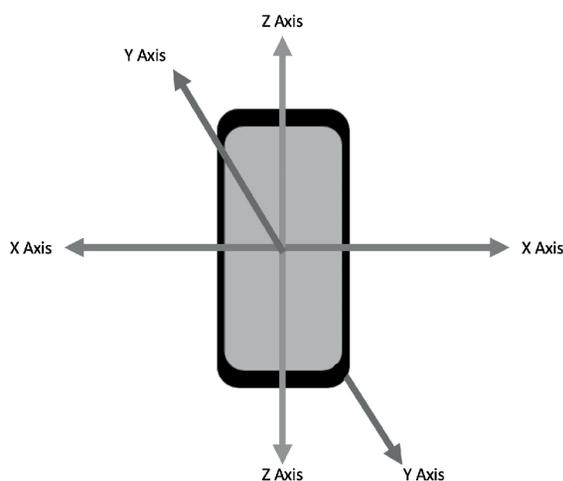


Fig. 2. A representation of the axes of a smartphone which were tested individually in phase 3 of the study.

the zero value (original starting orientation). Every subsequent tap would record the orientation at the time of the 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 app, it eliminated the need to develop multiple native apps for different devices to test the accuracy of their respective IMUs. In this study, an iPhone® X was used, although any modern smartphone that contains an IMU and has a recent operating system (iOS 4.2+, Android with Chrome 59) could use this web app.

Testing methods

Phase One. For the first phase of the study, the isokinetic dynamometer was set to 90° according to the simple goniometer. Five measurements were taken at each of 6 angles (90°, 105°, 120°, 135°, 150° and 165°); a total of 30 measurements, corresponding to the simple goniometer, and the values on 2 iPhone® X apps (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 5 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 app had to be standardized for statistical analysis.

Phase Two. During the second phase, the reliability of the custom-built web app was assessed, with the isokinetic dynamometer as the main control. Five measurements were taken at each of 6

angles (90°, 105°, 120°, 135°, 150° and 165°), similar to Phase One (a total of 30 measurements). The web app was set to 0° with the initial tap, and the measurements taken therefore had to be standardized to match the dynamometer, for statistical analysis.

Phase Three. The third phase of the study assessed the accuracy of the web app 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 (a total of 27 measurements).

Statistical analysis

Descriptive statistical analysis of means, SDs and coefficients of variance were calculated using Microsoft Excel 2019 (Microsoft Corporation, Redmond, Washington, USA). Further statistical analysis was performed using GraphPad Prism 8 (GraphPad Software Inc., San Diego, CA, USA).

RESULTS

Phase One

Descriptive statistical analysis of the various external controls against the simple goniometer, showed SDs and coefficients of variance of less than one for both external controls (isokinetic dynamometer and digital inclinometer), suggesting good reliability of the external controls, which prompted their use as primary controls in the second and third phases of experiments. The results of Phase One are shown in Table I. The 2 iPhone® apps analysed in this phase (Measure and PT Goniometer) also had SDs and coefficients of variance less than one, 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's 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 measurement demonstrate significant correlation with each other.

Phase Two

SD and coefficient of variance obtained were <0.5 for the measurements on the web app against the isokinetic dynamometer. Independent t -test generated a p -value of 0.99, demonstrating no significant difference, with

Table I. Descriptive statistics from the first phase of experiments

Simple goniometer		90°	105°	120°	135°	150°	165°
Isokinetic dynamometer (control)	Mean (SD)	91 (0)	105.6 (0.5)	120 (0)	134 (0)	148 (0)	162 (0)
	Coefficient of variance	0	0.5	0	0	0	0
Digital inclinometer (control)	Mean (SD)	90.24 (0.08)	105.44 (0.05)	120.59 (0.04)	136.75 (0.08)	151.77 (0.04)	166.72 (0.08)
	Coefficient of variance	0.09	0.05	0.03	0.06	0.03	0.05
Measure app	Mean (SD)	90.4 (0.5)	105.8 (0.4)	120.8 (0.4)	136.8 (0.4)	153 (0)	– (–)
	Coefficient of variance	0.6	0.4	0.4	0.3	0	–
PT Goniometer app	Mean (SD)	91 (0)	105.8 (0.4)	121 (0)	136.8 (0.4)	153 (0)	168.8 (0.4)
	Coefficient of variance	0	0.4	0	0.3	0	0.3

SD: standard deviation.

Table II. Descriptive statistics from the second phase of experiments

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

SD: standard deviation.

the Bland–Altman plots indicating differences of $<1^\circ$ between the 2 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 II).

