



Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Short communication

Concurrent validity and reliability of a mobile tracking technology to measure angular and linear movements of the neck

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ARTICLE INFO

Article history:

Accepted 11 September 2019

ABSTRACT

The neck can be moved in six degrees of freedom. Current 3D-optoelectronic motion-capture systems capable of measuring these movements are inappropriate for use in clinical practice because they are stationary, expensive and time-consuming. We therefore developed a less complex 3D-tracking technology based on Steam[®]VR to measure six degrees of freedom in a clinical setting. The aim of this study was to assess the validity and reliability of this system.

The developed prototype consists of two infrared-emitting lighthouses and sensors, mounted on the participant's helmet and trunk belt, to detect the orientation of the head and trunk. The system was evaluated by means of an infrared light-reflecting marker tracking system. Twenty healthy participants, equipped with these sensors and markers, performed thirteen neck movement tasks. Linear and angular movements were measured. These tasks were repeated after six to eight days to assess test-retest reliability. Concurrent validity was assessed by the root mean square error, and reliability with generalizability theory.

With an average root mean square error between 1.2 and 2.0° in angular and 0.4–0.5 cm in linear movements, the prototype was shown to precisely track these movements. Reliability of the prototype and the reference system was comparable for all tasks. A high contribution of participant's variability to the observed variance was generally detected, with the exception of joint repositioning error and upper cervical flexion.

The reliability was task-specific and did not differ between the systems. The prototype system was shown to be valid, although the reliability of the repositioning and upper cervical flexion tests needs to be reconsidered.

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1. Introduction

The anatomical and physiological characteristics of the cervical spine allow humans to rotate and translate their head relative to the thorax in all directions (six degrees of freedom) (Ordway et al., 1997; Park, 2015; Seo et al., 2013). Impairment of the neck is related to the cervical range of motion (Ernst et al., 2015; Hall et al., 2010). Clinical tests of global cervical range of motion are frequently used in clinics (Childs et al., 2008). These tests are valid and reliable to a certain extent (Audette et al., 2010) but lack the ability to reproducibly record data during neck movement and to provide visual patient feedback.

For the neck, it is important to assess not only angular but also translatory movements. Such translatory movements typically occur in the neck to keep the head upright. Prolonged protraction however, might lead to altered kinematics and muscle activity, which can lead to proprioceptive dysfunction (Yong et al., 2016) and pain (Abdulwahab and Sabbahi, 2000; Diab and Moustafa, 2012). Modern marker-based motion capture systems can accurately measure movement in six degrees of freedom (Richards, 1999), but they are time-consuming, expensive, stationary and inappropriate for clinical practice. Smaller inertial measurement units are used in clinical settings to track orientation, although they are prone to error when deriving translation (Wang et al., 2010). Niehorster et al., 2017, investigated a Steam[®]VR system, which showed a position offset whenever tracking was briefly lost. In order to have a constant position even with a loss of tracking, we developed a prototype to measure both linear and angular displacement that is appropriate to the clinical setting. The aim

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of this study was to assess the concurrent validity and reliability of this prototype.

2. Methods

2.1. Participants

Thirteen healthy female and seven healthy male participants (Table 1) were recruited amongst a university staff and students. Participants were free of acute or chronic diseases, had not previously undergone spinal surgery, were not taking perception-influencing drugs and measured less than five points on the Neck Disability Index (an indicator of no disability) (Vernon, 2008). The local ethics committee juristically verified the study and participants signed an informed consent form.

2.2. Data collection and analysis

2.2.1. System under test (SUT)

Angular and linear movements of head and trunk were measured using in-house developed trackers. The tracking principle followed the Steam®VR-Tracking technology, which is distributed by HTC® as part of a virtual-reality system (Yates and Selan, 2016). Our SUT consisted of two HTC laser-emitting lighthouses combined with two trackers for tracking head and trunk motion (Fig. 1). The head tracker consisted of 5 sensor boards that were fixed around a bicycle helmet. The trunk tracker consisted of 2 sensor boards in front of the sternum. The sensor boards were each equipped with four infrared light detectors geometrically arranged to guarantee a line-of-sight from the lighthouses to at least one of the sensor boards (Fig. 2). Both trackers were also equipped with an individual controller board to capture the time instants of a laser impinging on one of the photodiodes. These time instants were communicated via Bluetooth to a computer and allowed it to compute the positions and orientations at a rate of 30 Hz. The poses signaled by the SUT were represented as relative poses of the upper front board of the helmet (T_F) and the right-side board of the belt (T_T) relative to the lighthouse coordinate system (Fig. 2).

2.2.2. Reference system

The VICON® motion capture system (Vicon Motion Systems, Oxford, UK) was employed to compare and assess the validity of the SUT. This system was comprised of twelve infrared cameras combined with reflecting markers on the back of the helmet, on the right-side board of the belt and, during the static measurement, on the front of the helmet. The marker coordinates were sampled at 120 Hz and expressed with respect to the movement laboratory specific coordinate system. Data were then downsampled to 30 Hz. The pose of Vicon back of the head (T_B) to forehead (T_F) was determined through a static measurement. The forehead markers were then removed to allow better visibility of the sensor boards.

