A Home-Based Self-administered Assessment of Neck Proprioception

Angelo Basteris(✉), Charlotte Egeskov Tornbjerg, Frederikke Birkeholm Leth, and Uffe Kock Wiil

Health Informatics and Technology Center, SDU HIT, Mærsk McKinney Møllier Institute, Faculty of Engineering, University of Southern Denmark, 5230 Odense, Denmark
angelobasteris@gmail.com

Abstract. Proprioception is fundamental for maintaining balance and moving-hence for daily living. As proprioception deficits may occur with aging, neurological and musculoskeletal (especially cervical) conditions, assessment of proprioception can be relevant for a very large cohort of individuals.

We designed a web page that allows measuring the neck joint position sense while sitting in front of a standard webcam. The web page tracks the subjects' head movement and instructs them on how to perform a head repositioning accuracy protocol. We performed a test retest analysis of this tool in order to assess its feasibility and reliability. Eleven healthy subjects participated in two sessions over consecutive days, at their homes. We calculated average errors across four directions Bland-Altman level of agreement between the measurements on the two sessions.

All participants could complete the test in approximately six minutes. The average absolute error did not differ between the two sessions, showing close to zero bias and a 95% limit of agreement of 1.676°. These values changed significantly across directions, suggesting that the performance of the head tracking software for neck flexion movements may be limited.

By comparing our results with normative values, we suggest that the narrow limit of agreement we observed makes the web page potentially capable of distinguishing healthy subjects from subjects with proprioceptive deficit in the neck joint.

Keywords: eHealth · Movement analysis · Proprioception

1 Introduction

Neck pain is a highly prevalent condition, as it is estimated that 37% of people worldwide will experience neck pain at least once a year [1]. Not only it already is very common, but due to population growth and aging it is expected to become even more relevant in the next future [2]. The burden of neck pain worldwide is heavy both in terms of disability [3] and economically [4].

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A coarse classification of neck pain can be made based on whether it is of known (specific) or unknown (idiopathic) non-traumatic origin, or it is trauma-induced [5].

Regardless of the cause of neck pain, loss of proprioception ("*the sense of one's own body"*) is a symptom frequently associated with conditions which affect the neck joint. Also, aging is frequently associated with a progressive loss for vestibular function [6].

As proprioceptive deficits significantly impact quality of living, it is not surprising that several methods have been developed for assessment of cervical Joint Position Sense (JPS). The standard to measure JPS in clinical practice is to place a headband with a laser pointer on top of the person's head, in order to observe the errors–as distance of the laser dot from the center of a target placed in front of the person – when he/she moves the head back to the central position [7] after an either passive or active movement of the neck. However, this simple method is time-consuming as it requires a trained person to administer the test.

Technology has come into help for measuring JPS with systems which have so far been used mostly in research facilities. Proprioceptive assessment can be done with electrogoniometers [8], electromagnetic trackers [9] and optoelectronic systems [10]. Unsurprisingly, a more recent technology like VR head mounted displays have been used to monitor head stability [11]. Notably, all these systems require dedicated hardware, and this may limit accessibility to these methods. Moreover, all of these systems also require the subject to wear some equipment – with consequent burdens in terms of comfort and hygiene.

We previously proposed the use of webcam-based head tracking to measure JPS [12]. Our method showed that results in neurologically intact individuals who participated in a lab-based session under the supervision of a researcher were comparable to normative values described in literature. In this work, we aim at evaluating the feasibility and the reliability of remote unsupervised measurement of neck JPS.

2 Methods

2.1 Task

The task consisted in an active-active neck joint position sense test. The participant was asked to sit still and look straight ahead. Each repetition consisted of five phases. Transition between phases occurred based on subject's movement or actions (click).

1) *Initial.* The neutral, starting position acquired when the participant clicks, at the beginning of the session, is acquired as the reference (target) position with respect to which errors are calculated.
2) *Outward movement.* Once the target position is set by clicking, the participant is asked to close the eyes (so that the task relies only on his/her proprioception, and no visual information is used) and to move the head, as far as possible, in one of four possible neck movement directions (extension, flexion, right and left rotation)
3) *Matching.* The subject moves the head to return to the neutral position, trying to match it as accurately as possible. He/she confirms the response (*final position*) by clicking.

