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Original article

Validity and reliability of smartphone magnetometer-based goniometer evaluation of shoulder abduction – A pilot study

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A B S T R A C T

Background: Goniometers are commonly used by physical therapists to measure range-of-motion (ROM) in the musculoskeletal system. These measurements are used to assist in diagnosis and to help monitor treatment efficacy. With newly emerging technologies, smartphone-based applications are being explored for measuring joint angles and movement.
Objective: This pilot study investigates the intra- and inter-rater reliability as well as concurrent validity of a newly-developed smartphone magnetometer-based goniometer (MG) application for measuring passive shoulder abduction in both sitting and supine positions, and compare against the traditional universal goniometer (UG).
Design: This is a comparative study with repeated measurement design.
Methods: Three physical therapists utilized both the smartphone MG and a traditional UG to measure various angles of passive shoulder abduction in a healthy subject, whose shoulder was positioned in eight different positions with pre-determined degree of abduction while seated or supine. Each therapist was blinded to the measured angles. Concordance correlation coefficients (CCCs), Bland–Altman plotting methods, and Analysis of Variance (ANOVA) were used for statistical analyses.
Results: Both traditional UG and smartphone MG were reliable in repeated measures of standardized joint angle positions (average CCC > 0.997) with similar variability in both measurement tools (standard deviation (SD) $\pm$ 4°). Agreement between the UG and MG measurements was greater than 0.99 in all positions.
Conclusion: Our results show that the smartphone MG has equivalent reliability compared to the traditional UG when measuring passive shoulder abduction ROM. With concordant measures and comparable reliability to the UG, the newly developed MG application shows potential as a useful tool to assess joint angles.

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1. Introduction

The assessment of physiological range-of-motion (ROM) is a fundamental part of the physical examination of the musculoskeletal system. ROM is one of the key measures clinicians use to determine functional limitations, develop diagnosis, guide the treatment plan, and monitor progress throughout the course of treatment (Green et al., 1998).

The technical measurement of ROM at the shoulder varies between the clinic or research setting and a user's familiarity of equipment. Common techniques include: visual estimation,

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inclinometer and goniometer (Hayes et al., 2001; Terwee et al., 2005; Van De Pol et al., 2010). Less common methods including radiographs, cinematography, still photography, 3D gyroscopes, and human motion capture analysis methods, are either not practical or too expensive to use in a normal clinic setting and are reserved for research projects or large motion analysis laboratories (Gajdosik and Bohannon, 1987; McClure et al., 2006; El-Zayat et al., 2011). The most widely used tool in the clinic for ROM assessment for large joints such as shoulder or hip is the UG (Norkin and White, 2003). There have been many studies evaluating the validity and reliability of the UG in the clinical setting, showing good inter-rater and intra-rater reliability as well as clinical validity (Gajdosik and Bohannon, 1987; Riddle et al., 1987; Sabari et al., 1998; Hayes et al., 2001; Van De Pol et al., 2010; De Jong et al., 2012).

Since smartphones are becoming more ubiquitous and portable, clinicians are exploring their use as an easily accessible clinical tool, including several applications specifically designed for ROM measurements (Ferriero et al., 2011; Anderson et al., 2012; Kolber and Hanney, 2012; Shin et al., 2012; Ron, 2013; Yan et al., 2013; Werner et al., 2013; Milanese et al., 2014; Milani et al., 2014; Mitchell et al., 2014). Contemporary smartphones have numerous built-in sensors such as magnetometer, accelerometer and gyroscope that make the phone capable of detecting position in space to help gather ROM measurements. Having this application available on the clinician's smartphone allows for easy access, and creates the potential to offer features that the standard goniometer cannot, including: instant recording/logging of multiple points of data, and possibility of transmitting data directly to the patients' electronic medical record. Another possible benefit when using the smartphone is the ability for instant recording with the touch of a button, allowing for ROM to be captured more accurately, decreasing transcription errors, and eliminating inaccurate reading of numbers on the device. However, prior to using these applications in the clinic it is important to evaluate whether they are valid and reliable for use with research or patient care. Previous studies have focused on the reliability and validity of smartphone applications that use the built-in accelerometer or inclinometer (Ockendon and Gilbert, 2012; Shin et al., 2012; Milanese et al., 2014; Mitchell et al., 2014; Werner et al., 2013, 2014). However, to our knowledge, there is currently limited research in the area of smartphone-based applications that use the magnetometer as the primary source of positional data.

