The Validity and Reliability of Immersive VR Device in Measuring Craniocervical Range of Motion.

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Research

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Abstract

Background

Craniocervical range of motion (CROM) is a crucial index for assessing the neck's function. Its accurate evaluation could assist in detecting certain disorders, optimizing the therapy, and tracking intervention progress. In recent years, as VR technology has advanced rapidly, it has been widely applied in the medical field as it can simulate the real world. However, whether the novel immersive VR device could achieve a good performance in evaluating CROM remains explored.

Methods

This research aims to verify intra- and inter-rater reliability and validity of an immersive virtual reality (VR) device in measuring craniocervical range of motion (CROM) and compare its performance with the universal goniometer. Forty-two healthy adults without neck disorders were recruited for CROM measurement using an immersive VR device and a universal goniometer. We considered all six aspects of freedom, including flexion, extension, right/left lateral flexion, and right/left rotation. Two raters participated in the examination. The first rater was required to repeat measurements twice with a five-minute interval using an immersive VR device to evaluate intra-rater reliability while also measuring the same subject with the same subject universal goniometer. To ascertain inter-rater reliability, the second rater conducted the third examination using the immersive VR device. A two-way random effect model was employed in calculating intra-rater and inter-rater reliability (intra-class correlation coefficient (ICC)).

Results

The immersive VR device revealed excellent reliability of intra-rater (ICC from 0.885 for right rotation to 0.978 for extension) and inter-rater (ICC from 0.770 for left rotation to 0.920 for left lateral flexion). By analyzing Bland-Altman plot, a small mean difference ($\leq$1.64°) was revealed between the immersive VR device and universal goniometer. They demonstrated an excellent agreement in measuring CROM (r values from 0.833 to 0.964).

Conclusions

In healthy subjects, the immersive VR device provided excellent intra-rater and inter-rater reliability and a high agreement with the universal goniometer. Whether VR devices could achieve a similar performance between patients with neck disorders still requires future investigation.

1. Background

Craniocervical range of motion (CROM) refers to the motion of cervical spine in sagittal, coronal, and horizontal planes and encompasses six degrees of freedom, including flexion, extension, right/left lateral flexion, and right/left rotation[1]. Precise measurement of range of motion is a crucial index for evaluating the neck and cervical spine function, as most neck and cervical spine diseases would cause its change[2]. It may assist in assessing the conditions of patients' necks and developing a more effective treatment plan, particularly during surgery, preoperatively, as well as reflecting the effects of operation and rehabilitation postoperatively[3].

The complexity of cervical spine's anatomical structure and movement mode makes obtaining the accurate value of neck range of motion difficult. Numerous studies demonstrate a variety of instrumental approaches for measuring CROM device[4], cervical spine deformity (CSD) classification system[5], 3-dimensional Fastrak measurement system[6], dynamic radiographs[7], functional computed tomography (fCT)[8], eye-balling, and the Coda Motion 3-D Analysis system[9]. These devices may improve motion range measurements to a limited extent due to their high cost, inconvenient nature, or unstable reliability. There is currently no a "gold standard technique" for assessing cervical motion[10]. So far, the universal goniometer has been the most commonly used device for measuring range of motion in the clinical field. For instance, in patients with ankylosing spondylitis (AS), the goniometer-based approach demonstrates significant reliability and validity[11]. However, this method is limited by the requirement for a skilled operator familiar with both the process and the landmarks[12]. A practical and sophisticated approach should be investigated to make neck motion range measurements easier and more convenient.

Recent research indicates that virtual reality (VR) has a significant potential to emerge as a novel methodology for assessing and intervention of neck diseases, contributing to treatment and rehabilitation[13]. VR is a technology that can simulate a virtual environment. Additionally, it can be viewed as an experience designed to provide users with a sense of "being" or a high level of immersion. VR systems can be divided into three main categories based on their properties: immersive, non-immersive, and augmented. Chang and his colleagues[12] designed a VR-based smartphone application and explored its validity with a positive conclusion compared to the universal goniometer. However, the limitations of hardware and sensor they used may result in discrepancies between experimental results and actual data. Besides, their study did not use VR technology, and the effect of immersion was poor. Therefore, the research should incorporate a more advanced immersive VR device with a superior sensor to acquire more accurate angular variation.

As far as we know, this is the first article to compare highly immersive VR device performance with a universal goniometer in CROM measurement. The study aims to verify the validity and reliability of evaluating CROM using a novel immersive VR device and compare whether immersive VR or traditional universal goniometer displays a better measurement performance.

2. Materials And Methods

2.1 Participants

This study was conducted at West China Medical School and West China Hospital of Sichuan University from March 2021 to July 2021, using a two-stage repeated measure pattern. The inclusion criteria included the following: 1. Age ≥ 20 years old; 2. absence of evident cervical radiological changes, deformity, trauma, or previous surgery; 3. VAS of no more than one; and 4. NDI score more than 20. We excluded patients who did not complete the whole process of CROM evaluation.

By analyzing the correlation coefficient, we determined the required sample capacity. Based on previous similar researches[12], we supposed that measurements between the two devices had an r-value of 0.65. Type I and II errors were set below 0.05 and 0.2, respectively, and participants' attrition was allowed to be 20%. The total number required was at least 37 people. Finally, we obtained 42 participants in total. All participants were informed of the low risk of the test and signed an informed consent form before participation. This research was also supported by the ethics committee of West China Hospital.

