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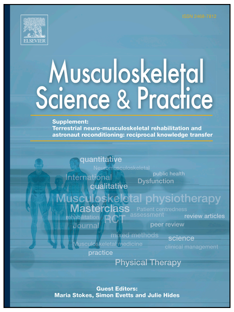

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ASSESSMENT OF RANGE AND QUALITY OF NECK MOVEMENT USING A SMARTPHONE-BASED APPLICATION

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Abstract

This study had the objective of measuring the validity of using a smartphone-based application to measure range of motion (ROM) and quality of movement (QOM) of neck motion by comparing it with 3D-motion capture analysis.

Methods: Thirty healthy volunteers participated in this cross-sectional study. A helmet fitted with markers for motion capture analysis and a smartphone were fastened to the head of the participants. The smartphone recorded data using a beta version of Balancy (*MEDEI, Denmark*). Assessments of full active movement in transverse and sagittal planes were performed. Recordings were made simultaneously with the camera system and the smartphone. ROM and jerkiness were compared with a repeated measures ANOVA and a Pearson product moment was calculated to compare the outcomes from the different applications. Bland-Altman plots were generated to determine the levels of agreement.

Results: No difference was found between modalities when comparing measurements of jerkiness or ROM. An excellent Pearson product moment was found for the outcomes of the two modalities for ROM *(Pearson's r: 0.83 - 0.96)* and jerkiness *(Pearson's r: 0.86 – 0.95).* The Bland-Altman plot revealed a systemic offset where the phone consistently measured higher values for ROM and lower values for jerkiness.

Conclusions: This study demonstrated that a smartphone-based application can be used to accurately measure ROM and jerkiness during neck movements. These results indicate the utility of using a smartphone-based application to assess neck movement in humans. The findings have implications for assessment of neck movement in research and clinical practice.

Introduction

Neck pain is a common problem which has grown to become one of the biggest reasons for years lived with disability worldwide (Hoy et al., 2014). It is well documented that pain may alter cervical motor control strategies in an otherwise healthy cohort (Christensen et al., 2017, Gizzi et al., 2015, Malmstrom et al., 2013) towards what is seen in clinical populations (Falla et al., 2010, Lindstrom et al., 2011, Treleaven et al., 2016); adaptions that might become one of the underlying drivers of persistent pain conditions (Hodges and Tucker, 2011). Capturing such strategies may therefore be a helpful guide for diagnostic purposes and thereby for clinical decision-making and useful for evaluating the effect of a rehabilitation intervention.

In research, different modalities have been used to assess neck movement, with the gold-standard being considered 3D motion capture analysis (Inokuchi et al., 2015). Applying such methods in clinical practice is however not feasible considering their cost, the necessary technical expertise and the time required for setup. In this regard, it is worth considering that smartphones include devices (gyroscopes, accelerometers, magnetometers) that can be used to record clinically relevant variables. In fact, existing evidence shows that smartphone-based technology demonstrates moderate to excellent accuracy when measuring active range of neck motion (ROM) when compared with a Cervical Range of Motion (CROM) device acting as gold standard (Quek et al., 2014). However, reductions in range of motion are only one of many sensory-motor disturbances contributing to the overall disability. Proprioceptive disturbance resulting in reduced quality of movement (movement jerk i.e. changes in acceleration)(Grip et al., 2007) and poorer repositioning sense (Stanton et al., 2016) also seems to contribute to the clinical picture. Developing assessment methods that are inexpensive and user-friendly but are able to detect small, but clinically relevant discrepancies in sensory-motor function during movement is therefore warranted.

The purpose of this study was to investigate the measurement accuracy of a smartphone-based assessment of neck ROM and quality of movement (QOM). The overall hypothesis were that smartphone-based measurements of neck movement would demonstrate good to excellent agreement for both ROM and QOM.

Methods

Thirty healthy individuals (11 females; age 27 (range 21-37), height 174.4cm (SD 9.3) and weight 72.8kg (SD 15.3)) with full, pain-free neck and shoulder range of motion were randomly chosen from a university population and included in this single-session, cross-sectional study. The protocol adhered to the Helsinki declaration and was approved by the regional ethics committee.