This study sought to understand the intra-rater and inter-rater reliability of a smartphone magnetometer-based goniometer (MG) application that uses the built-in 3 axis magnetometer, as well as determine the concurrent validity of this MG application by comparing against the universal goniometer (UG) to measure passive shoulder abduction ROM.

2. Method

This is a comparative study of a well-known and accepted method of joint ROM measurement, the traditional UG, to newly-developed smartphone-based MG software designed to measure joint range. To decrease bias, participating therapists were blinded to the angle readings on both the UG and MG and the devices were read by an independent observer from the study team.

2.1. Participants

One healthy male subject with no known shoulder pathology was used for all measurements to allow for multiple positions throughout the normal functional ROM at the shoulder. Three physical therapists with an average of 18 years of experience were selected to be the examiners. The three therapists had varied exposure to the phone application prior to using it in the study, ranging from 5 minutes to 3 hours. This study was approved through the University Institutional Review Board (IRB) for human subject research. All participants agreed to participate in the study and were provided written informed consent.

2.2. Devices

Two devices were used to measure ROM. The first device was a universal twelve-inch plastic EZ Read Jamar™ goniometer (UG) with the numerical face covered to prevent visual reading of angle measurement by testing therapist (Fig. 1a). The second device was an Android OS smartphone (first-generation Motorola Droid) programmed with a goniometer application developed jointly by the study investigators at University of California Berkeley (Computer Sciences and Electrical Engineering) and University of California, Davis School of Medicine (Fig. 1b).

The first device used was the UG which consists of two plastic arms; the stationary arm and the moveable arm. The stationary arm is placed over the body part according to standard anatomical landmarks. The moveable arm is rotated until it aligns over a second set of landmarks. The angle between the two is read in one degree increments. In this study, the face of the UG was covered and an independent observer read measurements from the device.

The second device was an Android OS smartphone with the investigator developed magnetometer-based goniometer (MG)