2.2 Procedure of Measuring Craniocervical Range of Motion

The evaluation was taken by two raters. In the beginning, the first rater conducted two measurements on participants using a VR device, with an interval of five minutes. After another five minutes, the second rater administered the third VR measurement to the same participant. Finally, after completing all VR measurements and taking a five-minute break, the first rater conducted one more measurement with a universal goniometer. In total, there were four measurements taken, three with VR and one with a goniometer. Each measurement should be repeated at least three times, and the maximal statistics were adopted for analysis.

2.3 Immersive VR Device for Measuring Craniocervical Range of Motion

In our program, different scenes correspond to six directions with pictures of arrows. The participants could see the arrow, which might serve as a direction indicator during their movements (FIGURE 1).

Before the test, the doctor guides participants to complete six directions of movement without wearing a VR device to ensure that they can complete the required movement.

The concrete procedure of VR measurement was as follows:

1. During the test, the participants were instructed to maintain their backs straight and close to the chair's back. The arms are naturally placed on thighs, while hips and knees are at 90 degrees. They were then assisted by raters in putting on VR device.

2. Following the instructions provided by the first rater, the participant was required to perform the movements in six directions: extension, flexion, left/right rotation, and left/right lateral flexion, keeping their shoulders as still as possible. The software would automatically record the correlative data (FIGURE 2).

3. The first rater should conduct two VR measurements, and the third measurement was conducted by the second rater. There was an interval of five minutes between every measurement.
The virtual reality program was designed to record the angle change in each direction 120 times per second. The recorded data was saved in TXT format. Following software processing of these data, an angle-velocity graph is generated, in which the maximal change of angle is taken as CROM in this direction (FIGURE 3).

2.4 Universal Goniometer for Evaluating Craniocervical Range of Motion

Following VR test, the participant repeated the six movements without a VR device, and the angles were measured using the goniometer. A graph of reference line was set on the wall for angle measurement with a goniometer.

The specific method was as follows:

While the participants' heads are extended and flexed, the goniometer should be placed at the apex of their mandibular angle with the axis along the vertical line to measure the angle. To test neck rotation flexibility, the goniometer was positioned in the center of the top of the head. To measure the range of lateral flexion, the goniometer was positioned on the spinous process of 7th cervical vertebrae (a body landmark) (FIGURE 2). The result of angle could be read directly.

The reproducibility of goniometer in measuring craniocervical range mobility was previously verified[14].

2.5 Statistical Analysis

All data are described in the form of mean±standard deviation (SD). By analyzing repeated measurements of the first rater with immersive VR device, intra-rater reliability could be concluded, while inter-rater reliability should be calculated from each rater's first VR device evaluation. A two-way random effects model and its 95% confidence interval (CI) were used to represent intra-class correlation coefficients (ICC) of data[15, 16]. An ICC higher than 0.75 was considered an indication of excellent reliability. The standard error of measurement (SEM) could estimate statistically reliable changes, reflecting the amount of random variation associated with an individual subject assessment[17]. While the minimal detectable change (MDC) refers to the minimal change that could be acquired beyond a random error in a specific confidence interval, MDC was used in this investigation as a judgment standard to exclude the inference of error[18].

Bland Altman analysis[19] was used to demonstrate the validity between immersive VR devices and universal goniometers, which can also contribute to detect potential systematic errors and abnormal values. To show the precision of VR devices measurement in contrast to goniometer measurement, the coefficient of repeatability (COR) was utilized. The paired t-test was employed to compare average differences between the two evaluation methods, and Pearson correlation analysis was deployed to analyze data obtained by the two evaluation methods. All analyses were conducted using SPSS (version

25.0.0.2, New York, USA) and MedCalc (version 14, Ostend, Belgium), while p-value < 0.05 was deemed statistically significant.

3. Results

3.1 Basic data

The study included 42 healthy volunteers with a mean age of 23.24 ± 1.36 years. Among participants, there were 33 male and 9 female participants, with an average height of 171.07 ± 7.98 meters and a mean weight of 61.98 ± 9.56 kilograms (Table 1).

Table 1
, Characteristics of participants.

Variable	Value*
Age (years)	23.24 ± 1.36 (range, 20 to 25)
Height (cm)	171.07 ± 7.98
Weight (kg)	61.98 ± 9.56
Male/female	33/9
* Values are presented as the ratio or as the mean ± SD.	

3.2 The consistency between immersive VR device and goniometer

CROM data obtained from VR device meet an excellent agreement with those from goniometer in five directions: extension (mean degree: 51.00° from VR, 51.45° from goniometer), flexion (mean degree: 37.83° from VR, 38.16° from goniometer), right rotation (mean degree: 44.19° from VR, 43.85° from goniometer), left lateral flexion (mean degree: 36.02° from VR, 35.61° from goniometer) and right lateral flexion (mean degree: 33.13° from VR, 32.28° from goniometer). Only one significant difference was detected between the two devices in measuring left rotation (mean degree: 46.55° from VR, 44.90° from goniometer; mean difference: 1.64, p=0.006). In addition, all correlation coefficient r values were above 0.75, ranging from 0.833 (CI: 0.709-0.907) for left rotation to 0.964 (CI: 0.933-0.980) for extension. The repeatability coefficient ranged from 4.53° to 8.04° (Table 2, FIGURE 4).

Table 2
, Comparisons between the hybrid device and universal goniometer for measurement of craniocervical ranges.

