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The concurrent validity and reliability of virtual reality to measure shoulder flexion and scaption range of motion

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Abstract

Background Shoulder pain commonly has a detrimental impact on patient's work and social activities. Although pain is the most common reason for seeking care, a reduction in shoulder range of motion (ROM) is another common impairment. ROM assessment is used as an evaluation tool and multiple methods are available to measure shoulder ROM. Virtual reality (VR) has been introduced into shoulder rehabilitation, mostly when exercise and ROM measurement is indicated. This study evaluated the concurrent validity and system reliability of active ROM measurements of VR for people with and without shoulder pain.

Methods Forty volunteers participated in this study. Virtual goniometry was used to assess active shoulder ROM. Participants performed flexion and scaption to six predetermined angles. Measurements from the VR goniometer and smartphone inclinometers were recorded simultaneously. To assess reliability, two identical test sequences were performed.

Results The concurrent validity ICCs were 0.93 for shoulder flexion and 0.94 for shoulder scaption. The VR goniometer application on average systematically overestimated the ROM compared to the smartphone inclinometer. The mean difference between goniometer values was -11.3 degrees for flexion and -10.9 for scaption. The system reliability was excellent with an overall ICC of 0.99 for the flexion movements and 0.99 for the scaption movements.

Conclusion Although the VR system demonstrated excellent reliability, and high ICC's for concurrent validity, the large range between the lower and upper 95% CI limits suggests it lacks measurement precision. This suggests VR, as used in this study, should not be used interchangeably with other measurement tools.

Contribution of the paper

- Virtual reality is a relatively new technology that is being increasingly adopted in clinical practice including the assessment and treatment of people with shoulder pain.
- Virtual reality can support the growing demand for improved efficacy and efficiency of healthcare delivery by enabling physiotherapy assessment and treatment of patients via tele-health services.
- The VR system (hardware and software) tested in this study demonstrated excellent reliability and excellent concurrent validity, however, the wide limits of agreement associated with the VR system suggest that the current VR system should not be used interchangeably with digital inclinometry.

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Keywords: Virtual reality; Range of motion; Shoulder; Validity; Software reliability

Introduction

As a group of conditions, musculoskeletal disorders are responsible for the longest number of years lived with disability [1]. Within this group of conditions, musculoskeletal shoulder problems are a common pain condition. Between 4% and 47% of the population experience shoulder pain during a one-year period and more than 30% of people over the age of 65 years experience shoulder pain on a daily basis [2]. As the shoulder contributes to a range of activities such as pushing, pulling, lifting, carrying, throwing, and placing, any loss of shoulder function is associated with a substantial impact on daily functioning. The assessment of shoulder range of motion (ROM) is therefore considered as a crucial part of the clinical examination. It plays an important role in establishing hypotheses about the origin of the symptoms and informs the clinician in his decision making process [3]. ROM measurements are also critical for providing baseline data, determining functional limitations, and monitoring changes in movement following treatment [4,5]. Also, randomized clinical trials evaluating the effects of exercise therapy in individuals with persistent shoulder pain universally include ROM measurements as an important outcome measure [6–9]. There are multiple measurement tools available to assess shoulder range of movement, which include simple visual estimation, analogue and digital goniometry, analogue and digital inclinometers, smartphone applications and other devices such as three-dimensional (3D) gyroscopes or markerless motion capture systems [10–15]. To date, the reference standard for measuring ROM of shoulder joints in clinical practice is the analogue universal goniometer. This instrument has been widely used due to its low costs and easy accessibility. However, several authors emphasize the increased risk of error of measurement while using both hands to stabilize the goniometer and the humerus making it difficult to keep the goniometer in place, on the correct bony landmarks and reading the instrument [16,17]. Since their introduction, and due to their ease and quickness of use, digital inclinometers such as smartphone inclinometer applications have become widely incorporated into clinical and research practice. They have been reported as reliable and valid tools to assess musculoskeletal shoulder range of motion in healthy controls and shoulder patients. [11,15,16,18–20]. The incorporation of new technologies to support telerehabilitation in response to the Sars-Cov-2 (Covid 19) pandemic, has necessitated greater reliance on measurement tools such as smartphone applications and in some cases, virtual reality [21]. Virtual reality (VR) has