2.2.3. Comparison of measurements

To compare the poses resulting from the two systems, they were expressed in the same coordinate system. The relative pose of the coordinate systems was calculated on the basis of the static measurement. The poses obtained from the Vicon system were expressed with respect to the SUT coordinate system. The reference coordinate System (T_R) was aligned with the movement in

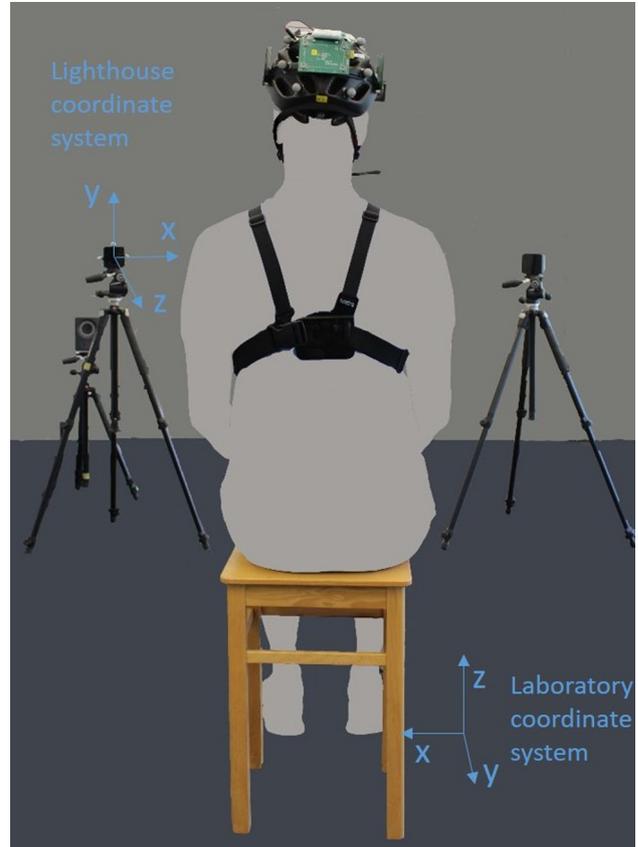


Fig. 1. Setup of the SUT with two Lighthouses and a Vicon camera; the subject is wearing head and trunk trackers. The origin of the Lighthouse coordinate system is in the lighthouse whereas the laboratory coordinate system has its origin on the floor.

sagittal, frontal and transverse planes. To achieve this, the coordinate system of the trunk (T_T) was transformed with

$$T_T^R = \begin{bmatrix} \cos\alpha & 0 & -\sin\alpha & tx \\ 0 & 1 & 0 & 0 \\ \sin\alpha & 0 & \cos\alpha & tz \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

with its origin between the two belt-fixed sensors in front of the sternum (Fig. 2, right bottom). The forehead coordinate system had its origin on the middle of the upper front sensor on the helmet (T_F). Movement between head and trunk was expressed as the pose T_T^F.

$$T_T^F = T_R^F (T_R^T)^{-1}$$

T_R^F: transformation matrix from the reference to the forehead coordinate system

2.2.4. Outlier elimination

In raw data, both pose measurement systems occasionally provided single erroneous pose samples, resulting in erroneous position as well as orientation measurements (less than 1.5% of all data-points). Especially range of motion values were influenced by these erroneous data points. Therefore an outlier detection was implemented to eliminate these pose samples. The affected

Table 1
Participants' characteristics; number of participants, mean (standard deviation) weight, height, Body Mass Index and age.

Female Participants	Male Participants	Weight [kg]	Height [m]	Body Mass Index	Age [years]
12	6	66.6 (10.5)	1.71 (0.09)	22.8 (2.5)	36.1 (13.1)