	First Rater First Evaluation in Degrees by the VR Device (Mean, 95% CI)	First Rater First Evaluation in Degrees by the Universal Goniometer (Mean, 95% CI)	Between-Device Mean Difference in Degrees (Mean, 95% CI)	*p* Value	Correlation Coefficient *r* Value (Mean, 95% CI)	*p* Value	Coefficient of Repeatability (Degrees)
Extension	51.00 (47.32 to 54.67)	51.45 (47.77 to 55.12)	-0.45 (-1.43 to 0.53)	0.361	0.964 (0.933 to 0.980)	0.001	6.19
Flexion	37.83 (35.28 to 40.37)	38.16 (35.63 to 40.69)	-0.33 (-1.46 to 0.79)	0.553	0.901 (0.822 to 0.946)	0.001	7.04
Left rotation	46.55 (44.45 to 48.64)	44.90 (43.08 to 46.72)	1.64 (0.48 to 2.80)	0.006*	0.833 (0.709 to 0.907)	0.001	7.89
Right rotation	44.19 (41.91 to 46.46)	43.85 (41.30 to 46.40)	0.33 (-0.95 to 1.62)	0.601	0.863 (0.757 to 0.924)	0.001	8.04
Left lateral flexion	36.02 (33.88 to 38.15)	35.61 (33.68 to 37.55)	0.40 (-0.31 to 1.12)	0.263	0.942 (0.894 to 0.968)	0.001	4.53
Right lateral flexion	33.13 (30.91 to 35.36)	32.28 (30.37 to 34.19)	0.85 (-0.33 to 2.04)	0.155	0.844 (0.727 to 0.914)	0.001	6.63

CI confidence interval

* $p < 0.05$

When focusing on Bland-Altman plots, there were 3 of 42 subjects for extension, 3 of 42 subjects for flexion, 2 of 42 subjects for left rotation, 4 of 42 subjects for right rotation, 2 of 42 subjects for left lateral flexion, and 4 of 42 subjects for right lateral flexion lie beyond 95% confidence intervals (FIGURE 5). These statistics revealed a high agreement between both methods in CROM measurement

3.3 The reliability of immersive VR device

CROM of six directions obtained from immersive VR device used by the same rater demonstrates a great consistency in general, particularly in five directions: extension (p = 0.092), flexion (p = 0.132), right rotation (p = 0.766), left lateral flexion (p = 0.576), and right lateral flexion (p = 0.518). There is a statistically significant difference when neck takes the left rotation (1.05°, p = 0.013). The results from several raters using VR device indicate a highly agreement when neck takes flexion, left rotation, left and right lateral flexion, except for extension (-1.71°, p = 0.028) and right rotation (1.26°, p = 0.016) (Table 3).

Table 3
, Intra-rater and inter-rater evaluations and corresponding differences of craniocervical motion range measured by the VR device.

	First Rater First Evaluation in Degrees (Mean, 95% CI)	**First Rater Second Evaluation in Degrees (Mean, 95% CI)**	**Second Rater Third Evaluation in Degrees (Mean, 95% CI)**	**Intra-Rater Mean Difference in Degrees (Mean, 95% CI)**	***p* Value**	**Inter-Rater Mean difference in Degrees (Mean, 95% CI)**	***p* Value**
Extension	51.00 (47.32 to 54.67)	50.35 (46.63 to 54.07)	52.71 (48.74to 56.68)	0.64 (-0.11 to 1.40)	0.092	-1.71 (-3.23 to -0.19)	0.028*
Flexion	37.83 (35.28 to 40.37)	38.41 (35.85 to 40.96)	39.18 (36.56 to 41.79)	-0.58 (-1.34 to 0.18)	0.132	-1.35 (–2.76 to -0.06)	0.061
Left rotation	46.55 (44.45 to 48.64)	45.49 (43.24 to 47.75)	45.18 (43.08 to 47.28)	1.05 (-0.23 to 1.87)	0.013*	1.37 (-0.01 to 2.75)	0.052
Right rotation	44.19 (41.91 to 46.46)	44.02 (41.45 to 46.58)	42.93 (40.27 to 45.58)	-0.56 (-1.49 to 0.36)	0.766	1.26 (0.24 to 2.27)	0.016*
Left lateral flexion	36.02 (33.88 to 38.15)	35.72 (33.48 to 37.97)	35.80 (33.67 to 37.93)	0.29 (-0.76 to 1.34)	0.576	0.21 (-0.58 to 1.01)	0.591
Right lateral flexion	33.13 (30.91 to 35.36)	32.92 (30.54 to 35.31)	32.85 (30.83 to 34.87)	0.30 (-0.38 to 0.99)	0.518	0.85 (-0.81 to 2.52)	0.507

CI confidence interval

* *p* < 0.05

ICC was used to evaluate intra-rater and inter-rater reliability of CROM measured by VR device. In intra-rater group, ICC values of all six evaluations ranged from 0.885 (CI: 0.797-0.973) for right rotation to 0.978 (CI: 0.959-0.988) for extension. In inter-rater group, ICC had a minimum of 0.770 (CI: 0.507-0.870) for left rotation and a maximum of 0.931 (CI: 0.875-0.962) for left lateral flexion (Table 4). SEMs for all six directions were minimal in both intra-rater and inter-rater groups, ranging from 1.45° to 2.62° for intra-rater group, and 1.79° to 3.59° for inter-rater group. MDC values were also small for all six directions in both intra-rater and inter-rater groups, ranging from 4.03° to 7.27° for intra-rater group, and 4.95° to 9.94° for inter-rater group (Table 4).