Experimental setup

The subjects were seated with a helmet on their head (fig. 1). The straps on the helmet (around the head and under the chin) were tightened securely to minimize accessory movement of the helmet. The smartphone was placed in a holster which was securely fastened to a wooden plate attached to the apex of the helmet. The overall weight of the experimental equipment (helmet, phone, wooden plate, and 3D markers) was 689g. During data collection, subjects were instructed to move the head as far as they were comfortable with into right rotation, left rotation, extension and flexion (in this order) at a self-selected pace and stop there. Here, recording was stopped and the data was stored. The average of three movements in each direction was extracted for data analysis. For blinding purposes, raw values were automatically stored on the phone and the computer and were unavailable to the assessor and participant until after the data collection.

Assessment of range of motion

Two clusters with 3 markers were attached to the helmet (fig. 1). The markers' positions were sampled at 50Hz (*Optotrak, Ontario, Canada*). Subjects sat in an oblique angle to the camera system to ensure that at least one cluster marker was visible throughout the movement into each direction.

A smartphone (*iPhone 6*, *Apple Inc.*) was used to record angular changes in the pitch (X), roll (Y) and yaw (Z) axes during the head movement. Data was recorded (sampling rate 50Hz) using a beta version of Balancy (*MEDEI, Aalborg, Denmark*) which was later analyzed using a custom-made matlab script *(MATLAB 2017b, The MathWorks, USA)*. As recordings were performed simultaneously, no effort was made to control the movement around a fixed axis.

Signal processing

For the smartphone, data from the Z-axis were used to quantify the head/neck motion during rotation while data from the X-axis was used for head flexion/extension movements. Neutral neck position was defined as the average value of Z- and X-axes during the initial 25 frames (from starting the camera but before any movement occurred). The Z-, Y- and X-axes during movement were subtracted from their respective angle obtained at the neutral neck position. A similar procedure was used for the camera data (details below). Both systems (smartphone and camera) were thereby aligned and started at zero degrees.

For rotation, the two top markers on the forehead-cluster were used but the bottom two markers from the side-cluster on the helmet were used for flexion/extension. The average vector position for both markers was calculated using the 10th frame (prior to initiation of movement). Neutral neck position was defined as the difference between both original vectors (3x1 vector). The same calculation was performed during movements, resulting in a second vector (3xN vector (N= the length of the data collection)) representing the neck position over time. Finally, the arctangent between neutral neck position and neck position over time vectors were calculated and defined as the angular position.

All signal processing were performed in the same way for both systems in Matlab. Data for angular position were filtered with a low-pass butterworth digital filter (zero lag, 1.5Hz, 4th order). Angular velocity, acceleration and the jerk over time was obtained by sequential derivatives. All data were trimmed between the start and end of movement (automatically detected by evaluating both the angular position and velocity for each trial). ROM was defined as the angular position range between start and end of movement. QOM was defined as the variance of the angular jerk between start and end of the movement. An example of the start and stop of movement can be seen in figure 2.

Statistics

Data were assessed for normality using the Shapiro-Wilk test. Outcomes from the two modalities were compared using a mixed model ANOVA where modality (smartphone or 3D camera system) was set as independent factor. Criterion-related validity of the smartphone compared to the camera system was determined by calculating a Pearson-Product moment for each movement direction. A Bonferroni correction was applied to account for the repetitive nature of the correlation analyses.

Measurement agreement between the two devices was visually inspected with Bland-Altman plots and the bias (difference between measurement methods where 0 = no difference) was calculated using a one-sample t-test. A Bonferroni correction was applied to account for multiple pairwise comparisons.

Results

One subject (male) had incomplete data from the camera and was therefore not included in the analysis. ROM data was normally distributed but QOM became normally distributed following a log-transformation of raw data. Log-transformed data was used to simplify the reporting of findings. For participant demographics, see table 1.

No significant difference between the two modalities was found in any direction with regards to ROM (ANOVA: F(3,2)=0.22, *P*>0.88) or QOM as an estimate of the variance of jerk (ANOVA: F(3,2)=0.08, *P*>0.97, fig. 3). For ROM, excellent correlations were demonstrated between the two modalities with correlations ranging between 0.83-0.96 (*P*<0.05, table 2). For QOM, correlation coefficients lay between 0.92–0.97 (*P*<0.05, table 2).

According to the Bland-Altman plots, the smartphone systematically measured a greater ROM than the camera system and systematically lower QOM for all directions (except flexion; table 2 and fig. 4).

Discussion

This study investigated the accuracy of a smartphone-based application for measuring ROM and QOM compared with a gold-standard. The overall findings indicate that measurements with the two modalities are comparable. The method and future perspectives will be discussed in the following.