been introduced into clinical practice as a measuring and rehabilitation device for a number of musculoskeletal health conditions [21,22]. It places an individual in a computer-generated environment. VR has many potential advantages and may support clinical practice. The technology is capable of assessing shoulder ROM, either retrospectively (by recording the movements), in real time, in the clinic, and remotely via tele-health applications. This facilitates self-assessment of shoulder ROM at home and means patients do not need to travel to the clinic for short consultations. Given the increased use of VR in musculoskeletal rehabilitation and its potential for measuring ROM outcomes remotely at home, there is a need to establish the clinimetric properties such as concurrent validity and reliability of VR as measurement device for assessing ROM. The main aim of this study was to evaluate the concurrent validity of the VR device to measure active shoulder flexion and scaption by comparing the ROM for shoulder flexion and scaption obtained by a VR goniometer with the measurements obtained using a smartphone inclinometer. Secondly, to evaluate the system reliability of the VR device by calculating the ICC's of its ROM measurements between the first and second testing sequence.

Materials and methods

Participants

A convenience sample of 20 people without shoulder pain and 20 people diagnosed with rotator cuff related shoulder pain (RCRSP) [23] were recruited between December 2020 and March 2021. The healthy volunteers were identified from the researchers' social networks. They were eligible for participation if they were over the age of 18 years, had no comorbidities such as systemic or neurological diseases, had no movement restrictions in their cervical and shoulder region and had not received any treatment to the neck or shoulder in the preceding 12 months. The participants with shoulder pain were recruited from a Sports Medical Centre, in Arnhem, the Netherlands. They were eligible for participation if they were over the age of 18 years and had had at least three months of unilateral RCRSP. The latter was confirmed by the presence of a minimum of three out of the following five criteria: i) pain during active shoulder flexion and/or abduction, ii) pain during active or resisted shoulder external rotation, iii) near normal passive range of shoulder flexion, abduction and external rotation, iv) a positive self-administered empty can test or v) a painful arc of shoulder abduction. Patients were excluded from participation if they had clinical signs of massive rotator cuff

tears as defined by presence of gross weakness of rotator cuff muscles in the absence of pain, or if they had adhesive capsulitis, osteoarthritis, fracture, acromioclavicular joint pathology, history of fractures or surgery to the cervical and shoulder regions. Patients with current pain in the cervical region, the presence of significant comorbidities such as systemic diseases or neurological diseases, shoulder external rotation less than 45 degrees and/or a 50% restriction of external rotation compared to the contralateral side were also excluded. All participants were required to be able to read, write, and speak the Dutch language.

Ethical approval: The study was approved by the HAN University of Applied Sciences Nijmegen Ethics Committee (approval number ECO 198.10/20). All subjects gave written informed consent. The reporting guideline GRRAS [25] has been followed when reporting this research article.

Materials

An Oculus Quest head mounted display (Facebook Technologies, LLC.) loaded with a custom built virtual goniometer developed by Karuna labs (Karuna labs, San Francisco, CA, USA) was used for the validity and reliability studies. The software projects a virtual goniometer on a virtual background with a vertical reference line with angular markings depicted on a line (Fig. 1). While holding and moving the handcontrollers the virtual goniometer becomes visible. Two Apple iPhone™ 7 Series smartphones



Fig. 1. A screen image produced by the VR software projecting avatars and a vertical reference line.

loaded with GetMyROM software (version 1.1; Interactive Medical Productions LLC, Hampton, NH, USA) were used as digital inclinometers for the smartphone measurements.