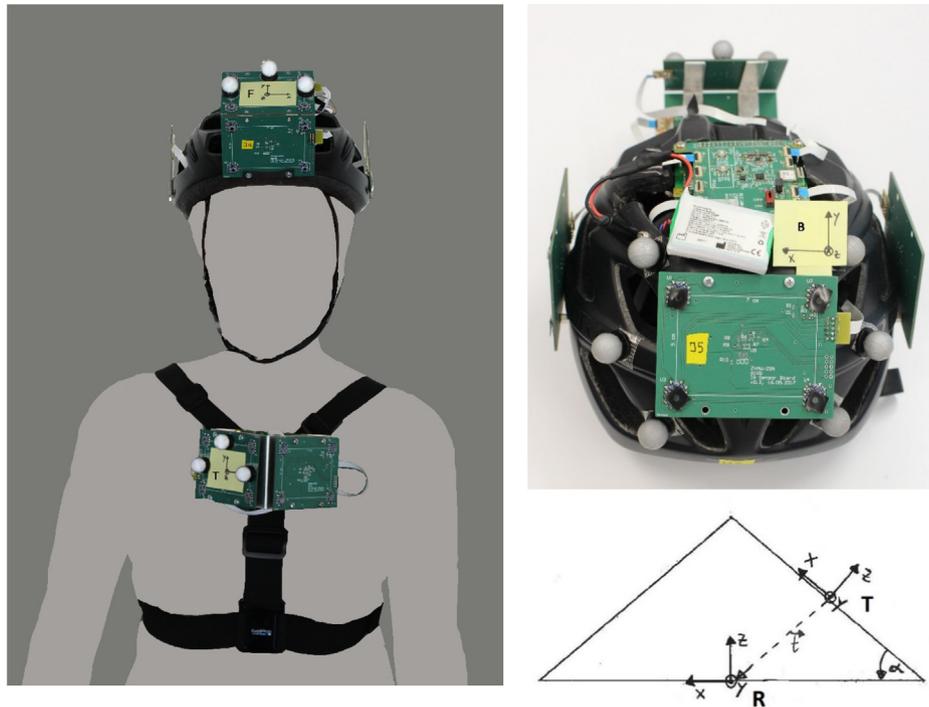


Fig. 2. Each sensor board has four IR sensors to detect lasers emitted by the lighthouses; left: sensor setup with the coordinate systems of the right-sided board of the belt (T_T) and forehead (T_F); right top: coordinate systems of the back of the head helmet (T_B); right bottom: transformation of the right-sided board coordinate system (T_T) to the reference coordinate system (T_R) of the trunk belt with view from top.

samples were regarded as invalid and ignored. Outcomes were then calculated without the erroneous samples. Outliers were detected via Hampel's method (Liu et al., 2004): if a position coordinate or an orientation variable deviated more than 1.5 standard deviations from the median of the recent 15 samples, the related pose was classified as an outlier. Outliers of both systems were detected and excluded from the analysis.

Transformation matrices were calculated for the SUT and the Vicon reference system. Rotation was parametrized by Euler angles in the 'zyx' order, which was found to be the best choice for our application to avoid gimbal-lock. All calculations were performed with Matlab R2017a and Software R (R Core Team, 2018).

2.3. Procedure

Following a static measurement in upright trunk posture seated on a chair, each participant performed the tasks described in Table 2. After a practice trial with manual guidance if necessary, seven repetitions of the tasks were performed in randomized order at a self-defined speed. Participants took a break of five seconds between repetitions and one minute between tasks. For range of motion (ROM) tasks they were instructed to move maximally, whereas for joint position error (JPE) to the perceived half of their ROM. For the task Zigzag (ZIZA) (Ernst et al., 2019), a laser pointer mounted on the helmet had to follow a Zigzag pattern through head movement. Participants were instructed to follow the pattern as accurate as possible.

To assess test-retest reliability, each participant repeated all the tasks some six to eight days later, in the same order and at the same time of day.

2.4. Outcome measures

2.4.1. Range of motion and joint position error

ROM was calculated for each participant's repetitions on both days (tasks described in Table 2).

Table 2

Abbreviations and exercise descriptions.

Abbreviation	Exercise description	Unit
UCEX	Upper cervical extension	°
UCFL	Upper cervical flexion	°
JPRL	Joint reposition error after rotation to the left	°
JPRR	Joint reposition error after rotation to the right	°
MEXT	Maximal extension	°
MFLX	Maximal flexion	°
MLFR	Maximal lateral flexion right	°
MLFL	Maximal lateral flexion left	°
MPRT	Maximal protraction	cm
MRET	Maximal retraction	cm
MROL	Maximal rotation left	°
MROR	Maximal rotation right	°
ZIZA	Follow a Zigzag pattern precisely, rotation angle is determined	°

$$ROM = |\max \alpha - \min \alpha|$$

α : measured angle in main movement direction

JPE, following a rotation to the left and right sides (JPRL, JPRR), was determined by the difference between rotation at the start and end of the repetition (Treleaven et al., 2003). For start and end positions, 50 frames were considered, since the subjects were told to hold the position for two seconds.

$$JPE = \left| \frac{\sum_{i=1}^{i=50} \alpha_i}{50} - \frac{\sum_{i=n-49}^{i=n} \alpha_i}{50} \right|$$

n : number of frames

α_i : measured rotation angle at frame i

2.4.2. Root mean square error

The root mean square error (RMSE) was calculated between both systems as a measure of concurrent validity:

$$RMSE = \sqrt{\sum_i (x_i - y_i)^2 / n}$$

x_i, y_i : measured position vectors (linear and angular) of the two systems at time frame i
 n : number of frames

RMSE was calculated for each repetition, participant and day in all six degrees of freedom. For the task ZIZA data of the helmet without differential signal to the trunk (in the forehead coordinate system T_f) were considered, since the trunk sensors were hidden behind the pattern for lighthouse visibility.

2.4.3. Reliability

For assessing reliability, a generalization of classical test theory with multiple sources of error, the Generalizability theory (G-theory) was applied (Brennan, 2001). The observed scores were ROM, JPE and RMSE. With the fully crossed participant \times day \times repetition ($p \times d \times r$) design, the decomposition of observed score variance σ_y^2 was given by

$$\sigma_y^2 = \sigma_p^2 + \sigma_d^2 + \sigma_r^2 + \sigma_{pd}^2 + \sigma_{pr}^2 + \sigma_{rd}^2 + \sigma_{prd}^2$$

The variance components are described in Table 3. The variance components were estimated with the linear mixed model implementation (lmer) in the R-package lme4 using restricted maximum

Table 3 description of variance components.