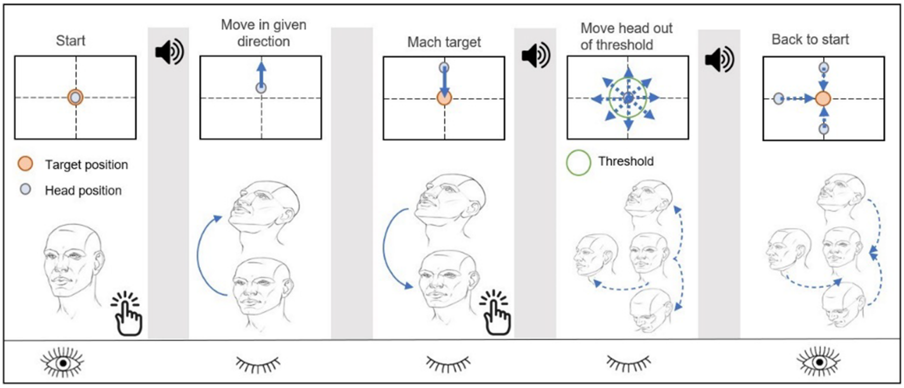

Fig. 1. Each repetition of a JPS measurement articulates in 5 phases: initial, outward movement, matching, distraction and return to center

4) *Distraction.* Once the final position was confirmed, the participants was asked to move the head for an amplitude of at least approximately 5°, still with the eyes closed; in this way, no feedback was provided before
5) *Return to center.* The subject can open the eyes and return to the target position (by aligning a cursor showing the head angles on the screen) in preparation for the next repetition.

2.2 Experimental Protocol

A convenience sample of eleven neurologically intact volunteers (5M/6F, age: 23 ± 1) participated in this study. A restricted access web page was set up, and participants were recruited through referral among peers. Information about this study, including instructions on how to take part in the experiment, and informed consent were provided and acquired through the same website.

Participants accessed the website without any supervision, from their homes and using their laptops. They were requested to place the camera at eye level in front of their eyes and they were instructed to repeat the test on two consecutive days, at the same time of the day. On each day, each participant performed a total of 28 repetitions (7 in each of the 4 directions) in a pseudo-randomized order. For each day, the first four repetitions (one per direction) were considered as familiarization and discarded from further analysis. Participants did not receive any feedback about their performance upon completion of the first session, while a graph showing the final positions on day 2 was display at the end of the second session.

2.3 Head Tracking Software

While the standard, responsive webpage was created using standard HTML and JavaScript code, the core of the functionality for proprioceptive assessment (i.e. movement analysis) was implemented using PoseNet [13]. PoseNet is a community supported library for markerless skeleton tracking. The library is built on top of TensorFlow models trained to find human poses on still images [14]. Once a human pose is found, the software provides an overall confidence for it (in range 0–1) and the estimates of 17 skeleton points. For each of these points (nose, plus eye, ear, shoulder, elbow, wrist, hip, knee and ankle on each side) the software measures horizontal and vertical coordinates on the camera plane, in pixel with origin on the bottom left corner, and a confidence score again in range 0–1. For the website, we used only the nose, eyes, and shoulders coordinates to estimate angles of rotation of the neck.

Angles of left and right rotation were estimated using only the lateral coordinates of the nose, left and right shoulder (x_N, x_{LS} and x_{RS}, respectively). We indicate with L and R the difference between the horizontal coordinates of the nose and of the left and right shoulder, respectively:

$$L = x_{LS} - x_N ; R = x_{RS} - x_N \tag{1}$$

Assuming that the subject is facing the camera and looking straight at it, these distances will be equal and opposite in sign ($L = -R$). Leftwards rotation causes L to decrease and R to increase, while rightward rotation provokes an opposite increase in L and decrease in R. We thus estimated angle of lateral rotation of the head as

$$\theta_L = +45 - \arctan\frac{L}{R} \tag{2}$$

causing $\theta_\mathrm{L} = 0°$ in the reference position and $\theta_\mathrm{L} > 0$ for rightward rotations.