Table 4
, Intra-rater and inter-rater reliability of craniocervical motion range measured by the VR device.

	Intra-Rater ICC (Mean, 95% CI)	**Intra-Rater SEM (Degrees)**	**Intra-Rater MDC (Degrees)**	**Inter-Rater ICC (Mean, 95% CI)**	**Inter-Rater SEM (Degrees)**	**Inter-Rater MDC (Degrees)**
Extension	0.978 (0.959 to 0.988)	1.75	4.85	0.914 (0.838 to 0.954)	3.59	9.94
Flexion	0.954 (0.916 to 0.975)	1.75	4.84	0.842 (0.721 to 0.912)	3.28	9.10
Left rotation	0.920 (0.842 to 0.958)	1.97	5.46	0.770 (0.507 to 0.870)	3.22	8.94
Right rotation	0.885 (0.797 to 0.937)	2.62	7.27	0.906 (0.819 to 0.950)	2.43	6.72
Left lateral flexion	0.886 (0.840 to 0.951)	2.36	6.54	0.931 (0.875 to 0.962)	1.79	4.95
Right lateral flexion	0.961 (0.929 to 0.979)	1.45	4.03	0.920 (0.857 to 0.956)	1.92	5.32

CI confidence interval, ICC intraclass correlation coefficient, SEM standard error of measurement, MDC minimal detectable change

* $p < 0.05$

4. Discussion

Numerous studies have recently reported applying VR technology in the cervical field, including surgical training, assistance in surgery, rehabilitation, and cervical spine mobility assessment. Chang et al.[12] developed a hybrid device containing a smartphone and virtual reality goggles to examine its reliability and validity in evaluating craniocervical mobility. By wearing such a device, the magnetometer and inclinometer of the smartphone could obtain changes in head posture. This study revealed that this hybrid device exhibited excellent intra-rater intraclass coefficient ≥ 0.925 and inter-rater intraclass coefficient ≥ 0.880 when used to assess healthy participants. However, using such hybrid VR devices, the assessment's accuracy is totally dependent on built-in sensors of smartphones, which are inaccurate enough. Also, their recording frequency is insufficient, implying a relatively low frequency of capturing head angle change.

After decades of development, numerous mature products of VR devices are available on the market. Taking HTC Vive (HTC Corporation, Taoyuan, Taiwan) as an example, this kind of VR device uses laser emitters (also called lighthouse) to determine posture and location of device and user. The virtual reality device using lighthouse for positioning has the characteristics of excellent accuracy and high recording frequency. With the help of such a device, the change in craniocervical motion angle can be recorded more accurately while also obtaining more details about the movement process, which can help doctors better understand the whole movement process. Therefore, this study used HTC Vive, an immersive virtual reality device, to accurately record more information.

This study compared reliability and validity of immersive VR devices and universal goniometers in CROM assessment. Our immersive VR technology was demonstrated to be an excellent method for evaluating CROM. Based on measurement data, CROM acquired by VR device was generally similar to that obtained in a previous study conducted by Chang et al.[12]. As a result of our speculation, this inconsistency may be related to different measurement procedures and races of participants, even with different times of measurement[20].

Our results indicated that Bland-Altman plot revealed a high consistency between immersive VR devices and universal goniometers, for a maximum of only 4 of the 42 paired measurements beyond 95% CI. A significant difference exists between both two methods in left rotation (1.64°, p□0.001). In Chang's study[12], they found significant differences between hybrid devices and universal goniometers in left lateral flexion, right, and left rotation. They explained that it is challenging for the goniometer to precisely locate at the head's center, indicating that neck rotation may not occur perfectly at the horizontal plane when measured with a universal goniometer. Compared to a goniometer, an immersive VR device is based on an external laser sensor, and the change of angle is determined by software, which determines that data it provides could accurately reflect the angle changing. As for discrepancies observed in left rotation but not in right rotation, we presumed that they were caused by limitations of goniometer measurement on the one hand and muscle fatigue of subjects while proceeding with the experiment on the other hand.

Besides the great consistency with goniometer, that of VR device itself should be emphasized too.

We observed that while the statistical result of immersive VR device assessment demonstrated remarkable consistency in the intra-rater group, a significant difference in left rotation was revealed ($p = 0.013$). In inter-rater group, there is a difference between extension ($p = 0.028$) and right rotation ($p = 0.016$). The average discrepancy is slight, which is acceptable for clinical evaluation. We speculate that these discrepancies may be associated with measurement methods, particularly the measurement process. Due to the several steps required for measurement, one participant must be measured five times, and neck muscles of participants may become fatigued. As the duration of measurements increases, the craniocervical mobility of participants may decrease. Therefore, we suspect that the assessment process should be perfectly designed. For instance, prolonging the interval between two assessments may be first considered, as this allows the neck muscles of participants to achieve better rest, which is helpful to improve consistency and reliability of measurement.

Apart from immersive VR, non-immersive VR and augmented VR are another two main categories of VR technology. Kiper's[10] research compared CROM measurements taken with immersive and non-immersive VR devices, demonstrating that immersive VR devices could provide more accurate assessment than non-immersive VR devices. In our study, we also found an outstanding ICC demonstrated by immersive VR devices. During measurements, ICC of intra-rater group ranges from 0.885 to 0.978, while ICC of inter-rater group ranges from 0.770 to 0.920. All of them were above 0.750, which was considered good.

