Measurement properties of the measure of cervical joint position error in people with and without chronic neck pain

A thesis submitted to the University of Birmingham for the degree of DOCTOR OF PHILOSOPHY

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May 2024

Abstract

Neck pain is a common musculoskeletal condition that affects people’s quality of life, physical level, emotional well-being, and daily functioning. It is ranked as the fourth cause of disability worldwide. People with chronic neck pain (CNP) often show proprioceptive deficits, which is commonly quantified by assessing cervical joint position error (JPE). Measurement properties encompass the qualities or attributes inherent in a measurement instrument or tool that dictate its capacity to gauge the intended construct or concept precisely and consistently. These properties play a vital role in guaranteeing that the measurement tool/measure yield results that are both valid and significant. The aim of this thesis was to assess the measurement properties of the measure of JPE in people with and without CNP.

In this thesis, one systematic review and two empirical studies have been carried out. The first study summarised and appraised the literature of the measurement properties of the measure of JPE in people with and without neck pain. Both absolute error (AE) and constant error (CE) were considered. The systematic review revealed that the reliability and validity of the measure of JPE showed sufficient results, but the levels of evidence were low/very low due to extreme risk of bias, imprecision, and inconsistency in the results. The results of this systematic review highlighted gaps in testing the reliability and validity of JPE using a laser pointer after returning from neck flexion, extension, right and left rotation. Moreover, the review revealed that the responsiveness of this measure has not been investigated. The second study in this thesis investigated the reliability, measurement error, and validity of JPE when assessed in sitting and standing in people with and without CNP. Tests of relocation accuracy to a neutral head position (NHP) and target head position (THP) tasks were tested. This study revealed that the JPE is a reliable and valid measure but not for all neck movements. In this study, differences in repositioning errors in people with and without CNP were also evaluated; people with CNP showed significantly greater JPE than the asymptomatic participants, but mainly when the absolute JPE was assessed. Differences in JPE between testing positions (sitting versus standing) in both groups (asymptomatic and CNP) were also tested. There were no significant differences between testing positions, apart from the constant JPE in people with CNP after returning from left rotation. In the third study, the responsiveness of the measure of JPE was investigated. JPE was assessed before and after four weeks of home-based proprioception training. Proprioception training comprised of repositioning errors tasks (NHP, THP) as well as movement sense tasks which included tracing a double ZZ bands and different circular shapes and arrows. The study showed that the measure of JPE was able to detect a change (internal responsiveness) after 4-weeks of home-based proprioception training intervention, but this was mainly so for the measure of absolute JPE. The correlation of change of scores (external responsiveness) obtained from the laser pointer and inertial measurement units (IMUs) was weak. Findings of this thesis indicates that the JPE test, using a laser pointer, is a reliable, valid measure. It also showed that the measure of JPE is responsive, however, further research, addressing the limitations identified in *Chapter 4*, is required. Overall, the findings of this thesis support the use of JPE, in assessing proprioception in research and clinical settings.

Acknowledgments

Praised be to Allah for his blessings and guidance through the journey of my PhD. Special thanks to my supervisors Professor Deborah Falla and Dr Janet Deane for their endless support and guidance throughout this journey. Also, I would like to thank the Civil Service Commission at the State of Kuwait for sponsoring me. I would like also to thank my colleagues Shouq Althobaiti for being a second reviewer in my first study and Valter Devecchi for being a second author in my second and third studies. My deepest thanks to my father for his support throughout my oversees journey. My deepest thanks to my great wife, who was also a PhD student at the University of Birmingham, for her support and love. She was a PhD student, a mother of three great kids, and a great friend during my postgraduate life.

This thesis is dedicated to my lovely mother who passed away in 2005 due to cancer. RIP mom.

List of publications

During this Ph.D. at the School of Sport, Exercise, and Rehabilitation Sciences, some of the work in this thesis has been published in scientific journals, therefore, sections of this thesis include verbatim text from published work. Some sections in this thesis were developed from published work in terms of structure and content with slight changes to build the overall argument of this thesis.