Smartphone-based assessment of neck movement

Considerable focus has been on utilizing Smartpone-based applications for measuring neck ROM where recent studies have collectively demonstrated that this is a feasible option (Quek et al., 2014, Stenneberg et al., 2018, Tousignant-Laflamme et al., 2013, Ullucci et al., 2018). This current study however, used a smartphone to measure the quality of movement in terms by focusing on changes in acceleration. Considering that clinical groups only present with small discrepancies in sensory-motor function compared with controls (Stanton et al., 2016), calls for methods that can measure these more precicely in the clinic.

This study showed higher correlation coefficients for neck ROM measured with the two devices (table 1) than previous studies with similar aims (Quek et al., 2014, Tousignant-Laflamme et al., 2013). These studies however, used the CROM device (Audette et al., 2010) as gold-standard which uses an analogue scale to present movement the ROM. This may explain the superior outcome seen here. Interestingly, a significant measurement overshoot was seen for ROM in the smartphone and an undershoot for jerkiness (fig. 4). Importantly however, these differences fall within what has been considered minimal detectable change when comparing measurements of neck ROM between two devices (Audette et al., 2010). Moreover, these differences are far below what is detectable with the naked eye, regardless of level of training (Hirsch et al., 2014). Lastly, the systematic nature of the bias (fig. 4) and the strong correlation (table 2) indicate that using the smartphone could be useful in measuring changes in neck ROM and QOM as the two divices seem to detect change in position and movement similarly.

Methodologic considerations and limitations

This study only recruited healthy subjects to reduce the likelihood of factors such as pain or pain-related fear of movement possibly affecting the measurements. Further studies need to replicate this setup in a clinical population where focus should not only be on the accuracy of measurements but also on the feasibility of using the device.

The movement directions were not randomized and the participants did not perform any warm-up prior to data collection. Considering the purpose of this study however, it was not considered to have an effect on the outcome as measurements were performed simultaneously on both devices.

Assessment of reliability was not considered important here, mainly for two reasons. First of all, two technical devices were used for data acquisition and a MatLab-based script was used to automatically extract data. Second, it is known that healthy subjects demonstrate significant variability in neck ROM when assessed over time (Assink et al., 2008, Koerhuis et al., 2003) with patients demonstrating even a greater variability (Bergman et al., 2005). On the same note, the relevance of trying to accurately reproduce measurement findings between sessions is questionable given these natural fluctuations and the expectation that any given treatment intervention is, in fact, intended to improve pain-free neck movement (Jull et al., 2007).

The smartphone was stored on a helmet sitting on the subject’s head. This is relevant considering the weight of the helmet and the smartphone, especially for sagittal plane movements where the added mass would act as an extra weight. This is an important factor to consider, especially concerning the use of this method in clinical practice. The added weight will inevitably affect the movement (both quality and range), especially in clinical populations where poor motor control may be a feature of the clinical picture. Different methods need to be developed for quick and easy placement of a measurement device, with smaller overall weight, without compromising measurement accuracy and reproducibility.

Neck movement consists of reciprocal movement coupling where e.g. rotation does not occur without being coupled with lateral flexion to the same side (Bogduk and Mercer, 2000, Ishii et al., 2004). Constraining the subject to perform *´true´* movement into each direction (Grip et al., 2007, Quek et al., 2014) may indeed provide actual measures of movement. The clinical value of such an assessment is however questionable as it constrains movement to a predefined pattern instead of what comes naturally to the subject. Accurately determining each component of the movement (movement coupling) was not possible using the current method as both ROM and QOM were determined by calculating an average vector based on the X, Y and Z-axes. However, considering that healthy indiviuals present large variability in inter-segmental neck ROM (Anderst et al., 2015, Frobin et al., 2002) such an assessment would probably be redundant.

Conclusion

This study investigated the accuracy of smartphone-based measurements of neck ROM and QOM in healthy individuals. The results indicate an excellent agreement using the two methods, suggesting their feasibility in experimental and clinical settings. The novelty of this study pertains to the assessment of QOM. The findings indicate that smartphone-based technology is a feasible option for assessing neck movement and warrants further investigation of other aspects of neck movements using this technology.

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Figures legends

Figure 1. Experimental setup. Subject was seated in a chair with a helmet fitted to the subjects' head and fastened with a strap under the chin. The smartphone was securely fastened on a wooden plate mounted on the top of the helmet.

Figure 2. Example of how raw data from smartphone (dark line) and 3D camera system (faded line) appeared. The current example shows the beginning and end of rotation to the right in one subject

which was automatically detected by evaluating the angular position and velocity for each trial**.** The data are presented as a percentage (%) of the movement cycle for position (A), velocity (B), acceleration (C) and jerk (D).