Variance component	Description
σ_p^2	Variance component occurring from the person
σ_d^2	Variance component occurring from the day
σ_r^2	Variance component occurring from the repetition
σ_{pd}^2	Variance component occurring from the interaction person \times day
σ_{pr}^2	Variance component occurring from the interaction person \times repetition
σ_{rd}^2	Variance component occurring from the interaction repetition \times day
σ_{prd}^2	Residual variance component

Table 4 Range of motion and joint position error measurements with its mean and standard deviation; percentual variance components for participant (σ_p^2), participant \times day (σ_{pd}^2), and residual (σ_{prd}^2); Number of repetitions required to reach an index of dependability (Φ) $>$ 0.75 on a single day measurement. UCEX: upper cervical extension, UCFL: upper cervical flexion, MEXT: maximal extension, MFLX: maximal flexion, MLFR/MLFL: maximal lateral flexion right/left, JPRL/JPRR: joint position error rotation left/right, MROL/MROR: maximal rotation left/right, MPRT: maximal protraction, MRET: maximal retraction.

	Instrument	Mean ROM [$^\circ$.cm]	SD ROM [$^\circ$.cm]	σ_p^2 [%]	σ_{pd}^2 [%]	σ_{prd}^2 [%]	repetitions required for $\Phi >$ 0.75	repetitions required for $\Phi >$ 0.4
UCEX	SUT	29.9	10.7	69.3	18.8	7.6	5	1
	Vicon	29.9	10.5	66.8	19.9	8.6	$>$ 7	1
UCFL	SUT	24.4	8.6	33.2	50.4	12.9	$>$ 7	$>$ 7
	Vicon	26.0	8.9	35.8	48.3	11.5	$>$ 7	4
MEXT	SUT	53.3	12.9	70.8	18.4	10.2	3	1
	Vicon	53.6	13.5	71.1	17.8	9.9	3	1
MFLX	SUT	64.5	8.2	71.7	14.7	8.8	2	1
	Vicon	67.5	8.8	70.6	17.1	8.2	3	1
MLFR	SUT	38.3	9.1	86.9	6.0	6.4	1	1
	Vicon	37.7	8.9	87.0	6.0	6.3	1	1
MLFL	SUT	36.6	8.7	85.8	6.9	4.9	1	1
	Vicon	37.0	8.8	84.8	8.2	4.7	1	1
JPRL	SUT	1.7	1.4	12.5	3.3	71.4	$>$ 7	6
	Vicon	1.7	1.4	14.9	5.3	67.6	$>$ 7	5
JPRR	SUT	1.8	1.6	40.4	7.0	52.6	$>$ 7	1
	Vicon	1.8	1.6	40.7	6.0	53.3	$>$ 7	1
MROL	SUT	67.0	8.7	64.0	18.7	8.7	$>$ 7	1
	Vicon	68.4	8.5	63.8	19.0	8.9	$>$ 7	1
MROR	SUT	63.1	8.5	66.5	21.8	9.0	$>$ 7	1
	Vicon	64.5	8.7	66.6	21.2	9.2	$>$ 7	1
MPRT	SUT	4.0	1.8	66.0	13.8	18.3	3	1
	Vicon	4.2	1.9	67.7	13.6	16.4	3	1
MRET	SUT	4.2	2.6	72.1	11.7	15.3	2	1
	Vicon	4.2	2.5	73.6	10.0	16.0	2	1

likelihood (Bates et al., 2015; Jiang, 2018). For a short description of G-theory, see Appendix A.

The universe of generalization was *day* and *repetition*. The object of measurement was *participant*. The universe score was the expected value of the observed scores for *participant* over the conditions in the universe of generalization.

Given the variance components, the index of dependability (Φ) could be computed. This index is defined as the proportion of the observed score variance that is attributable to participants variance.

$$\Phi = \frac{\sigma_p^2}{\sigma_p^2 + \sigma_d^2 + \sigma_r^2 + \sigma_{pd}^2 + \sigma_{pr}^2 + \sigma_{rd}^2 + \sigma_{prd}^2}$$

ROM and JPE for both systems and each repetition were used as outcomes. RMSE values were also analyzed in a second analysis.

The above mentioned Φ represents the reliability when generalized over one day and one repetition. To quantify the reliability for the mean of k repetitions, i.e. generalizing over one day and an average of k repetitions, the quantities σ_r^2 , σ_{pr}^2 , σ_{rd}^2 and σ_{prd}^2 were divided by k . This *decision-study* then examined how many repetitions are required for an acceptable dependability Φ . In this study, this was performed for $k = 1, 2, 3, \dots, 7$ repetitions.

The index ranges were from 0 to 1, with less than 0.4 indicating poor, 0.4–0.75 moderate and $>$ 0.75 excellent reliability (Santos et al., 2008).

3. Results

Data from eighteen subjects were used in the analysis. Two were excluded due to a non-responding sensor board.

3.1. Range of motion and joint position error

ROM and JPR data are presented in Table 4 and Fig. 3. Although ROM and JPR showed a wide range of measured values, consistency between SUT values and Vicon was observed (Fig. 4).