Published articles

AlDahas A, Heneghan NR, Althobaiti S, Deane JA, Rushton A, Falla D. Measurement properties of cervical joint position error in people with and without neck pain: a systematic review and narrative synthesis. BMC Musculoskeletal Disorders. 2024 Dec;25(1):1-9.

AlDahas A, Devecchi V, Deane JA, Falla D. Measurement properties of cervical joint position error in people with and without chronic neck pain. Plos One. 2023 Oct 12;18(10):e0292798.

AlDahas A, Devecchi V, Deane JA, Falla D. Responsiveness of the cervical joint position error test to detect changes in neck proprioception following four weeks of home-based proprioceptive training. Plos One. 2024 April.

Poster presentation

AlDahas A, Rushton A, Althobaiti S, Falla D, Heneghan N. Measures of spinal proprioception and their measurement properties: A systematic review and narrative synthesis. Physiotherapy. 2022 Feb 1;114:e146-7.

Contents

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List of Abbreviations

Term	Abbreviation
Absolute error	AE
Central nervous system	CNS
Cervical movement sense	CMS
Cervical range of motion	CROM
Cervicogenic disc disease	CDD
Chronic neck pain	CNP
Clinical cervical movement sense test	CCMST
Consensus-based Standards for the Selection of health Measurement Instrument	COSMIN
Constant error	CE
Control group	CG
Craniocervical flexion	C-CF
Dizziness Handicap Inventory	DHI
Figure of eight	F8T
Grading of Recommendations Assessment, Development, and Evaluation	GRADE
Head repositioning accuracy	HRA
Head repositioning to 30 degrees test	HR30T
Head repositioning to neutral	HRNT
Inertial measurement unit	IMU
Intraclass Correlation Coefficient	ICC
Joint position error	JPE
Joint position sense	JPS
Limits of agreement	LoA
Minimal important change	MIC
Neck Disability Index	NDI
Neck pain	NP
Neutral head position	NHP
Numerical rating scale	NRS
Patient-Reported Outcome Measures	PROMs
Pearson’s correlation	r
Preferred Reporting Items for Systematic Review and Meta-Analysis	PRISMA
Randomised controlled trials	RCTs
Range of motion	ROM
Rehabilitation group	RG
Risk of bias	RoB
Sample, Phenomena of Interest, Design, Evaluation, and Research	SPIDER
Standard error of measurement	SEM
Tampa Scale of Kinesiophobia	TSK
Target head position	THP
Torsion test	TT
Ultra-Sound	US
Visual analogue scale	VAS
Weighted kappa	WK
Whiplash associated disorders	WAD

List of appendices

Chapter 1: Introduction

1.1 Overview of chronic neck pain

Chronic neck pain (CNP) is characterised by pain persisting for more than three months (1). Globally, the prevalence of CNP ranges between 30% to 50% (2); it is more prevalent in women than men (2) and highest in the 40-45 years age (3). As for the incidence rate, it has been shown that healthcare workers, office workers, and transit operators have a higher incidence of neck pain than the general population (4). Office and computer workers have a particularly high incidence; 57% in the US, 36% in Sweden, and 34% in Finland (5). In the UK, it is reported in one-fifth of adults had neck pain in the past 12 months (6). A study in the UK among adults showed that people with neck pain will continue to have persistent pain for the next 12 month (7). Several risk factors may predispose an individual to the development of neck pain. These include genetics, depression, anxiety, sleep disorders, smoking, and a sedentary lifestyle (8,9). Also, it is higher in people who are obese (8).

Although neck pain is not associated with high morbidity rates, the high prevalence rates of neck pain incurs substantial costs to the individual, their families, healthcare systems, and businesses (3). Absence from work and disability is cited to account for 77% of this cost, while 23% accounts for direct health costs (10). In the UK, neck pain is one of the conditions that most frequently led to absence from work, accounting for 30 million lost workdays in 2016 (11). In the Netherlands, it is estimated that neck pain costs 686 million US dollars (10). In the US, costs of back and neck pain account for 87.6 billion US dollars, ranking third highest after costs of diabetes and heart disease (9).