We estimated neck flexion/extension movements by using the nose, left and right shoulders vertical coordinates (y_N, y_{LS} and y_{RS}, respectively). Let E be the vertical coordinate of the midpoint between the eyes:

$$E = \frac{y_{LE}+y_{RE}}{2} \tag{3}$$

and D_0 the value of E when the subject is facing the camera, in the initial position. As the subject turns the head downwards, the value of E decreases (that is, the projection of the eyes on the camera plane appear closer to the projection of the nose than in the initial position), while upwards rotation likewise cause an increase of E. We thus estimated angle of vertical rotation of the head as

$$\theta_V = -45 - \arctan\frac{y_N - E}{D_0} \tag{4}$$

causing $\theta_\mathrm{V} = 0°$ in the reference target position and $\theta_\mathrm{V} > 0$ for neck extension.

2.4 Data Analysis

For each repetition, the software measured the absolute error and the constant error (absolute value and value of the difference between final and target position). We retained only the angle θ_L after lateral rotations and only θ_V after vertical movements, so that movements off the main movement axis were not accounted for in the error amplitude. We calculated the absolute error for each subject, direction and session as median value of the six repetitions, and the average of the four values as an indication of subject's accuracy. We compared the time taken to complete the experiment and the absolute error for each day by a paired samples t-test.

We also performed a Bland-Altman analysis to establish the bias and the level of agreement for the head tracking software across the two days [15]. The Bland-Altman method reveals systematic differences between two measurements and the limit of agreement represent the 95% confidence interval due to random fluctuations of the measurement method. We repeated the same Bland-Altman analysis were repeated on the median values in each of the four directions, in order to understand whether reliability of the proposed software method differed across movement direction.

3 Results

3.1 Test Duration

Figure 2 displays the duration of the test for each subject on both days. On the first day, subjects could complete the test in an average of 400 s (range: 312–520 s). On the second day, it took all subjects a lower time to perform the same test ($p < .001$), with an average duration of 312 s (range: 240–366 s).

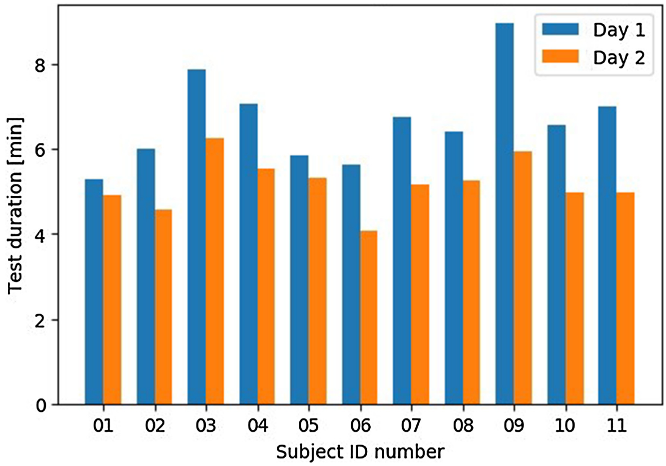

Fig. 2. Time taken to complete the full test (28 repetitions) by each subject on two consecutive days

3.2 Absolute Error – All Directions

Figure 3 shows the average error for each subject on both days. Subject 11 showed errors higher than the average of the other participants (three to four times higher) and his data were than excluded from further analysis.

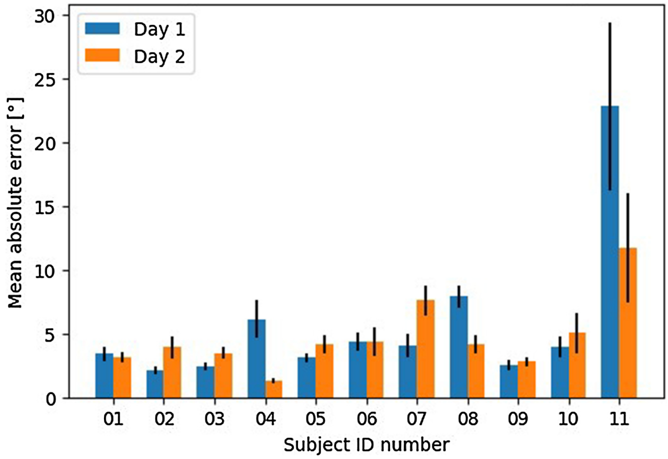

Fig. 3. Mean absolute error for each subject, on both days. The mean value was calculated among the four median values (one per direction) among six repetitions. Errorbars represent the standard error of the mean.