Methods

Concurrent validity

During all measurements, a safe environment was created to ensure the participants safety. This is necessary when using VR as the real world is obscured from the user. Participants were allowed to move freely within the safe environment and instructed not to move outside of it. Participants were then asked to stand in a consistent position (marked by removable tape on the floor) and to remain at this position during all measurements. The two smartphones were placed in a smartphone holder and attached to the distal part of both the left and right upper arms (3 cm above the lateral epicondyle). Participants were then shown the VR head mounted display (HMD) and hand controllers. The investigator then explained how to wear the HMD and hold and use the hand controllers. They were also instructed how to access the shoulder range of motion measurement program within the virtual environment and how to interact with the virtual environment. Once familiar with the hand controllers and the VR system, participants started using the program. Within the application, participants were asked to perform active shoulder flexion and scaption (elevation in the plane of the scapula). To perform these movements the participants mimicked the movements performed by an avatar within the virtual environment. When moving the arm, the participants were able to use a virtual vertical reference line to guide their movements. This reference line had angular markings and ranged between 0° and 150°. The system did not allow for measurements of hand behind the back or shoulder external rotation and these were not tested. Shoulder flexion and scaption measurements followed a randomized testing sequence generated using www.random.org software. Specific predetermined angles (Table 1) were chosen to compare the digital inclinometer and VR software measurements to investigate low, mid-range, and higher ranges of motion. At the time this study was designed and conducted, one of the most advanced VR head mounted display (HMD) was used. However, the built-in cameras of the HMD were not able to capture angles above 150 degrees, therefore, pre-determined angles up to 140 degrees of flexion and scaption were chosen. All shoulder ROM measurements were repeated four times. The measurements for left and right arm for flexion and scaption took approximately 10 min. Following the first testing sequence, the participants were invited to rest for 15 min while moving around freely and enjoying refreshments. Fifteen minute rest periods have been used in other studies assessing shoulder movement reliability [24]. Participants with shoulder pain were instructed not to place their arms in

Table 1
Shoulder range of motion angles used during the testing sequence.

Movement direction	Left arm	Right arm	Left arm	Right arm	Left arm	Right arm
flexion	55°	40°	100°	105°	140°	130°
Scaption	Right arm 60°	Left arm 30°	Right arm 90°	Left arm 95°	Right arm 125°	Left arm 140°

During measurements, participants were asked to move to these 6 different angles of flexion and scaption subsequently, alternating the left and the right arm.

extremes of range or perform fatiguing activities during this time. Following the 15-minute rest, participants completed the second sequence of measurements. Table 1 details the required ranges of movement each participant performed in a randomized order.

Participants experiencing shoulder pain were instructed to move within a tolerable level of pain which should not to exceed a subjective three out of 10 on a numeric pain rating scale where 0 represented no pain and 10 represented very severe pain. All participants were instructed to stop moving if they experienced motion sickness or dizziness.

During the ROM measurements the investigator stood alongside the participants and read the angles from the smartphone-inclinometers that were attached to the left and right humerus in a smartphone holder.

Data collection and analysis

The following participant characteristics were recorded: age, sex, Shoulder Pain And Disability Index (SPADI), the Quick-DASH (short version of disability of arm shoulder and hand) [25,26], and the HADS (Hospital anxiety and depression scale) [27] by means of a structured questionnaire. In addition, all participants recorded the severity of their pain during the day and at night in the week preceding the measurements using the Numeric Pain Rating Scale (NPRS) [28], ranging from 0 (no pain) to 10 (very severe pain).

Because we were only interested in evaluating whether the two devices were producing comparable ROM values during each separate movement attempt, the latter were considered and analyzed as independent events. For concurrent validity, first systematic differences in the shoulder flexion (1673 paired observations) and scaption (1680 paired observations) range of motion measurements between the smartphone inclinometer and the virtual goniometer embedded within the VR-system were assessed. The smartphone inclinometer was used as the ‘reference standard’. To test these systematic differences, the Wilcoxon signed-rank test was used because shoulder flexion and shoulder scaption were performed to six predetermined maximum motion ranges (instead of to the participants’ actual maximum range of motion) which resulted in the data not being normally distributed. Second, intraclass correlation coefficients (ICCs) were calculated using an absolute agreement, two-way random, single measures model (95% confidence interval) to evaluate the correlation between the virtual goniometer software and the smartphone

inclinometer measurements. Third, to examine the level of agreement between the measurements obtained with the smartphone -and VR inclinometer, Bland-Altman plots were constructed with their associated limits of agreement (LOA) for the shoulder flexion and scaption motions (Fig. 2A/B). Additionally, mean motion ranges, mean differences and upper and lower limits of agreement for each separate shoulder movement were analyzed descriptively. Data was analyzed using IBM® SPSS® v27 (for Apple Macintosh) and the statistical programming language R.

Reliability

In order to assess the system reliability of the VR goniometer application, the ICCs of the shoulder flexion (714 paired observations) and scaption (720 paired observations) ROM measurements between the first and second testing sequence were calculated. The second measurement sequence consisted of the same randomized testing sequence as the first measurement sequence.