In the literature, different methods exist to classify neck pain. For example, Werneke et al. (12) proposed that neck pain can be categorised according to centralisers and noncentralisers where centralisation means less disability and pain. A more comprehensive classification was proposed by Childs et al. (13). This was based on clinical findings and, specifically, treatment aims. In this review (13), five neck pain classifications were proposed (Figure 1.1): mobility, centralisation, conditioning and increased exercise tolerance, pain control, and reduce headache.

In the mobility classification, patients often are younger in age with a primary reduction in range of motion (ROM). During clinical examinations, patients typically present with side-to-side differences in lateral rotation and side-bending. Symptoms are mainly in the neck and do not peripheralise into the upper quadrant. In the centralisation classification, patients with neck pain may be categorised into this class if they present symptoms of nerve root compression (i.e. radicular pain to the extremities). Centralisation occurs when the movement of the neck results in reduction of pain and movement of symptoms from areas more distal in the upper quadrant to areas more proximal to the neck (13). Patients who were categorised into this classification may be further sub-classified into radicular or referred symptoms to the upper quadrant or mid-scapular area. In addition, patients who were diagnosed, based on radiological findings with cervical radiculopathy may be classified into the centralisation category (13).

Patients who were categorised into the conditioning and increased exercise tolerance classification did not present clinical signs or mobility restrictions or referred pain. Those patients tended to have lower disability and pain levels but persistent symptoms for longer periods. Patients who are commonly referred to physiotherapy clinics for clinical instability fit into this classification. Improving motion and centralisation does not benefit these patients. A proposed treatment is focusing on strength and conditioning (13). Moreover, patients who fit in the headache reduction classification typically present with a headache that starts in the neck and progresses to the fronto-ocular area and unilateral headache. Other findings may be excruciating or throbbing pain that is triggered by neck movement or pain elicited by pressure on the same side of the neck. Lastly, the pain control classification. Patients that present with severe neck pain may be categorised into this classification. These patients do not tolerate any clinical examination and usually have high pain and disability levels, ROM restrictions, and radicular pain (13).

Figure 1. 1. Classification of neck pain with key examination findings and proposed treatment methods (13).

Classification	Examination Findings	Proposed Matched Interventions
Mobility	• Recent onset of symptoms • No radicular/referred symptoms in the upper quarter • Restricted range of motion with side-to-side rotation and/or discrepancy in lateral flexion range of motion • No signs of nerve root compression or peripheralization of symptoms in the upper quarter with cervical range of motion	• Cervical and thoracic spine mobilization/manipulation • Active range of motion exercises
Centralization	• Radicular/referred symptoms in the upper quarter • Peripheralization and/or centralization of symptoms with range of motion • Signs of nerve root compression present • May have pathoanatomic diagnosis of cervical radiculopathy	• Mechanical/manual cervical traction • Repeated movements to centralize symptoms
Conditioning and increase exercise tolerance	• Lower pain and disability scores • Longer duration of symptoms • No signs of nerve root compression • No peripheralization/centralization during range of motion	• Strengthening and endurance exercises for the muscles of the neck and upper quarter • Aerobic conditioning exercises
Pain control	• High pain and disability scores • Very recent onset of symptoms • Symptoms precipitated by trauma • Referred or radiating symptoms extending into the upper quarter • Poor tolerance for examination or most interventions	• Gentle active range of motion within pain tolerance • Range of motion exercises for adjacent regions • Physical modalities as needed • Activity modification to control pain
Reduce headache	• Unilateral headache with onset preceded by neck pain • Headache pain triggered by neck movement or positions • Headache pain elicited by pressure on posterior neck	• Cervical spine manipulation/mobilization • Strengthening of neck and upper quarter muscles • Postural education