Figure 3. Mean (SD) Range of motion (A) and quality of movement (B) using the smartphone (empty bars) and camera system (black bars). The camera consistently measured lower values than the smartphone for range of motion but higher values for the quality of movement. None of these differences were significant.

Figure 4. Bland-Altman plots for showing the limits of agreement for range of motion (ROM) (A-D) and jerkiness (E-H). Data is based on raw values for ROM and on log-transposed data for jerkiness. The unbroken line indicates the mean bias and the broken lines indicate the upper and lower limits of agreement.

Table 1

	Mean age in years (range)	Mean height in cm (SD)	Mean weight in kg (SD)
Males	28 (22-37)	178.9 (8.1)	80.4 (14.1)
Females	25 (21 – 29)	169.9 (6.7)	60.3 (6.1)
Total	27 (21-37)	174.7 (9.3)	72.8 (15.3)

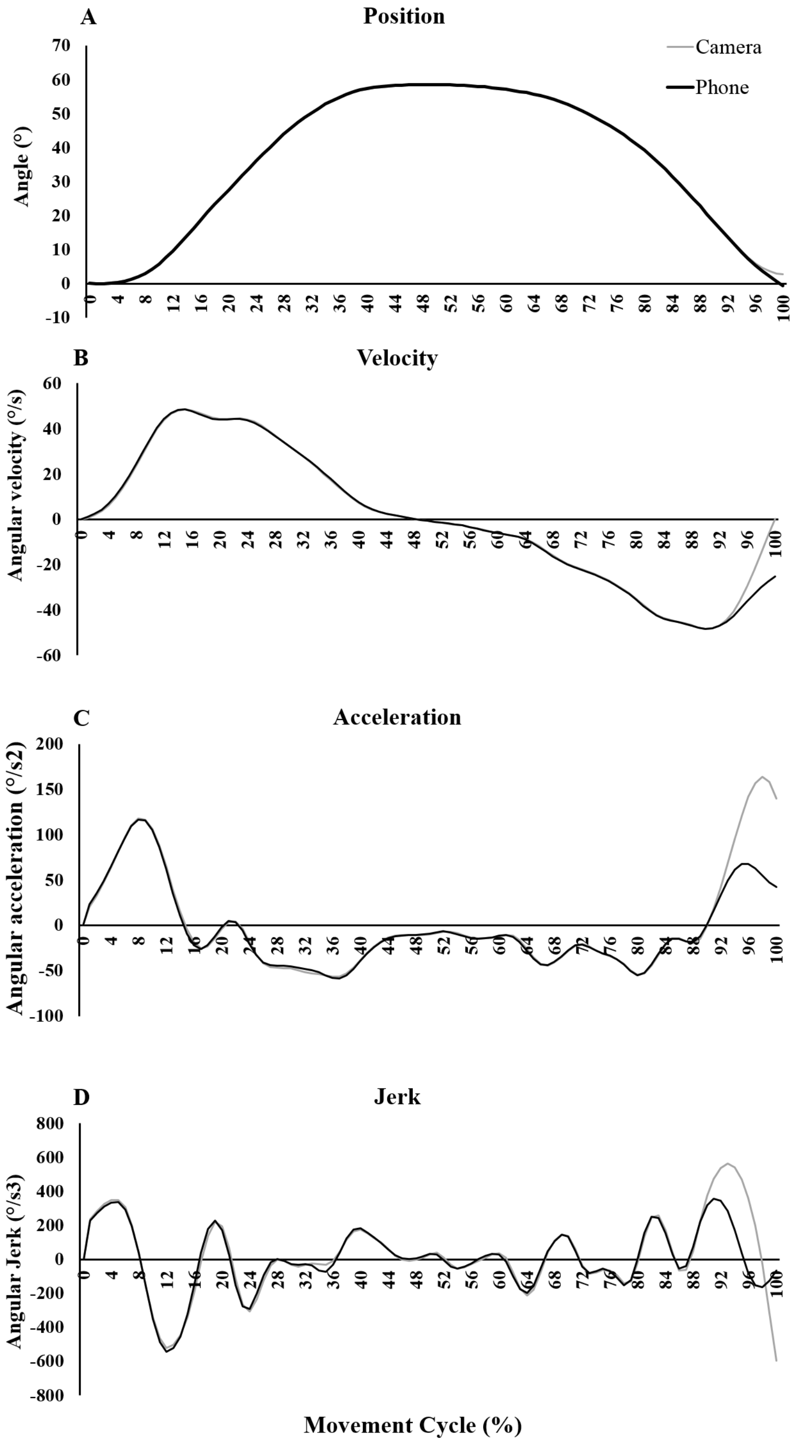
Table 1 Demographic information of participants. Data are presented as mean and range (for age) or SD for height and weight for males and females separately and as pooled data.