Range of motion and joint position error

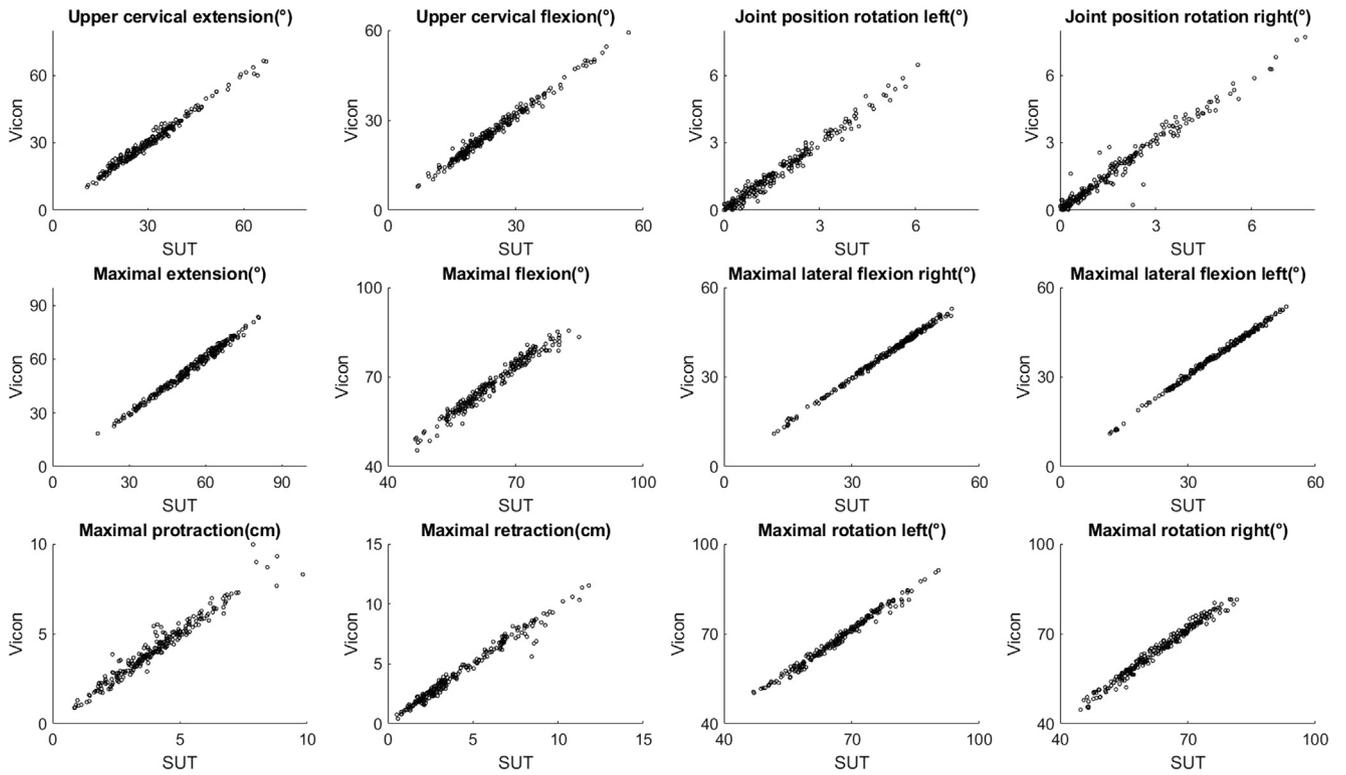


Fig. 3. Range of motion measured with the Vicon and System under test (SUT) for all participants' seven test and retest repetitions.