Compared with previous measurement methods, using immersive virtual reality technology for assessing head and neck mobility offers more advantages. First, using conventional VR devices, including devices based on smartphones and VR goggles, angular displacement and angular velocity of head and neck in six directions can be detected, which could not be obtained using a goniometer[14]. Simultaneously, by incorporating more advanced external sensors into virtual reality devices, such as lighthouse technology based on laser sensors, displacement and speed of user can be determined. Additionally, immersive VR devices can create a virtual environment that highly simulates the real world. It can provide three-dimensional instructions to subjects during the course of the test. Simultaneously, the immersive scene can make the subjects' visual and vestibular systems receive information, better guiding movement. These characteristics enable the immersive VR technology to assist participants in completing the target task more effectively. Lastly, the immersive VR device could provide a higher frame rate and resolution, reducing nausea and a sense of disequilibrium associated with other devices.

Some limitations should be improved. First, we mainly adopted healthy volunteers from students in medical college, which may introduce selection bias. Second, this study focuses on almost normal, healthy people without neck diseases. As a result, whether this plan could be applied to patients and its effect remain unknown. Third, because VR device we employed is so heavy and the whole procedure is so lengthy, it may cause discomfort to subject's neck. That is why we should investigate subjects' satisfaction with this device and address the weight issue. In addition, during research, we only compared immersive VR devices with traditional universal goniometers; however, there are many plans and devices for measuring CROM. Last but not least, the sequencing of VR and goniometer measurements could result in a potential error; if the goniometer's evaluation was conducted before VR, the final result might be affected to some extent. As a result, we need to conduct additional comparisons between VR devices and those methods to determine the most effective measurement.

5. Conclusion

In this research, we proved excellent intra-rater and inter-rater reliability of immersive VR devices in measuring CROM. In addition, the immersive VR device demonstrated a great correlation with traditional universal goniometers in healthy subjects. Whether an immersive VR device could achieve similar performance on patients with neck disorders requires future investigation.

List Of Abbreviations

Craniocervical range of motion (CROM)

cervical spine deformity (CSD)

functional computed tomography (fCT)

virtual reality (VR)

standard error of measurement (SEM)

minimal detectable change (MDC)

coefficient of repeatability (COR)

Declarations

Ethics approval and consent to participate: This research has been approved by the ethics committee of West China Hospital.

Consent for publication: All participants were informed of the low risk of the test and signed an informed consent form before participation.

Availability of data and materials: All data generated or analysed during this study are included in this published article and its supplementary information files.

Competing interests: The authors declare that they have no competing interests.

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Authors' contributions: BW and HL provided the concept and funding. CY and XG designed the VR system and established the relevant software. CY, HW and YJ acquired, analyzed and interpreted the participants' data. CY and HW was major contributors in writing the manuscript. HL, BW and TW reviewed and corrected the article. All authors read and approved the final manuscript.