Other methods also exist to classify neck pain. For example, classifying neck pain according to the duration or mechanism of onset (8). Categorisation by the duration of pain is as follows: acute (<6 weeks), subacute (≤3 months), and chronic (>3 months) (8). In terms of the mechanism, it can be categorised as mechanical, neuropathic, or secondary to another cause (8). Mechanical pain is pain that arises from structures around the spine, like ligaments or muscles, or it may originate from the spine itself (8). An example of mechanical pain would be pain originating from spinal facet joints. Neuropathic pain can be defined as pain originating from an injury to peripheral nerve roots. A herniated disk with radiating pain or spinal stenosis are examples of the cause of neuropathic pain (8). On the other hand, neck pain as a cause of trauma (e.g., whiplash injury) can happen by rear-end or side car collisions and may lead to various clinical manifestations called Whiplash Associated Disorders (WAD) (14). Although people with CNP have several impairments (sleep disturbances, emotional impact, and social limitations), this thesis will focus on physical impairments, specifically proprioception.

1.2 Physical impairments in people with chronic neck pain

People with CNP present a myriad of disturbances in physical function. This includes reduced muscle power and ROM (15), reduced smoothness of neck movement (16–19), and changes in muscle coordination (20–23). A further impairment is impaired proprioception. Revel et al. (24) were the first to investigate and demonstrate impaired proprioception in people with CNP quantifying joint position error (JPE). Since then, extensive research has aimed to investigate whether there is an impairment in proprioception among those with neck pain. The following section will define proprioception and review studies assessing sensorimotor control in people with neck pain.

1.3 Proprioception

The term proprioception was first introduced in 1906 by Charles Sherrington. It was defined as ‘‘the perception of joint and body movement as well as the position of the body, or body segment in space" (25). Proprioception is described as having three roles: to protect against excessive joint movements via a reflex mechanism, to stabilise joints during the static posture, and to coordinate movements of the body while performing activities of daily living (25). The sense of proprioception is provided by mechanoreceptors that convert mechanical stimuli into action potentials and transmit these to the central nervous system (CNS) (26). Mechanoreceptors can be found in muscles, tendons, joints, and fascia.

Muscle spindles are the most important mechanoreceptors (27). They are highly sensitive, and their density is very high in the sub-occipital muscles (i.e. rectus capitis posterior major, rectus capitis posterior minor, obliquus capitis inferior, and obliquus capitis superior) (28,29). Joint proprioceptors are another type of mechanoreceptors. However, their contribution to proprioception is less clear than that of muscle spindles, with a somewhat controversial role described within the literature (26). Some research findings suggest that joint proprioceptors are limited to being a type of limit detector and send afferent information only at the end of ROM (30), while other research indicates that joint proprioceptors send afferent information throughout the whole ROM (31,32).

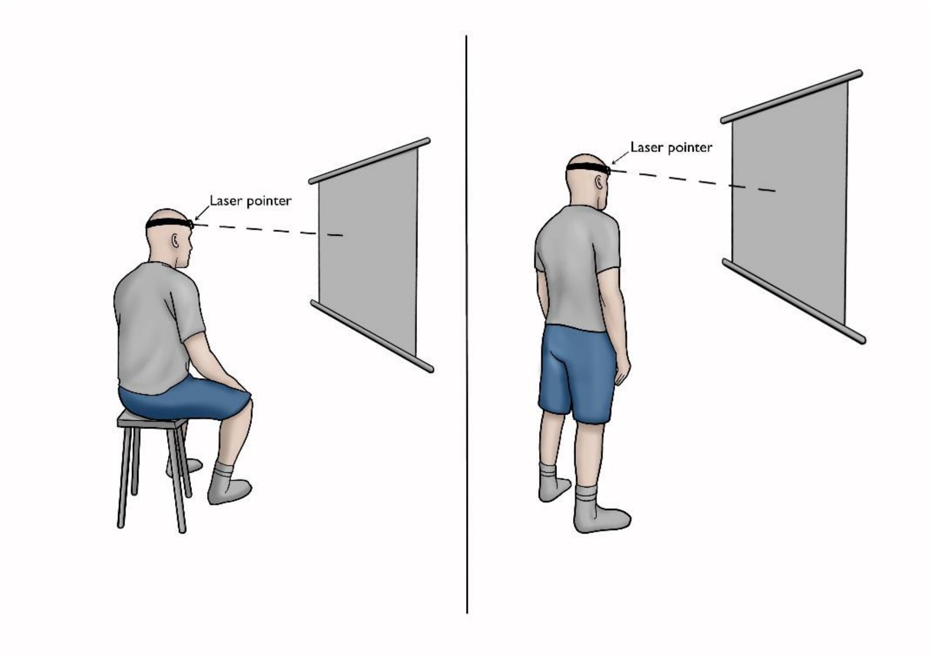
Proprioceptive information may be processed by conscious and unconscious proprioception. During conscious proprioception, information from mechanoreceptors is sent to the medulla and thalamus and then to the somatosensory cortex via ascending pathways. During unconscious proprioception, information is sent to the cerebellum via the spinal nucleus.