Phase Three

To assess the reliability of measurement of the web app in the x, y and z planes, measurements were taken against the digital inclinometer. Independent *t*-test analysis suggested no significant difference between the web app and the digital inclinometer ($p=0.99$). Bland–Altman analysis showed differences of $<1^\circ$ between the 2 methods. These data confirm the reliability of the web app in all 3 planes, accounting for angle differences during multi-plane movement.

DISCUSSION

The first phase of this study analysed the reliability, accuracy and validity of the measurements obtained from the various controls and the 2 iPhone® apps (Measure and PT Goniometer); reliability indicating the accuracy of the measurement, with repetition and validity referring to how the measurements compare with the gold standard used in the industry. A simple goniometer was used as the primary control for this phase, due to its common use in clinical settings. This facilitated the analysis of the validity and reliability in measurements between the simple goniometer and the 2 other external controls; an isokinetic dynamometer and a 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 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 measurement, while others recommend cautious

use of digital inclinometers for goniometric measurement, while carefully adhering to measurement protocols, as significant differences exist between the 2 devices (25–28). 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 app 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 app has been analysed in only a few studies for reliability in goniometric measurement, despite its availability and unlimited access. The other app used studied was the PT Goniometer app. Several studies have been performed on various goniometric apps, however most of the apps analysed in research are available at a cost from the Apple App Store. The PT Goniometer was chosen as the second app to be analysed as it is available to download for free, and currently there are no studies evaluating its reliability.

A total of 30 measurements were taken in Phase One, using the various modes of measurement, at angles between 90° and 165° , at 15° intervals. Studies assessing the reliability and validity of smartphone apps for goniometric measurements usually perform between 20 and 40 measurements (18, 29, 18, 30–32). Results from Phase One were dissected, so that each of the different methods of measurements could be analysed for measurements of reliability and accuracy against the simple goniometer. The accuracy of each measurement method was variable at different angles of measurement, 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 I). This also prompted the use of the isokinetic dynamometer and digital inclinometer as control measures in Phases Two and Three of the current study, respectively.

During Phase One of this study 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 app

that could provide the unaltered raw data obtained from the IMU of the iPhone® in all 3 axes. All of the apps evaluated in the literature display the angular changes in only a single axis (18, 28–32).

The new web app evaluated in the current study was designed to display the raw as well as processed data for all 3 axes of rotation. This web app has 3 main advantages:

- A web app is easier and quicker to develop than a smartphone app.
- The web app could be run on any modern smartphone with an IMU and a recent operating system (iOS 4.2+, Android with Chrome 59).
- The raw data generated could facilitate analysis of the reliability, accuracy and precision of a smartphone's IMU data for the purposes of joint angle measurement.

Phase Two of this study was similar to Phase One. The web app demonstrated significant correlation with the isokinetic dynamometer and had only small differences, of less than 1°, compared with the Bland–Altman analysis of the Measure and PT Goniometer apps, which showed much larger deviations, although the differences may not be clinically relevant (33, 34). It can therefore be deduced that the web app 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 app compared with the digital inclinometer, throughout all 3 axes (independent *t*-test, $p=0.99$). Correlation analysis suggested a high degree of correlation of the measurements of the web app and the digital inclinometer ($r=1$ with 99% confidence, $p<0.001$), while Bland–Altman analysis showed differences ranging between 0° and $\pm 0.75^\circ$ between the 2 methods of measurement. Therefore, it can be concluded that the data derived from the IMU using the web app is extremely accurate, reliable and valid across the 3 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 from the 3 phases of this study indicate a high degree of precision and accuracy of the apps evaluated compared with 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 apps 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 apps are reliable, accurate and precise for goniometric measurements. This finding is in agreement with other studies that have analysed smartphone goniometric apps, and indicates 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 apps were reliable compared with those of the simple goniometer, isokinetic dynamometer and digital inclinometer, the PT Goniometer and Measure apps have some limitations. Based on the results obtained in this study, it can be concluded that the data derived from the IMU demonstrate a high degree of intra-tester reliability, accuracy and precision compared with the industry standard simple goniometer, as well as the other external controls. Therefore, a smartphone IMU-based app could be a reasonable alternative to a simple goniometer in a clinical setting for ROM measurements. Moreover, the app is easy to use, requiring minimum training. However, the use of such apps in clinical practice cannot be recommended until further research is carried out to assess its reliability and validity in different joints, across different planes of movement, and among subjects with various joint pathologies.

The authors have no conflicts of interest to declare.

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