Range of motion (degrees)						
	Mean bias*	**SD**	**LoA****	**P – value**	**Pearson's r**	**P – value**
Rotation Right	4.3	3.0	(-3.1) – (10.1)	< 0.0001	0.96	< 0.0001
Rotation Left	4.1	3.2	(-2.1) – (10.3)	< 0.0001	0.95	< 0.0001
Extension	5.2	4.7	(-4.0) – (14.3)	< 0.0001	0.82	< 0.0001
Flexion	6.2	3.8	(-1.2) – (13.6)	< 0.0001	0.84	< 0.0001
Jerkiness						
Rotation Right	-0.10	0.16	(-0.42) – (0.22)	< 0.02	0.97	< 0.0001
Rotation Left	-0.06	0.09	(-0.24) – (0.12)	< 0.004	0.94	< 0.0001
Extension	-0.09	0.09	(-0.28) – (0.09)	< 0.0001	0.92	< 0.0001
Flexion	-0.04	0.10	(-0.24) – (-0.16)	< 0.12	0.96	< 0.0001

Table 2 *Bias (difference in measurement with smartphone and 3D camera system) and correlation coefficients for range of motion (above) and jerkiness (below). Compared with the 3D camera system, the smartphone systematically measured greater level of movement than the camera system and smaller jerkiness (except for flexion). All P-values are Bonferroni corrected.*

** For ROM the mean bias is indicated in degrees but for Jerkiness it is indicated in LogDegrees/s*^{3}

***Limits of agreement (lower) – (upper)*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Position
Camera
Phone
Angle (°)
70
60
50
40
30
20
10
0
-10
0 4 8 12 16 20 24 28 32 36 40 44 48 52 56 60 64 68 72 76 80 84 88 92 96 100
B
Velocity
Angular velocity (°/s)
60
40
20
0
-20
-40
-60
0 4 8 12 16 20 24 28 32 36 40 44 48 52 56 60 64 68 72 76 80 84 88 92 96 100
C
Acceleration
Angular acceleration (°/s2)
200
150
100
50
0
-50
-100
0 4 8 12 16 20 24 28 32 36 40 44 48 52 56 60 64 68 72 76 80 84 88 92 96 100
D
Jerk
Angular Jerk (°/s3)
800
600
400
200
0
-200
-400
-600
-800
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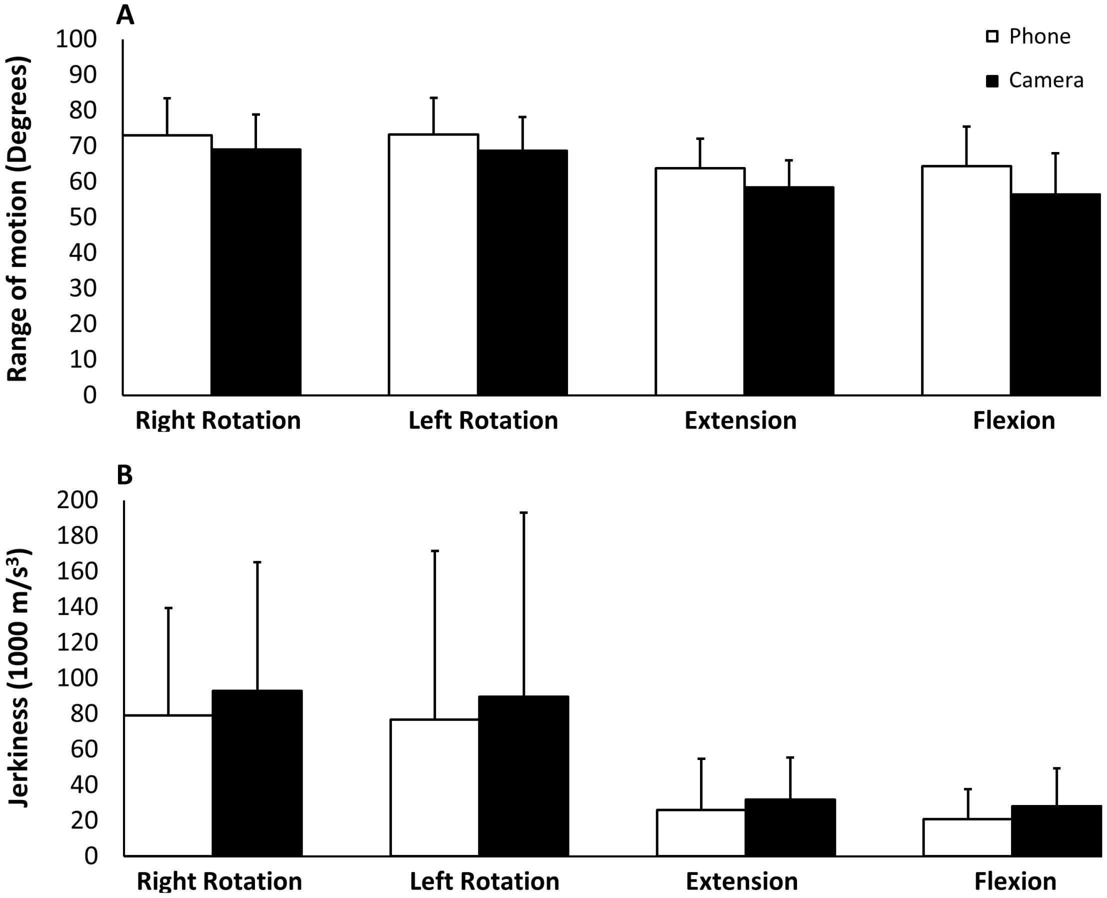
Movement Cycle (%)