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Figures

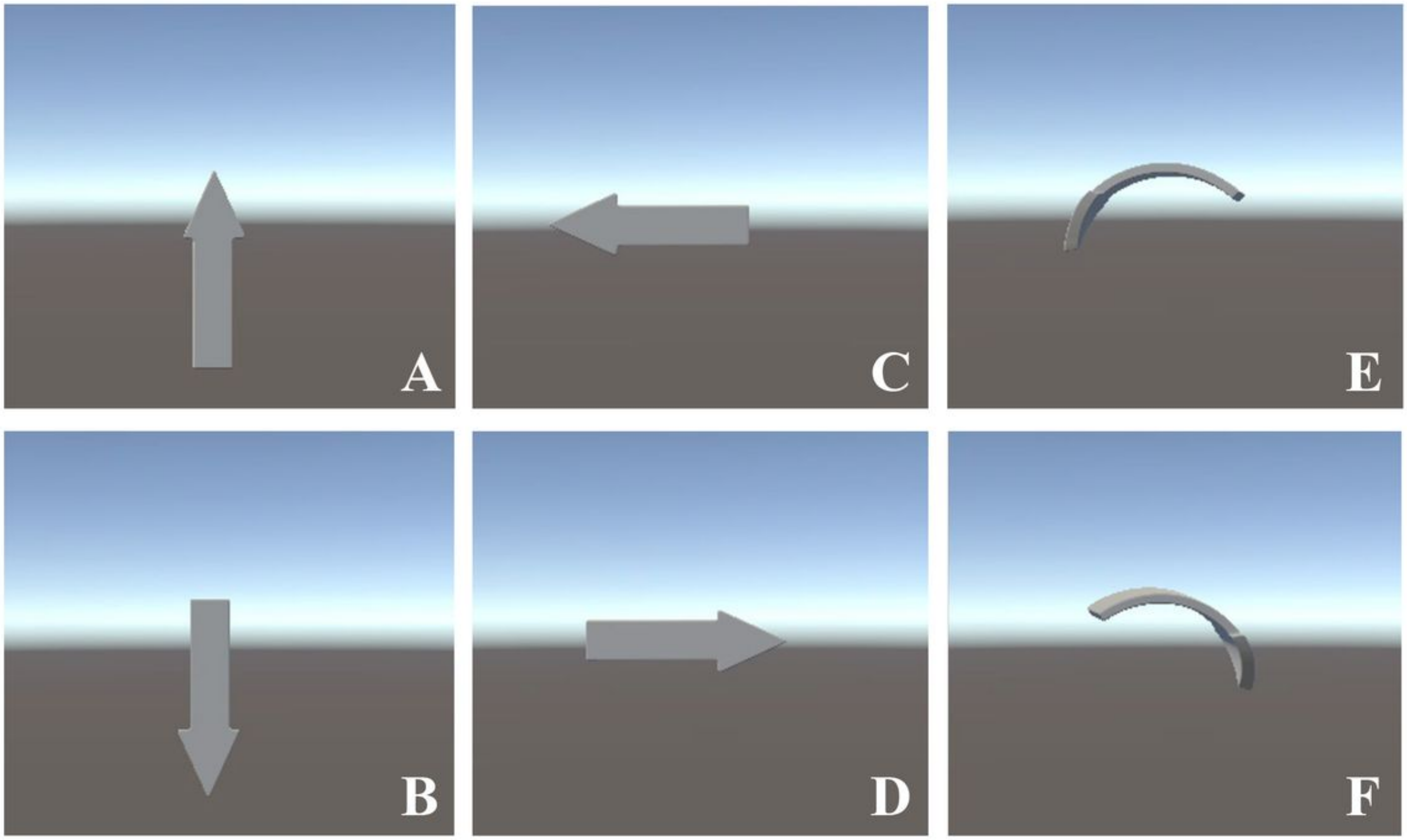

Figure 1

The images shown to the participants through the immersive VR device according to different instructions as (A) extension, (B) flexion, (C) left rotation, (D) right rotation, (E) left lateral flexion and (F) right lateral flexion.

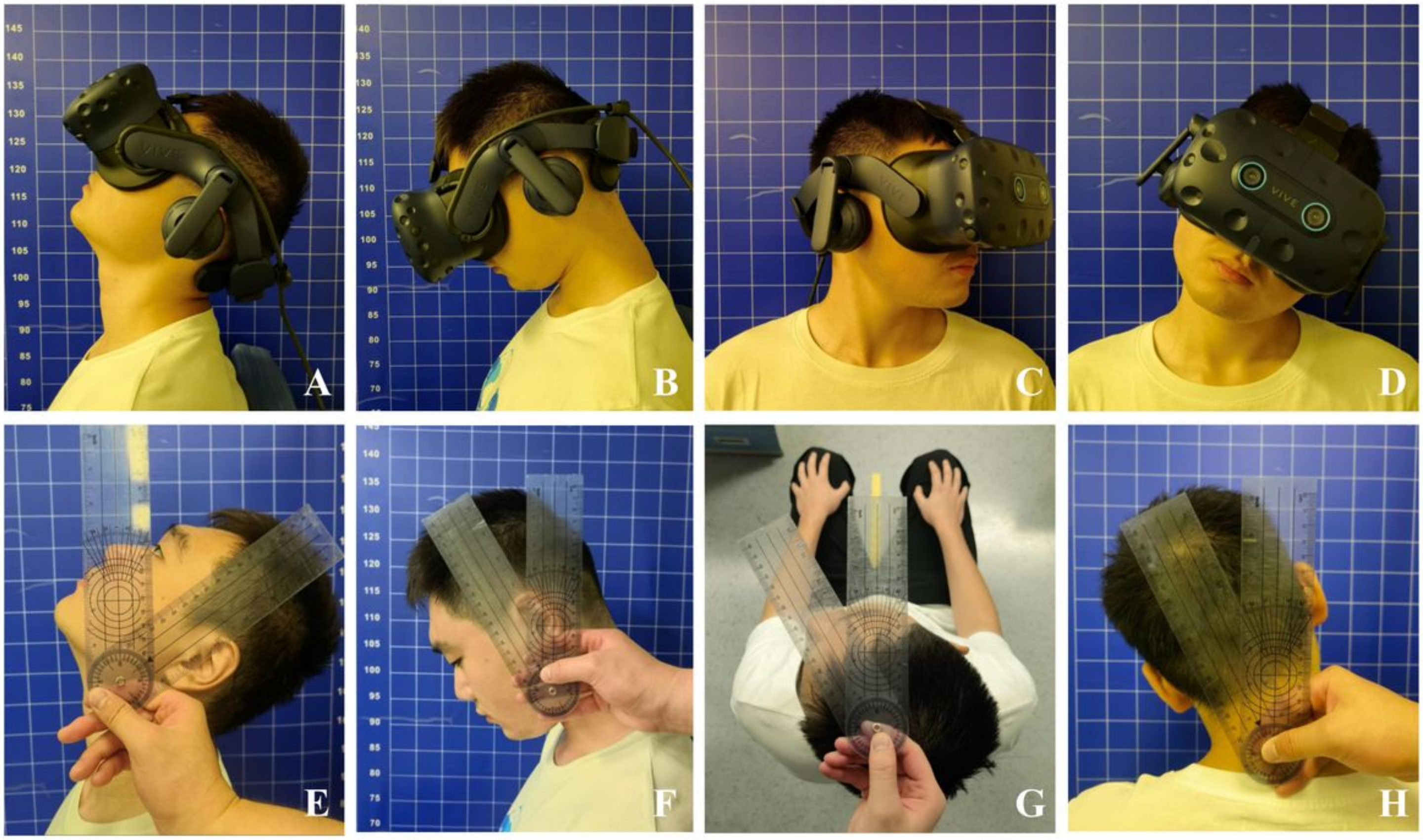

Figure 2

Use of the immersive VR device and universal goniometer to measure craniocervical range of motion in (A, E) extension, (B, F) flexion, (C, G) left rotation and (D, H) left lateral flexion.