Results

Concurrent validity

VR goniometric measurement and the smartphone inclinometric measurement data for 40 participants were available for analysis. For participant characteristics see Table 2. There were systematic differences in shoulder flexion ($Z = -33.5, p < 0.001$) and scaption ($Z = -34.1, p < 0.001$)

Table 2
Participants characteristics.

	Symptomatic Participants n = 20	Asymptomatic Participants n = 20
Female n (%)	40	60
Mean age in years (SD)	50 (11,8)	39 (12,8)
SPADI, median (IQR)*	33.0 (21.8–49.8)	0.0
Quick Dash, median (IQR)*	18.2 (13.6–35.2)	0.0
HAD’s, median (IQR)*	6.5 (1.2–11)	1.5 (0.00–5.2)
Dominant hand R / pain R (%)	40	90
Dominant hand R / pain L (%)	35	
Dominant hand L / pain L (%)	20	10
Dominant hand L / pain R (%)	5	

* IQR interquartile range of SPADI and Quick Dash total scores, R=right, L=left

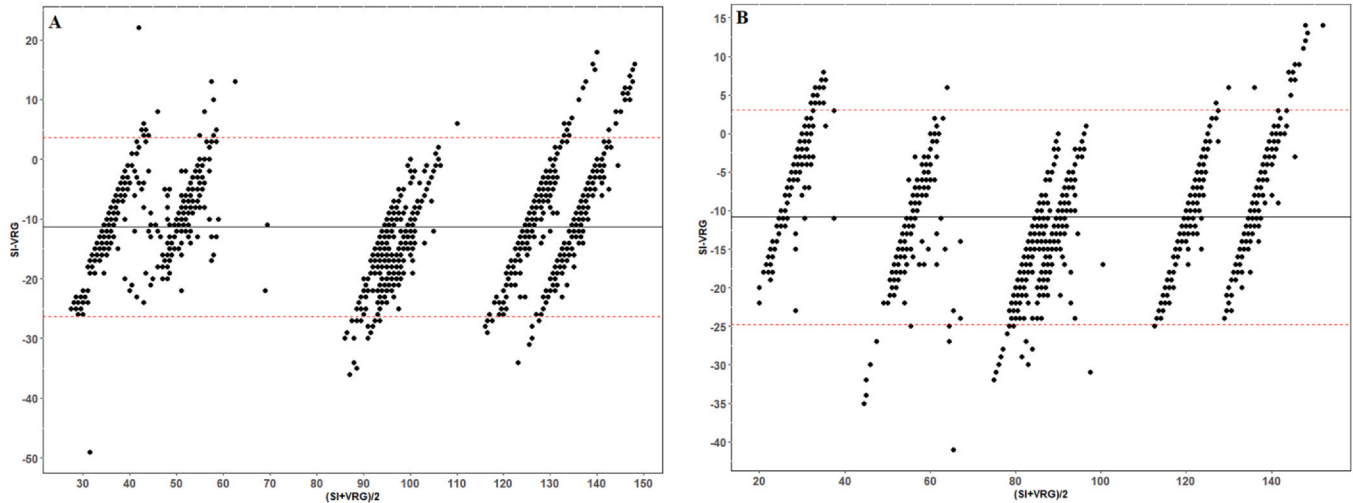


Fig. 2. A/B: Bland-Altman plots of the flexion (A) and scaption (B) range of motion measurement values. Please note that both plots are visualizing the combined datapoints of those obtained with the smartphone inclinometer (SI) and those obtained with the virtual reality goniometer (VRG), representing the motion ranges of the six distinct predetermined flexion and scaption arm movements. Because the patients only performed two low, two mid-range, and two higher shoulder movements, clear gaps are visible between the datapoints. Both plots clearly show that there was systematic bias in one of the measurement techniques, and that this bias was consistent across the six different motion ranges.

ROM measurements obtained with the virtual goniometer and smartphone inclinometer. The ICC for the flexion range of motion measurements was 0.93 (95% CI 0.23–0.98), and 0.94 (95% CI 0.24–0.98) for the scaption range of motion measurements. The mean difference between the measurements with the smartphone inclinometer and the measurements with the VR goniometer application within the head mounted display was -11.3 degrees (95% CI -26.3 to 3.7) for the flexion ranges of motion (Figs. 2a) and -10.9 (95% CI -24.8 to 3.1) for the scaption ranges of motion (Fig. 2b).