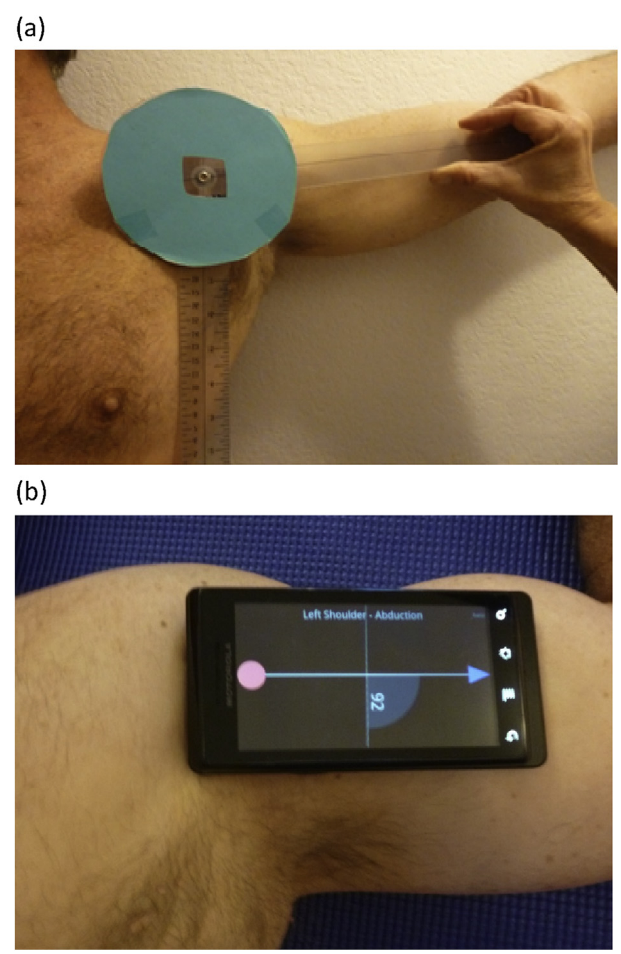

Fig. 1. Examples of goniometers used in the study. The UG with numeric values covered (a), and the smartphone MG (b). During data collection, the readings from the MG were covered with a devised faceplate.

application. The MG application is used in a similar manner to the traditional UG. It displays a directional arrow beginning at a fulcrum point. The phone is placed over a body part lining the arrow up according to standard anatomical landmarks, and an area of the smartphone face screen can be touched to lock in a starting point. In a vertical position (seated), the smartphone will default to a vertical zero starting point unless the screen is touched. The phone is then moved and placed over the second body part aligning the phone's directional arrow according to standard anatomical landmarks. To capture the final position, the phone screen is touched again. The MG software application will then determine the angle between the two captured positions (starting and end points) and displays it on the screen (Fig. 1b). For the purpose of this study, the portion of the screen showing the angle measurement was covered with a faceplate so that the participating therapists were blinded to the recorded data.

The initial development and testing of the application including comparison of angle measurements by the smartphone MG against a full-scale motion capture system has been published previously by the investigators (Yan et al., 2013). Briefly, the developed application utilizes a built-in magnetometer in the phone, for magnetic orientation function. The orientation has three-axes of measurement (azimuth, pitch, roll), and the application uses different axes of the orientation sensor depending on whether it is horizontal (azimuth axis) or vertical (pitch axis). These provide the angular orientation of the phone, and are the basis for determining angles. When used in the vertical or upright position, zero automatically aligns to the vertical axis and can be used as a starting point for measurements. However, if body habitus or body part is not appropriate to use the vertical axis as a starting point, then the examiner must mark a starting position. Since the magnetometer in a smartphone can drift, the investigators have noted that it may be important to calibrate the device prior to using in horizontal orientation. Once calibrated, the therapist must select the starting point and ending point of the angle being measured, similar to the use of the two arms of the UG.

2.3. Procedure

All study procedures were standardized among the study participants. Standard anatomical landmarks for shoulder abduction goniometry were reviewed with the examiners along with verbal instruction and demonstration on how to use the MG. Shoulder ROM was measured in both seated and supine orientation on a volunteer subject. A series of four fixed abduction positions were simulated in each orientation and held for a maximum of 10 minutes. While seated, the volunteer subject had his arm positioned into fixed abduction using an adjustable plinth, adjustable wedge and weights to secure the position (Fig. 2a). In supine, a wedge and/or weights were used to stabilize the subject's position (Fig. 2b). Angles varied from 35 to 170°.

Each of the three participating therapists took a series of four measurements with each device in various positions and orientation (seated and supine). The therapists did not know, a priori, the joint position of the subject. To further reduce potential for bias, the order of device was determined by a random number table. The device was removed and read by an independent observer allowing time separation between measurements and devices. In the seated position, the starting point was automatically determined by the MG application since it vertically aligned with the midline of the sternum. In supine, the smartphone was calibrated using a simple figure eight rotation of the phone prior to use. Once aligned with the limb, smartphone screen was simply touched to collect the starting point of limb position then touched again at the end of the ROM to record the angles.