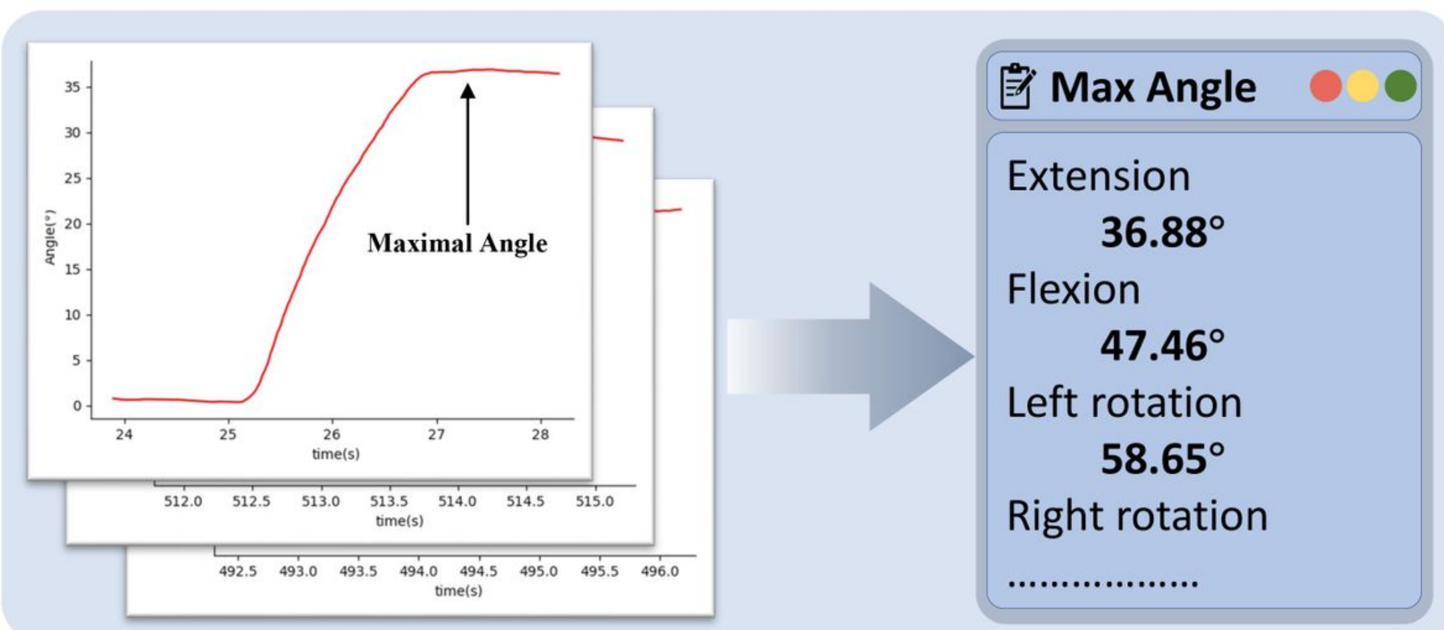

Figure 3

Angle – Time graphs and illustration about the output of maximal angle in every direction.