Appendix 1 shows that the mean ROM measurement values of all separate shoulder movements obtained with the VR goniometer were consistently higher than those obtained with the smartphone inclinometer ('reference').

Reliability

The reliability of the VR system was excellent. The ICC was 0.99 (95% CI 0.99–1.0) for all flexion measurements and 1.0 (95% CI 1.0–1.0) for all shoulder scaption measurements. The ICC's reflect the reliability of the VR system which is an important prerequisite for its clinical use.

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Discussion

This study evaluated the concurrent validity of a VR device measuring active shoulder flexion and scaption by comparing

the ROM for shoulder flexion and scaption obtained by a VR goniometer with the measurements obtained using a smartphone inclinometer. This study also evaluated the system reliability of the VR system by calculating the ICC's of range of motion measurements between the first and second testing sequence. Active ROM measurements have been chosen as the VR HMD allows for measuring and exercising remotely from the clinic and therefore asks patients to measure themselves.

Despite the excellent concurrent validity ICCs, the results of this study also demonstrated that there were systematic differences between the ROM measurement values obtained with the goniometer application within the head mounted display and those obtained with the smartphone inclinometer. During the large number of active ROM measurements, the VR goniometer application on average systematically overestimated the flexion and scaption ranges of motion by approximately 11 degrees compared to those obtained with the smartphone inclinometer. This means that there was lack of agreement between the devices' measurements. The wide limits of agreement imply that the two methods (VR and smartphone inclinometer) will produce measurement values that may differ up to 25 degrees between them as long as the same of the two measurement devices are consistently used over time (e.g. in a study or in clinical practice) shoulder ROM can still be assessed reliably. However, it is of note that measurement results obtained with the current version of the VR-goniometer will likely overestimate the 'true' value of the patients' shoulder flexion and scaption ROM.

The large difference in range of motion between the VR software and the smartphone inclinometer can be caused by the difference in measuring method. Unlike a goniometer or smartphone inclinometer, the VR HMD does not measure the glenohumeral joint range of motion but rather measures the angle of the arm relative to the floor by calculating the distances

between the hand-controllers, the built-in cameras and the floor. When using VR, range of motion is determined by the embedded software calculating the distance between the handheld controllers and the HMD. As such, when performing tasks such as elevating the arm during measurements or functional tasks, such as reaching to a shelf to return or retrieve an object, people use their upper limbs differently. Variations in wrist flexion and extension, forearm supination and pronation, elbow flexion and extension, will vary the distance between the hand controller and the HMD. These variations will influence the calculation in distance between the controllers and the HMD and will impact the output angles.

Similar challenges may also account for large confidence intervals in other studies measuring the concurrent validity of different range of motion measurement tools in the shoulder. Boissy et al. reported large confidence intervals in their validity study of a smartphone digital inclinometer and an optical motion tracking system [19]. The disparities were partly due to the assumption that the devices are aligned orthogonally with the axis of motion of the humerus and that this motion is performed in one axis. They argue that this might be true for an articulation with a single degree of liberty such as the knee, the motions performed by the shoulder joint have 3 degrees of freedom in flexion and abduction and have a potentially confounding effect on the trueness of the range of motion measurements. Kolber et al. [16] found ICCs values ≥ 0.85 for the concurrent validity of a smartphone inclinometer compared to a standard goniometer but the difference between these two measurement instruments could be expected to vary by 2–20° with differences dependent upon the movement being measured (active shoulder flexion and abduction have broader 95% confidence intervals compared to external rotation). They argue that the inclinometer uses a fixed vertical reference point realized by gravity, and thus is accurately calibrated. In contrast, traditional goniometry requires visualization of the vertical reference point, which may compromise measurement reproducibility. Despite the excellent ICC's for concurrent validity, the broad limits of agreement suggest that the VR system should not be used interchangeably with a smartphone inclinometer. This study shows excellent system reliability of the VR system, which is a pre-requisite for its clinical use. It means that changes in ROM before and after a period of treatment can be measured reliably with this device.