3. Statistics

Statistical analysis was performed using Stata v13. Tests for normality were run for both instruments, ROM data, and positions of testing. Appropriate assumptions of normality for statistical analyses were met. One-way Analysis of Variance (ANOVA) of repeated measures were used to assess differences between the MG and UG throughout the ROM seated and in supine. Pearson product-moment correlations were calculated at 95% confidence intervals (CI) to assess recorded measures from the smartphone MG application and the UG compared to the predetermined joint angles (that the examiners were blinded to) in both the seated and supine positions. The concordance correlation coefficient (CCC) along with the 95% confidence interval was used to assess the reliability of the UG and MG measurements within each examiner (four repeat measurements) and between the three examiners in the seated and supine positions (Lin, 1989). Agreement between the UG and MG measurements was assessed separately and overall. Scatter plots were used to assess agreement between UG and MG measures to a pre-determined joint angle of shoulder abduction in both the seated and supine measurements. Bland–Altman plots were used to investigate the existence of any systematic difference between the

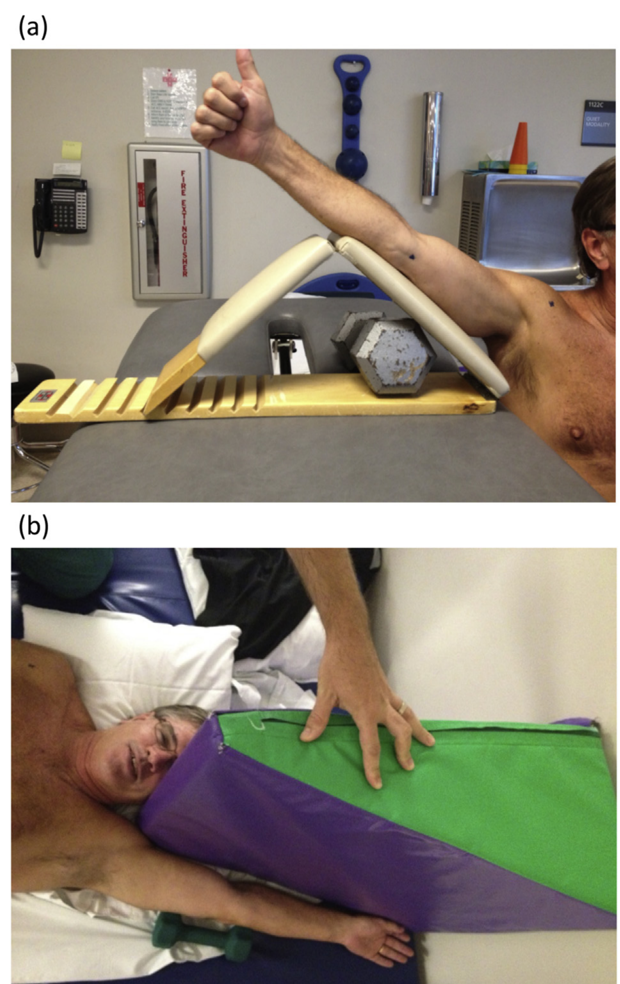

Fig. 2. Examples of how subject was statically positioned in seated (a) and supine (b).

measurements and to compute 95% limits of agreement for each comparison (Bland and Altman, 1986).

4. Results

Descriptive analysis and summary of data from both UG and MG are presented in Table 1. Overall, both instruments (UG and MG) were comparable in measurement error. The UG had an average standard deviation (SD) of ±4° in both seated and in supine positions. While the MG showed the least variability in seated positions with an average SD of ±2°, it also had the highest variability averaging ±7.5° in the supine position (Table 1).

As shown in Table 2, the intra-rater reliability of both UG and MG to measure the pre-determined shoulder abduction joint angle, as assessed by the CCC, was greater than 0.992 for all examiners (range 0.992–0.999), regardless of position or measurement method employed.

The inter-rater reliability among the three examiners was excellent as demonstrated by the very high correlation to the pre-determined ROM among the three examiners (Table 3).

The inter-rater CCCs of the UG-measured ROM were highly correlated with the pre-determined ROM values in both the seated (CCC = 0.991) and supine positions (CCC = 0.997). Similarly, the CCCs of the smartphone MG-measured ROM were highly correlated with the pre-determined ROM values in both the seated (CCC = 0.995) and supine positions (CCC = 0.989). As shown in Figs. 3 and 4, there was a strong agreement between the MG and UG measurements in both the seated position (CCC = 0.989; CI = 0.976–0.995) and supine position (CCC = 0.992; CI = 0.978–0.997). The overall CCC between the two measures regardless whether the measurement was obtained seated or supine was 0.991 (0.978–0.996).