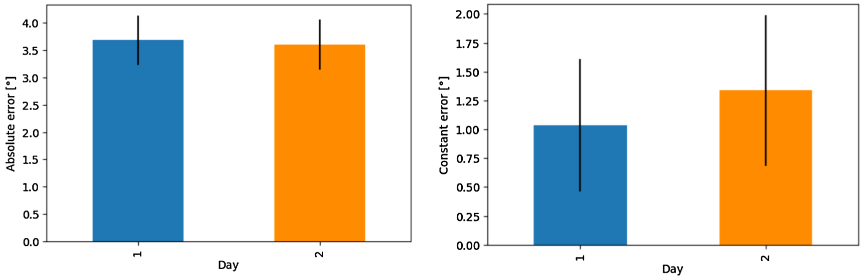

Fig. 4. Average absolute error (left panel) and constant error (right panel) for each day, all subjects.

Figure 4 shows the average absolute error (among all subjects) on first and second day, in the left panel. It is noteworthy that, despite the lower time, the absolute error did not differ across days ($p = 0.95$). Figure 4 also shows, in the right panel, that the constant error was positive on both days, meaning that subjects tended to overshoot the target position, with a non-significant increase in constant error on the second day.

Figure 5 shows the agreement between the measurements on the two days. The method was proven to have very low bias (0.079°) and a 95% level of agreement interval of 1.676° (range between −1.597° and 1.755°).

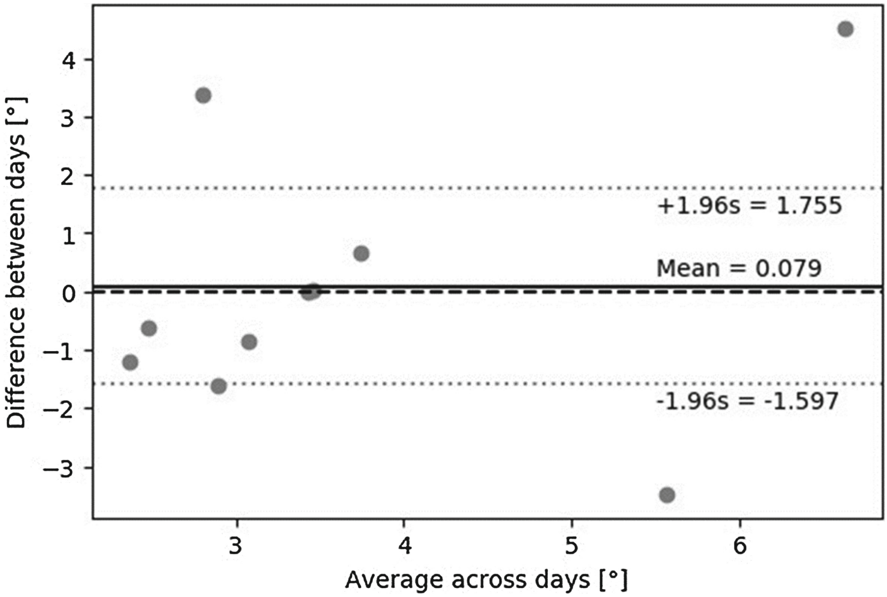

Fig. 5. Bland-Altman plot showing 95% level of agreement between repeated measures of neck JPS