Strengths and limitations

A strength of this study is, that we investigated a VR immersive system to measure shoulder flexion and scaption ROM using both healthy volunteers and participants with shoulder pain. This allows for generalization of our results to both subgroups. A limitation of the study is that participants were not allowed to have pain scores above three out of ten on

a numeric pain rating scale, therefore we don't know the validity and reliability of the VR system when measuring ROM in patients with higher pain scores. Also, angles above 150 degrees could not be captured by the camera's of the head mounted device, therefore these angles could not be tested.

Overall, the findings of the present study suggest that the VR shoulder flexion and scaption ROM software used in this study had excellent system reliability, but that it should not be used interchangeably with a smartphone inclinometer until improvements in the ROM measuring software of the VR application within the head mounted display are available. When designing software for musculoskeletal rehabilitation, software engineers should take into account that users move their arm with different angles of their wrist, elbow and different rotations in their humerus which at the moment seem to influence the outcome of range of motion measurements. With software improvements, the VR system could offer the opportunity for clinicians to measure range of motion in the clinic, remotely, in real life or post-measurement. It could help creating valid safe zones for patients using VR applications in shoulder rehabilitation post operatively and therefore enhance the use of VR systems in the clinic and on remote places.

Conclusion

To the author's knowledge, this investigation was the first to evaluate the concurrent validity and reliability of a virtual goniometer imbedded in a head mounted display measuring active shoulder flexion and shoulder scaption. The VR system shows excellent reliability which is an important prerequisite for its clinical use. Although good to excellent concurrent ICC's for validity were produced, the wide range between upper and lower 95% CI limits suggests the VR system lacks measurement precision. In summary, the VR system as used in this study, should not be used interchangeably with other measurement tools such as smartphone inclinometry.

Ethical approval: The study was approved by the HAN University of Applied Sciences Nijmegen Ethics Committee (approval number ECO 198.10/20). All subjects gave written informed consent. This is stated in the manuscript in the materials and methods section. The reporting guideline GRRAS [29] has been followed when reporting this research article.

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Conflict of interest: The authors declare that they have no competing interests.

Appendix A

See Table A1

Table A1
Range of motion data (degrees) of the separate shoulder flexion and scaption movements.

Movement	Mean (SD) ROM obtained with the SI	Mean (SD) ROM obtained with the VRG	Mean difference (SD) between VRG and SI	Lower and upper LOA
Flexion (R) 40°	30.7 (6.5)	41.2 (1.6)*	10.6 (6.6)*	–23.5 to 2.3
Flexion (L) 55°	47.3 (6.3)**	55.8 (3.6)	8.6 (6.6)**	–21.6 to 4.4
Flexion (L) 100°	86.8 (5.8)	101.4 (1.5)	14.6 (6)	–26.3 to –2.9
Flexion (R) 105°	91.1 (6.1)	105.9 (0.8)	14.8 (6.1)	–26.8 to –2.8
Flexion (R) 130°	121.1 (10.1)	130.8 (5.5)	9.7 (8.4)	–26.2 to 6.7
Flexion (L) 140°	131.5 (9.2)	141 (0.9)	9.5 (9.2)	–27.6 to 8.6
Scaption (L) 30°	25.4 (6.3)	31.1 (1.3)	5.7 (6.3)	–18.1 to 6.7
Scaption (R) 60°	49.4 (6.8)	61.6 (3.5)	12.2 (7.1)	–26.2 to 1.8
Scaption (R) 90°	76.6 (6)	91.4 (2.2)	14.8 (5.7)	–26 to –3.5
Scaption (L) 95°	83.5 (5.6)	96.1 (1.1)	12.6 (5.7)	–23.8 to –1.4
Scaption (R) 125°	114.3 (8.4)	125.5 (5.7)	11.2 (6.3)	–23.5 to 1.1
Scaption (L) 140°	132.3 (7.7)	141 (1.1)	8.7 (7.6)	–23.6 to 6.2

*, $n = 277$, **, $n = 276$.

Abbreviations: L, left shoulder; LOA, limits of agreement; R, right shoulder; ROM, range of motion; SD, standard deviation; SI, smartphone inclinometer; VRG, virtual reality goniometer (application within the head mounted display).

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