Bland–Altman plots (Figs. 5 and 6) showed high agreement between the measurements by the two devices and the pre-determined joint angle in both seated and supine positions, with most values falling within 95% confidence interval.

For the seated position Bland–Altman plot, the mean difference between UG and MG measured angles and the pre-determined angles is −1.7 and the confidence interval = 1.96 × SD = 6.63.

For the supine measurement Bland–Altman plot, the mean difference between the UG and MG measured angles and the pre-determined angles is 1.4 and the confidence interval = 1.96 × SD = 13.4.

Table 2
Intra-rater reliability. CCCs as well as upper and lower 95% confidence intervals were used to determine the reliability of each examiner using the UG and MG to measure the pre-determined joint angles in both the seated and supine positions.

Examiner	Measurement method	CCC	Lower 95% CI	Upper 95% CI
1	UG seated	0.999	0.997	0.999
2	UG seated	0.999	0.989	0.999
3	UG seated	0.997	0.989	0.999
1	MG seated	0.998	0.991	0.999
2	MG seated	0.998	0.993	0.999
3	MG seated	0.999	0.995	0.999
1	UG supine	0.999	0.998	0.999
2	UG Supine	0.999	0.995	0.999
3	UG supine	0.999	0.997	0.999
1	MG supine	0.998	0.989	0.999
2	MG supine	0.992	0.967	0.998
3	MG supine	0.998	0.999	0.999

5. Discussion

With exciting opportunities for integration of smartphone-based applications in physical therapy, it is important to assess the reliability and validity of these applications prior to clinical use. Review of the literature shows relatively few systematic evaluations that provide reliability and validity data regarding these newly-developed technologies. This study sought to determine if the use of an MG application using the phone's built-in magnetometer was a valid and reliable tool when compared to the currently used standard method, UG. The high overall concordance correlation coefficients show that the developed MG application is both valid and reliable when measuring both vertical axis (seated), and horizontal axis (supine) passive abduction ROM in shoulder in evaluators with different levels of experience using the MG application.

This is the one of the first studies to evaluate an innovative MG application using built-in magnetometer-sensor technology as applied to measuring joint ROM. Other studies in the literature have used accelerometer-based devices as well as the inclinometer and/or accelerometer/trigonometric estimation to measure movement (Kolber and Hanney, 2012; Ockendon and Gilbert, 2012; Shin et al., 2012; Werner et al., 2013; Milanese et al., 2014). These applications assessed positional data by different methods to determine the angle and may not necessarily be comparable or show

Table 1
Summary of measured angle data.

	Position	Location	Pre-determined joint angle (°)	Mean measured angle (°) ± SD			Total (°) ± SD
				Examiner 1 (n = 4)	Examiner 2 (n = 4)	Examiner 3 (n = 4)	
UG	Seated	1	105	105 ± 1	105 ± 1	98 ± 1	103 ± 4
		2	92	94 ± 1	94 ± 1	91 ± 2	93 ± 2
		3	40	41 ± 1	35 ± 1	38 ± 1	38 ± 3
		4	122	122 ± 1	115 ± 2	115 ± 2	117 ± 4
	Supine	1	35	35 ± 2	37 ± 1	35 ± 1	36 ± 2
		2	150	151 ± 2	152 ± 2	152 ± 1	152 ± 2
		3	58	58 ± 1	57 ± 3	69 ± 1	61 ± 6
		4	170	162 ± 1	165 ± 1	166 ± 2	164 ± 2
MG	Seated	1	105	106 ± 2	101 ± 2	106 ± 1	104 ± 3
		2	92	91 ± 1	93 ± 1	92 ± 6	92 ± 1
		3	40	37 ± 1	34 ± 2	34 ± 2	35 ± 2
		4	122	123 ± 1	123 ± 2	125 ± 1	124 ± 2
	Supine	1	35	35 ± 3	35 ± 2	32 ± 2	34 ± 3
		2	150	129 ± 2	151 ± 8	151 ± 5	143 ± 12
		3	58	48 ± 2	62 ± 7	69 ± 5	60 ± 10
		4	170	161 ± 3	169 ± 6	166 ± 4	165 ± 5

SD = standard deviation; n = sample size/number of trials.