A
Range of motion (Degrees)
100
90
80
70
60
50
40
30
20
10
0
□ Phone
■ Camera
Right Rotation
Left Rotation
Extension
Flexion
B
Jerkiness (1000 m/s³)
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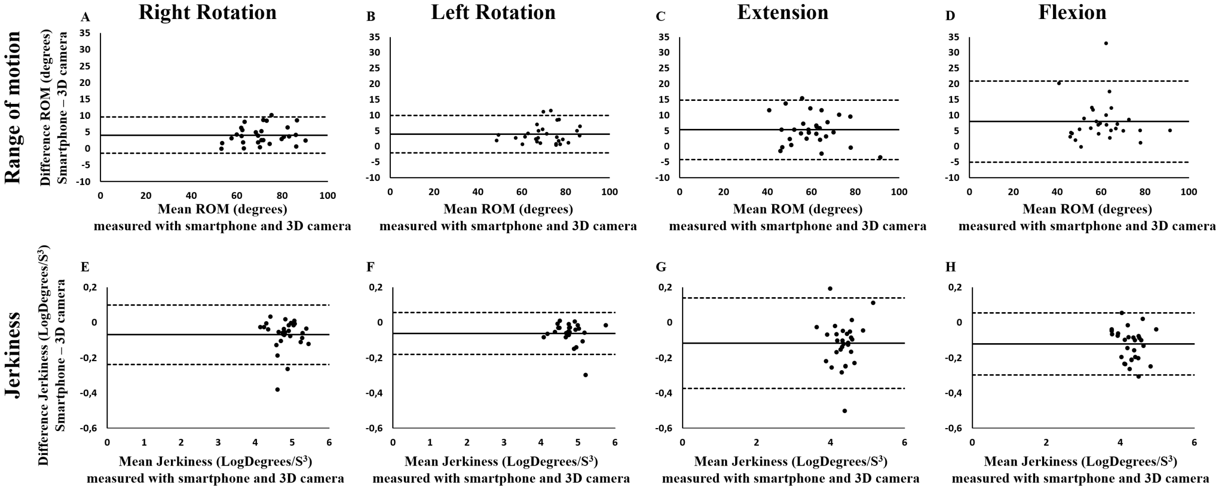
180
160
140
120
100
80
60
40
20
0
Right Rotation
Left Rotation
Extension
Flexion


Range of motion
Jerkiness
A
Right Rotation
B
Left Rotation
C
Extension
D
Flexion
Difference ROM (degrees)
Smartphone – 3D camera
35
30
25
20
15
10
5
0
-5
-10
0
20
40
60
80
100
Mean ROM (degrees)
measured with smartphone and 3D camera
E
F
G
H
Difference Jerkiness (LogDegrees/S³)
Smartphone – 3D camera
0,2
0
-0,2
-0,4
-0,6
0
1
2
3
4
5
6
Mean Jerkiness (LogDegrees/S³)
measured with smartphone and 3D camera