Maximal flexion

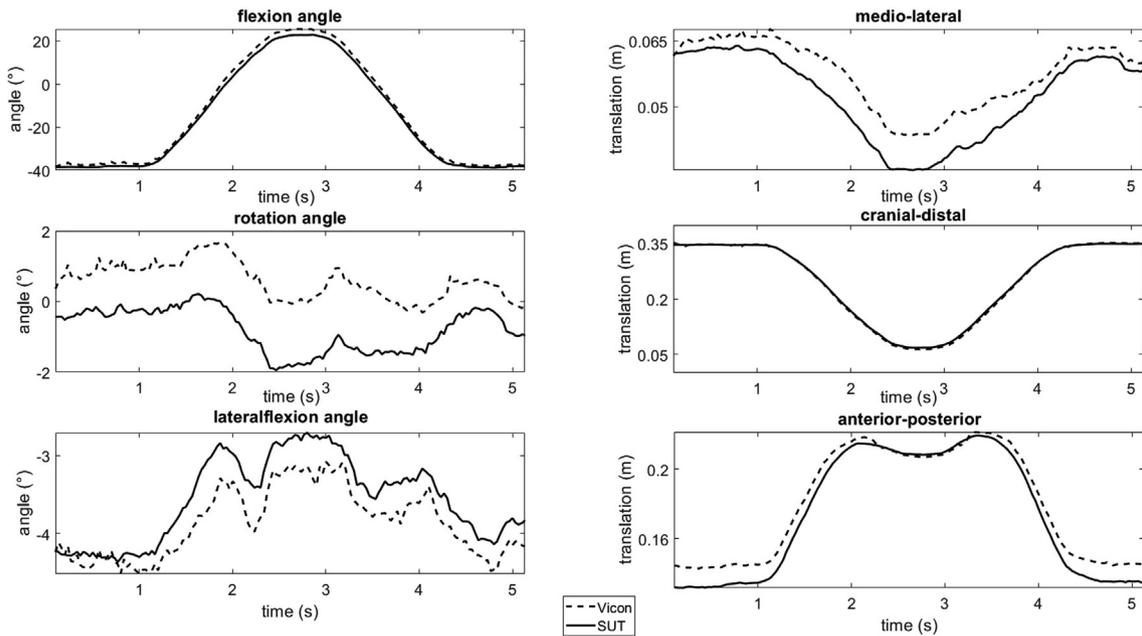


Fig. 4. Example of a maximal neck flexion measured with Vicon and SUT in six degrees of freedom.

Table 5

Root mean square values for all tasks and directions. UCEX: upper cervical extension, UCFL: upper cervical flexion, JPRL/JPRR: joint position error rotation left/right, MEXT: maximal extension, MFLX: maximal flexion, MLFR/MLFL: maximal lateral flexion right/left, MPRT: maximal protraction, MRET: maximal retraction, MROL/MROR: maximal rotation left/right, ZIZA: follow the Zigzag pattern.

	Angular movement			Translation		
	Lateral flexion [°]	Rotation [°]	Flexion/extension [°]	Lateral – medial [cm]	Cranial – caudal [cm]	Anterior – posterior [cm]
UCEX	1.1	1.9	2.0	0.4	0.6	0.4
UCFL	1.0	1.7	1.9	0.4	0.5	0.3
JPRL	1.1	2.1	2.0	0.4	0.5	0.4
JPRR	1.5	1.9	2.2	0.4	0.7	0.4
MEXT	1.2	2.0	2.0	0.6	0.7	0.4
MFLX	1.0	1.7	1.6	0.8	0.4	0.4
MLFR	1.0	1.8	1.7	0.5	0.5	0.5
MLFL	1.0	1.8	2.9	0.4	0.4	0.5
MPRT	1.1	1.8	2.2	0.4	0.5	0.4
MRET	1.0	1.8	2.3	0.4	0.5	0.5
MROL	1.5	2.5	2.0	0.4	0.5	0.5
MROR	3.1	1.7	2.9	0.4	0.9	0.4
ZIZA	0.2	0.4	0.8	0.2	0.2	0.1
Mean overall	1.2	1.8	2.0	0.5	0.5	0.4
Maximum overall	3.1	2.5	2.9	0.8	0.9	0.5

3.2. Validity

RMSE values for all tasks are presented in Table 5. Based on the mean of all tasks, the RMSE values were determined for angular movement as 1.2–2.0° (max. 3.1°) and for translation as 0.4–0.5 cm (max. 0.9 cm).

3.3. Reliability

All variance components were determined for the ROM values. See Table 2 for the definition of abbreviations and description of exercises. The MFLX, MEXT, MLFL, MLFR, MROL, MROR, MPRT, MRET and UCEX all showed a high relative σ_p^2 , indicating that the observed variance had a high participant contribution (Table 4). UCFL showed the highest variance contribution from person \times day interaction, which shows that some person moved variable on different days, which could be due to the task difficulty of UCFL. Repositioning tasks, however, showed a high percentage of residual variance, which cannot be attributed to a specific cause. Lateral flexion showed excellent reliability from one repetition. MEXT, MFLX, MPRT and MRET also showed excellent reliability after three repetitions. A moderate reliability was shown for MROL, MROR and JPRR from one repetition (Table 4).

Table 6

Generalizability theory results for root mean square error values of each task. Percentage variance components for participant (σ_p^2), participant \times day (σ_{pd}^2), and residual (σ_{prd}^2): UCEX: upper cervical extension, UCFL: upper cervical flexion, JPRL/JPRR: joint position error rotation left/right, MEXT: maximal extension, MFLX: maximal flexion, MLFR/MLFL: maximal lateral flexion right/left, MPRT: maximal protraction, MRET: maximal retraction, MROL/MROR: maximal rotation left/right, ZIZA: follow the Zigzag pattern, linear movement medio-lateral.

	σ_p^2 [%]	σ_{pd}^2 [%]	σ_{prd}^2 [%]
UCEX	0.0	95.3	4.7
UCFL	0.0	95.5	4.0
JPRL	14.6	80.9	3.5
JPRR	20.3	72.2	4.8
MEXT	0.0	95.1	4.8
MFLX	0.0	92.1	7.9
MLFR	34.6	56.5	8.1
MLFL	48.0	35.1	8.5
MPRT	41.8	36.4	16.1
MRET	44.0	41.2	14.7
MROL	11.1	85.6	2.3
MROR	31.8	66.2	2.0
ZIZA	18.0	17.1	62.7

The contributions of day, repetition, participant \times repetition, and repetition \times day to the total variance were negligible and are consequently not presented in the overview.