Table 3
Inter-rater reliability. CCCs as well as upper and lower 95% confidence intervals were used to determine the reliability of the UG and the MG measured angles against the standardized, pre-determined angles.

Measurement device	Measurement position	CCC	Lower 95% CI	Upper 95% CI
UG	Seated	0.991	0.972	0.997
UG	Supine	0.997	0.991	0.999
MG	Seated	0.995	0.99	0.998
MG	Supine	0.989	0.966	0.997

similar results. The MG application in this study primarily used the phone's native, built-in magnetometer which is unique and contrasts distinctly from an accelerometer based application. A magnetometer provides a more versatile and robust method to measure ROM, allowing for measurements to be taken in both the horizontal and vertical planes as well as being less prone to motion artifact.

The study showed high reliability between the UG and the MG. Variability of measured angles between raters averaged ±4° for both the UG and MG in the vertical axis (seated), while the MG had greater variability on average of ±7.5° in the horizontal axis (supine). Both values are comparable to the variability shown in recent published studies investigating the reliability of the standard goniometer with shoulder flexion and abduction (Hayes et al., 2001; El-Zayat et al., 2011; Kolber and Hanney, 2012; El-Zayat et al., 2013). One possible explanation for the difference in variation from the vertical axis and horizontal axis may be due to the technology the application uses in determining angles in horizontal versus vertical plane, and the necessity of calibrating in the horizontal (supine) orientation. Further exploration in this area is needed.

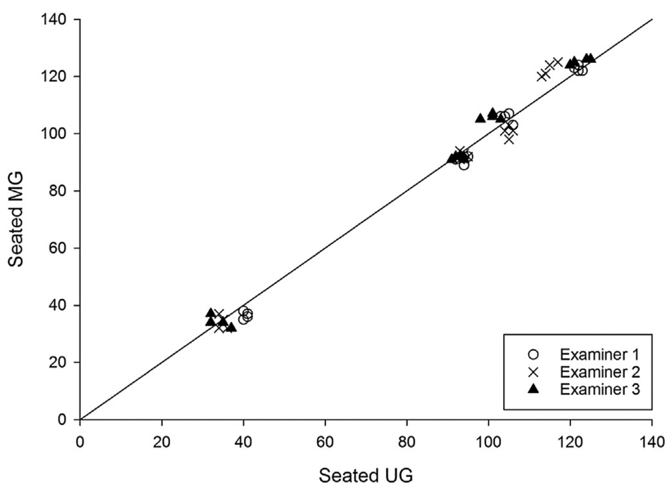

Fig. 3. Agreement between UG and MG measured shoulder abduction joint angle (degrees) in seated position; solid line = line of identity (CCC = 0.989; CI = 0.976–0.995).