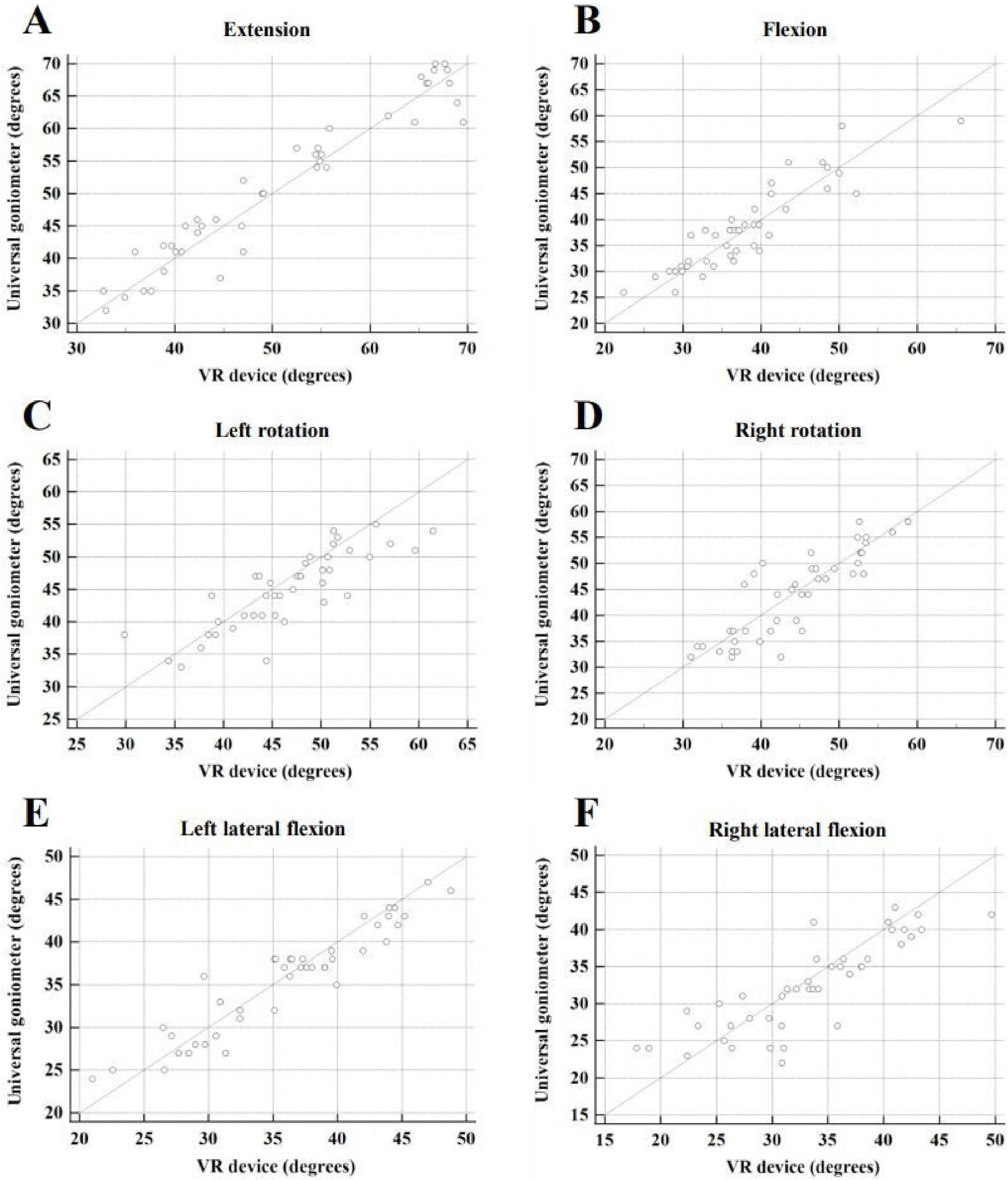

Figure 4

The correlation of CROM measured by the immersive VR device and universal goniometers in (A) extension, (B) flexion, (C) left rotation, (D) right rotation, (E) left lateral flexion (F) right lateral flexion.

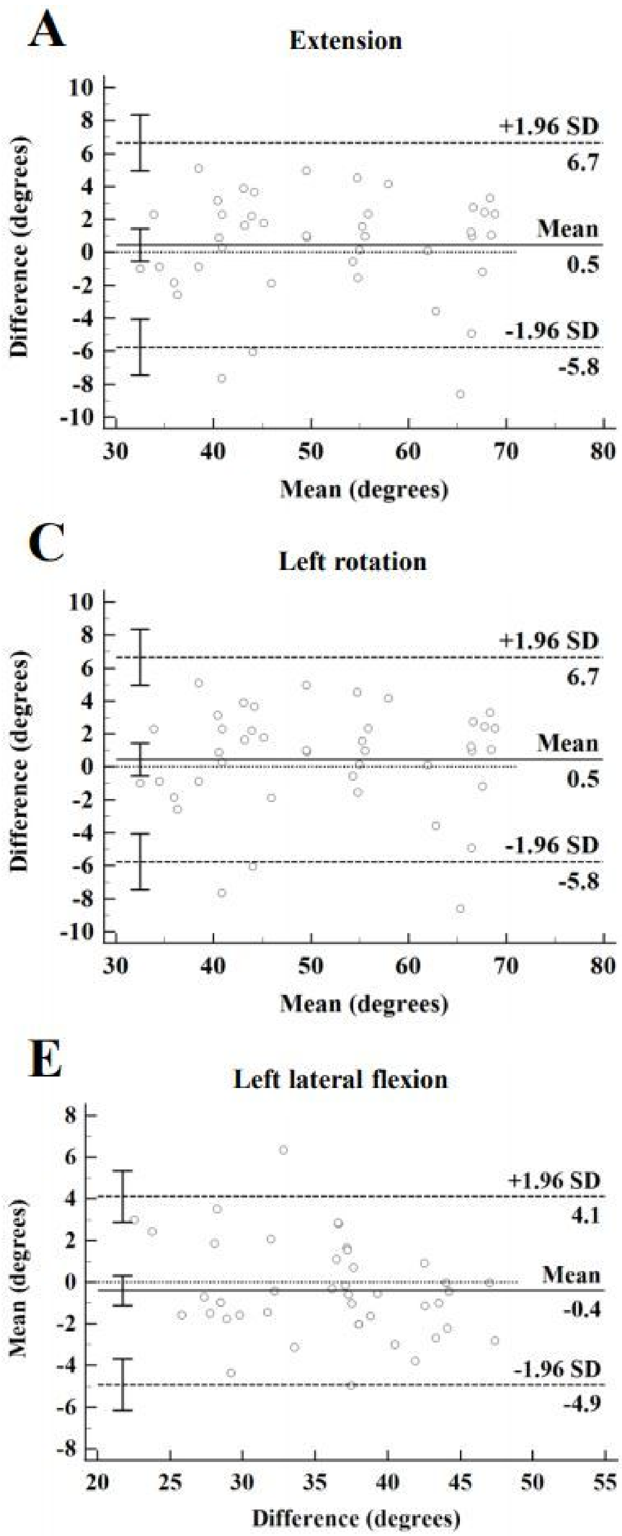

Figure 5

The Bland–Altman plot for CROM measured by the immersive VR device and universal goniometers in (A) extension, (B) flexion, (C) left rotation, (D) right rotation, (E) left lateral flexion, (F) right lateral flexion. The black solid line indicates the mean values of all he subjects, whereas the black dotted line refers to its upper and lower limits (mean ± 1.96 standard deviation).