3.3 Effect of Movement Direction on Absolute Error

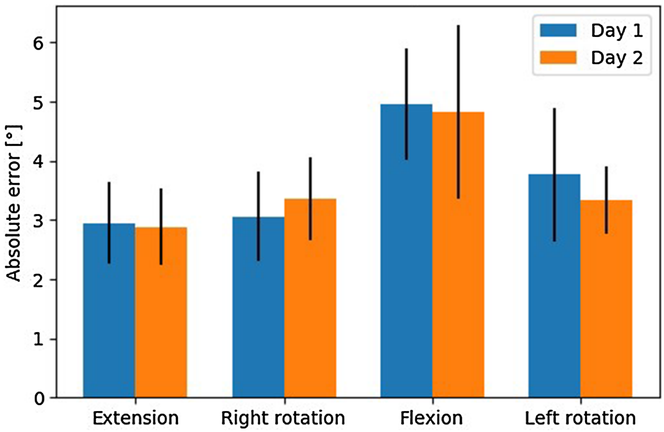

Fig. 6. Average error for all subjects after each of the four movement directions.

Errorbars represent the standard error of the mean.

Figure 6 shows the average error on both days, for each direction. While no significant changes were observed among days, our results show higher error when trying to match the target position after returning from flexion movement. Also, it is noteworthy left rotation movements led to slightly higher error than right rotation.

Not only the average absolute error, but the level of agreement showed strong variation among directions, as shown in Fig. 7. Along with the higher average absolute error, flexion movements also led to the larger extent for the level of agreement.

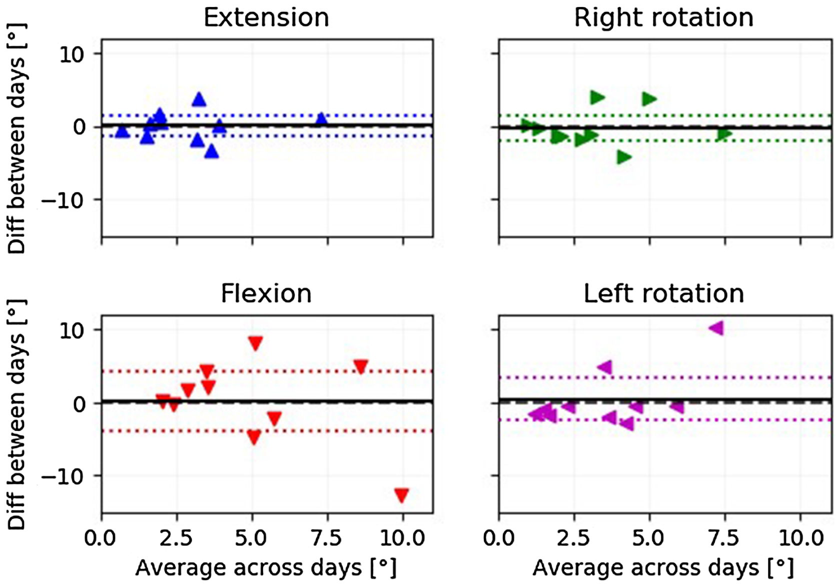

Fig. 7. Bland-Altman plot for repeated measures across four different directions, all subjects. Dashed lines mark 95% level of agreement.

Table 1 summarizes these results: the bias between days appeared higher for lateral rotations than for flexion and extension. In a similar fashion as the average absolute error, also the the level of agreement differed between left and right rotations.

Table 1. Average absolute error and Bland-Altman bias and 95% confidence level of agreement between measurements on two consecutive days after movement in each of the four different directions.

Direction	Absolute error [°]	Bias [°]	Level of agreement [°]
Extension	2.91	0.057	1.387
Flexion	4.89	0.135	4.14
Right rotation	3.21	−0.301	1.791
Left rotation	3.55	0.427	2.877

4 Discussion

4.1 Feasibility of Self Administered Assessment of Neck Proprioception.

Our results prove the feasibility of a home-based, self-administered assessment of the neck joint position sense. Previous work using hardware compatible with a home environment included gaming devices like the WiiMote [16], and it was also suggested that a 3D camera could be used for postural assessment [17]. Unfortunately, these devices are not available to many users. A more inclusive solution is the use of smartphone for vestibular rehabilitation [18]. However, our solution only relies on the availability of a webcam, and it is thus potentially available to any user of a standard laptop or smartphone. Also, the same solution can be easily adapted to measure proprioception of the other body joints (i.e. shoulder, elbow, knee) already tracked by the skeleton tracking software used in this study.