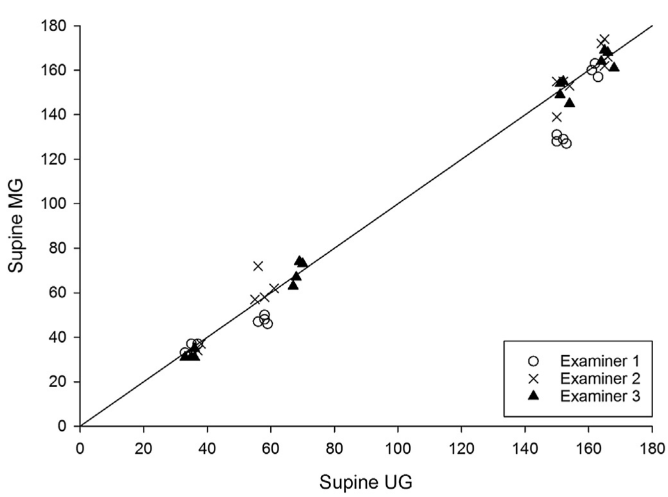

Fig. 4. Agreement between UG and MG measured shoulder abduction joint angle (degrees) in supine position; solid line = line of identity (CCC = 0.992; CI = 0.978–0.997).

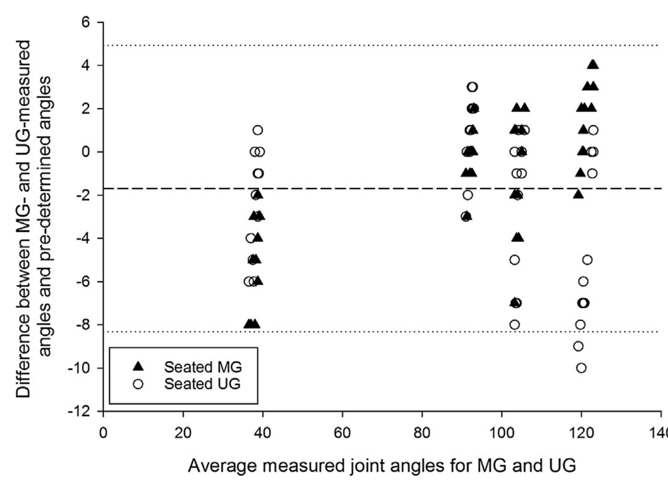

Fig. 5. Bland–Altman plot of differences between measured angles and pre-determined joint angles in the seated position (x-axis: average measurement trial angles and y-axis: difference in angles).

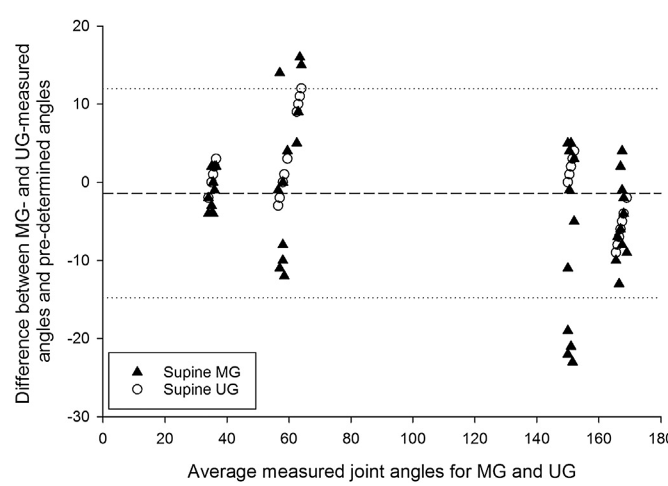

Fig. 6. Bland–Altman plot of differences between measured angles and pre-determined joint angles in the supine position (x-axis: average measurement trial angles and y-axis: difference in angles).

The findings from this study are encouraging for further development in this rapidly burgeoning area of digital health technologies. The limitations of this pilot study, including single subject design and single plane of motion warrant further research of this novel technology. Therefore, future research should focus on the use of a magnetometer-based smartphone goniometric application with other joints and positions, measurement of active versus passive ROM, and studies that include participants with dysfunction or pathology versus healthy subjects. Further research and education in calibration must be included for applications based on magnetic orientation sensors.

6. Conclusion

This study demonstrates the validity of the smartphone goniometer application utilizing a built-in 3 axis magnetometer sensor when compared against a previously-proven and universal goniometer. The MG also demonstrates comparably high reliability in measuring passive shoulder abduction ROM in both the seated and supine positions. These results suggest the newly developed MG application shows potential as a useful tool to assess joint angles in vertical and horizontal orientations.

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