The same analysis of variance was performed for RMSE values (Table 6). Participant \times day had the highest contribution for most tasks.

4. Discussion

The primary aim of this study was to assess the concurrent validity and reliability of an in-house developed tracking system (SUT), built for measuring the relative motion of the head with respect to the trunk in a clinical setting. With an average RMSE of between 1.2 and 2.0° for angular movements and 0.4–0.5 cm for linear movements, the SUT was shown to be able to track movements precisely.

The reliabilities of the SUT and Vicon were comparable over all tasks. Poor reliabilities were found for joint repositioning error and upper cervical flexion, which were not due to measurement inaccuracy. For joint repositioning, a possible cause lies in the small range (mean 1.7°–1.8°) detected, making it difficult to distinguish between subjects. These findings concur with other studies that show poor reliability for repositioning tasks (Jørgensen et al., 2014; Lee et al., 2006).

A ROM of 4.2 cm (SD 2.6) retraction to 4.0 cm (SD 1.8) protraction was found for linear movements. While Lee et al. (2005) have reported a protraction of around 23 cm, our findings are similar to the sagittal mobility (retraction to protraction) of 9.1 cm (SD 1.9) reported by Severinsson et al. (2012). This measurement is calculated from the signal between the trunk and head, taking the trunk belt as the reference. It was observed, however, that the advancement of the head to protraction caused the trunk board to tilt downwards through a slight movement of the trunk. This changed the coordinate system alignment and had an influence on the measured ROM.

When fully extending the neck in MEXT, the helmet occasionally slid backwards. Consequently, participants extended only as far as when the helmet stayed fixed. For future use of the SUT, the helmet should better fit to multiple head forms and the trunk belt should have an improved fixation.

RMSE values had a high variance component of person \times day interaction. This could be due to the setup of the helmet, trunk belt and lighthouses, as well as the calibration and position of the participant.

A limitation of the current SUT were the erroneous pose samples, which were eliminated by the outlier detection. This method could only be implemented real-time with $\frac{1}{2}$ s delay to the actual movement. A possible source of these outliers might lie by the infrared light emitted by the Vicon, which interfered with the lighthouse laser. In addition, the change from one sensor board to another might have led to erroneous samples. In a next step, the aim is to improve the prototype, that these outliers should no more occur. A technical improvement can be done for the calibration of the SUT.

As a conclusion, the reliability of the prototype SUT was comparable to Vicon and has been shown to be valid for measuring not only angular but linear movements in a clinical setting. For tasks such as joint repositioning, it's reliability must be reconsidered.

Declaration of Competing Interest

The authors are not aware of any financial or personal relationships with people or organizations that could have improperly influenced this work. Dr. Lars Lünenburger is an employee of Hocoma AG (Volketswil, Switzerland), a company that might implement the novel tracking technology.

Acknowledgments

The authors would like to thank Karen Linwood for editing the language. This study was co-funded by Innosuisse (25624.1 PFLS-LS).

Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jbiomech.2019.109340>.

References

- Abdulwahab, S.S., Sabbahi, M., 2000. Neck retractions, cervical root decompression, and radicular pain. *J. Orthop. Sports Phys. Ther.* 30, 4–12. <https://doi.org/10.2519/jospt.2000.30.1.4>.
- Audette, I., Dumas, J.-P., Côté, J.N., De Serres, S.J., 2010. Validity and between-day reliability of the cervical range of motion (CROM) device. *J. Orthop. Sports Phys. Ther.* 40, 318–323. <https://doi.org/10.2519/jospt.2010.3180>.
- Bates, D., Maechler, M., Bolker, B., Walker, S., 2015. Fitting linear mixed-effects models using lme4. *J. Stat. Softw.* 67, 1–48. <https://doi.org/10.18637/jss.v067.i01>.
- Brennan, R.L., 2001. *Generalizability Theory (Statistics for Social and Behavioral Sciences)*. Springer-Verlag, New York.
- Childs, J.D., Cleland, J.A., Elliott, J.M., Teyhen, D.S., Wainner, R.S., Whitman, J.M., Sopky, B.J., Godges, J.J., Flynn, T.W., Delitto, A., Dyrw, G.M., Ferland, A., Fearon, H., MacDermid, J., Matheson, J.W., McClure, P., Shekelle, P., Smith, A.R., Torburn, L., 2008. Neck pain: clinical practice guidelines linked to the international classification of functioning, disability, and health from the orthopaedic section of the american physical therapy association. *J. Orthop. Sports Phys. Ther.* 38, A1–A34. <https://doi.org/10.2519/jospt.2008.0303>.
- Diab, A.A., Moustafa, I.M., 2012. The efficacy of forward head correction on nerve root function and pain in cervical spondylotic radiculopathy: a randomized trial. *Clin. Rehabil.* 26, 351–361. <https://doi.org/10.1177/0269215511419536>.