The subjects participated in tests from their homes, without any live interaction with the researchers. They only received an email with the information sheet and instructions about their participation, and they were then guided by the website by means of voice guidance provided through speech synthesis, during the test. This potentially saves work hours from the healthcare professionals, who can then dedicate their time to treat patients, and resources for unnecessary travels for the patients. Of the 11 subjects who participated in this study, only one (subject 11) showed abnormal values on both days. It is possible that the instructions were somehow not clear to this participant, but as no information about the participants', other than the results of their tests was recorded, it is no possible to ascertain the reason for this exceptionally high values.

The test proven to be quick to be performed, as all the subjects could complete it in less than 9 min, with an average of 400 s on the first day. The fact that on the second day all participants could perform within a smaller duration suggests that there is some familiarization with the test. However, the similarity of results across the two days, also considering that no feedback was provided, reduces the concerns raised by this familiarization.

4.2 Test-Retest Reliability of the Proposed Method and Implications for Diagnostic Value

The average absolute error across the two days was $3.64 \pm 2.62°$, with a small change (0.08°) between the two days, and a 95% level of agreement of 1.676°. The average value is comparable with the values reported by other studies which used conventional methods for using the neck JPS. There are indeed two other studies reporting 3.6° as the average absolute error for healthy subjects [19, 20]. Armstrong et al. reported $3.25 \pm 2.32°$ as absolute error for healthy subjects [8] when averaging all movement directions, while Revel et al. had previously suggested $3.50 \pm 0.82°$ for lateral rotations and 3.37 $\pm$ 0.73°.

A review about evidence of impaired proprioception in chronic idiopathic neck pain considered 10 studies, indicating a absolute difference in error between people with chronic neck pain and healthy controls ranging from 0.1 to 3.0 [21]. As the extent of our level of agreement falls within this range, our test may be reliable enough to distinguish between people with chronic neck pain and healthy individuals, with potential diagnostic value – that needs however to be assessed in a specific study.

4.3 Effect of Direction on Average Error and Test-Retest Reliability

Our system performed differently along movement directions. It is important to stress that our system estimated the rotation angles based on the method described in Sect. 2.3 (Eq. 2 and 4). Concerning lateral rotations, there was a small difference between left and right rotations. However, the amplitude of such difference is compatible with those reported by a number of other studies (e.g. 0.3 [10]) and may be affected as an instance by subjects' handedness [22]. The high difference in level of agreement between the two lateral directions may be a consequence of the low number of subjects who participated in this study.

We found a high difference between errors after flexion and extension movement, with higher errors after flexion. Also, the level of agreement for the former was approximately three times higher than for the latter. These results may be a consequence by factors that we could not control for, in particular, the camera positioning. If the camera was placed below the participants' head, the misalignment between the camera optics and the head's rotation axis would have caused errors in the vertical angle estimation. We rely that this may have been the case, especially if subjects performed the test using a standard laptop and did not follow the instructions of facing the camera directly. Further studies may use the position of the shoulders– as it was successfully done for the lateral angle - also for estimating the vertical angle.

4.4 Limitations of This Study

This study involved only young healthy individuals (average age 23 years). A population with higher age range may show a significantly higher absolute error, and possibly altering the level of agreement. Also, the head tracking system is not yet validated against a gold standard, which would provide estimates of its precision in tracking the head movement.

5 Conclusions

Our results prove that a webcam-based face tracking system can be used for a remote, unsupervised assessment of proprioception. This will allow people with neck pain to monitor their performance in proprioceptive tests at home, without the supervision of a healthcare professional.

The good level of agreement observed in this study between measurements on two consecutive days on healthy individuals suggests that the tool has good reliability, especially after extension, left and right rotation movements – while results after flexion movements require further testing.

The level of agreement found in this study - lower than differences in JPS error between healthy individuals and people with neck pain reported in literature – supports future studies aimed at establishing the diagnostic value of this tool by comparing results in populations with and without proprioceptive impairment.

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