- Ernst, M.J., Crawford, R.J., Schellendorfer, S., Rausch-Osthoff, A.-K., Barbero, M., Kool, J., Bauer, C.M., 2015. Extension and flexion in the upper cervical spine in neck pain patients. *Man. Ther.* 20, 547–552. <https://doi.org/10.1016/j.math.2014.12.005>.
- Ernst, M.J., Williams, L., Werner, I.M., Crawford, R.J., Treleaven, J., 2019. Clinical assessment of cervical movement sense in those with neck pain compared to asymptomatic individuals. *Musculoskelet. Sci. Pract.* 43, 64–69. <https://doi.org/10.1016/j.msksp.2019.06.006>.
- Hall, T.M., Briffa, K., Hopper, D., Robinson, K.W., 2010. The relationship between cervicogenic headache and impairment determined by the flexion-rotation test. *J. Manip. Physiol. Ther.* 33, 666–671. <https://doi.org/10.1016/j.jmpt.2010.09.002>.
- Jiang, Z., 2018. Using the linear mixed-effect model framework to estimate generalizability variance components in R: a lme4 package application. *Methodology* 14, 133–142. <https://doi.org/10.1027/1614-2241/a000149>.
- Jørgensen, R., Ris, I., Falla, D., Juul-Kristensen, B., 2014. Reliability, construct and discriminative validity of clinical testing in subjects with and without chronic neck pain. *BMC Musculoskelet. Disord.* 15 (408). <https://doi.org/10.1186/1471-2474-15-408>.
- Lee, H., Nicholson, L.L., Adams, R.D., 2005. Neck muscle endurance, self-report, and range of motion data from subjects with treated and untreated neck pain. *J. Manipulat. Physiol. Ther.* 28, 25–32. <https://doi.org/10.1016/j.jmpt.2004.12.005>.
- Lee, H.-Y., Teng, C.-C., Chai, H.-M., Wang, S.-F., 2006. Test-retest reliability of cervicocephalic kinesthetic sensibility in three cardinal planes. *Man. Ther.* 11, 61–68. <https://doi.org/10.1016/j.math.2005.03.008>.
- Liu, H., Shah, S., Jiang, W., 2004. On-line outlier detection and data cleaning. *Comput. Chem. Eng.* 28, 1635–1647. <https://doi.org/10.1016/j.compchemeng.2004.01.009>.
- Niehorster, D.C., Li, L., Lappe, M., 2017. The accuracy and precision of position and orientation tracking in the HTC vive virtual reality system for scientific research. *Percept* 8, 1–23. <https://doi.org/10.1177/2041669517708205>.
- Ordway, N.R., Seymour, R., Donelson, R.G., Hojnowski, L., Lee, E., Edwards, W.T., 1997. Cervical sagittal range-of-motion analysis using three methods. Cervical range-of-motion device, 3space, and radiography. *Spine Phila Pa* 1976 22, 501–508.
- Park, S.H., 2015. Kinematic analysis of the lower cervical spine in the protracted and retracted neck flexion positions. *J. Phys. Ther. Sci.* 27, 135–137.
- R Core Team, 2018. *R: A language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria.
- Richards, J.G., 1999. The measurement of human motion: a comparison of commercially available systems. *Hum. Mov. Sci.* 18, 589–602. [https://doi.org/10.1016/S0167-9457\(99\)00023-8](https://doi.org/10.1016/S0167-9457(99)00023-8).
- Santos, B.R., Delisle, A., Larivière, C., Plamondon, A., Imbeau, D., 2008. Reliability of centre of pressure summary measures of postural steadiness in healthy young adults. *Gait Posture* 27, 408–415. <https://doi.org/10.1016/j.gaitpost.2007.05.008>.
- Seo, S.H., Hwang-Bo, G., Yuk, G.-C., Han, J.-T., Kim, J.-H., Park, S.H., 2013. Dynamic intervertebral body angle of the lower cervical spine during protracted head extension using measured by fluoroscopy. *J. Phys. Ther. Sci.* 25, 237–239.
- Severinsson, Y., Elisson, L., Bunketorp, O., 2012. Reliability of measuring the cervical sagittal translation mobility with a simple method in a clinical setting. *Rehabil. Res. Pract.* 2012, 1–9. <https://doi.org/10.1155/2012/629104>.
- Treleaven, J., Jull, G., Sterling, M., 2003. Dizziness and unsteadiness following whiplash injury: characteristic features and relationship with cervical joint position error. *J. Rehabil. Med.* 35, 36–43. <https://doi.org/10.1080/16501970306109>.
- Vernon, H., 2008. The neck disability index: state-of-the-art, 1991–2008. *J. Manipulat. Physiol. Ther.* 31, 491–502. <https://doi.org/10.1016/j.jmpt.2008.08.006>.
- Wang, J., Hsu, Y., Liu, J., 2010. An inertial-measurement-unit-based pen with a trajectory reconstruction algorithm and its applications. *IEEE Trans. Ind. Electron.* 57, 3508–3521. <https://doi.org/10.1109/TIE.2009.2038339>.
- Yates, A., Selan, J., 2016. POSITIONAL TRACKING SYSTEMS AND METHODS - Patent. 20160131761.
- Yong, M.-S., Lee, H.-Y., Lee, M.-Y., 2016. Correlation between head posture and proprioceptive function in the cervical region. *J. Phys. Ther. Sci.* 28, 857–860. <https://doi.org/10.1589/jpts.28.857>.