1.4 Assessment of neck proprioception

Different outcome measures were identified in the literature that are used to assess neck proprioception: the JPE, the fly test, the clinical cervical movement sense test, and the movement sense test. The fly test requires special software and a laser pointer to acquire the data and then a MATLAB code to analyse the data. The movement sense test requires a specialised machine where a pad is placed behind the participant's head, and they press a button once they perceive a movement. Again, to analyse the data it requires a MATLAB code. The CCMST requires a camera that is placed behind the participant to video record data collection. Data analysis is carried out by replaying the video to count the number of deviations from the ZZ and figure of eight bands and to also count the time spent to complete the task. In contrast to these tests, the JPE seems more suitable for clinical settings. It is low cost, and the data analysis is easy to implement.

The JPE measure is the most commonly used to quantify proprioceptive deficits (33). The measure of JPE was first introduced in 1991 by Revel et al. (24) to measure cervical joint position sense (JPS), a major component of proprioception (33). JPS can be measured either by instructing the patient to relocate the head to a neutral head position (NHP) or to relocate the head to a predefined target (THP) set by the researcher or by the participant (34). This test can be quantified using a variety of tools, for example a cervical range of motion (CROM) device (35), non-invasive electromagnetic devices such as the 3-Space Fastrak (36), or a head-mounted laser pointer (24). The measure is carried out by having the participant sit or stand in front of a target on the wall that is 90cm away. The test is carried out with eyes closed to limit visual cues and at a self-paced speed to limit vestibular cues (Figure 1.2). The difference between the starting position (zero) and the point of return in the plane of movement is measured in centimetres (37–39) and then converted to degrees using this formula: angle=$\tan^{-1}$[error distance/90 cm] (38). The following section will review the measurement properties of the cervical JPE test.

Figure 1. 2 The participant sits/stands in front of a wall target positioned 90cm away. A laser pointer is mounted on the participant's head while the participant. The participant is asked to perform flexion, extension, right rotation, and left rotation then return to neutral head position (NHP) or a target head position (THP) determined by the participant or the assessor.



1.5 Measurement properties of the JPE test

Good measurement properties are essential for an outcome measure to be used in research and clinical settings, as such properties reflect accuracy and precision of the measure (40). This section is aimed at reviewing studies that have tested the measurement properties (reliability, validity, and responsiveness) of the JPE test.

1.5.1 Reliability

Reliability can be defined as the extent to which measurements can be reproduced by either the same person (intra-rater reliability) or two different persons (inter-rater reliability) (41). For clinical applications, the reliability of an outcome measure must be established before it can be used (41). Two forms of reliability were identified: absolute and relative. Relative reliability is “ the degree to which individuals maintain their position in a sample with repeated measurements’’, while absolute reliability is “the degree to which repeated measurements vary for individuals’’ (42). Relative reliability can be measured using the intra-class correlation coefficient (ICC). Values range from 0 to 1, with values closer to 1 representing stronger reliability (41). The following criteria can be used for ICC interpretation: <0.5= poor, 0.5-0.74= moderate, 0.75-0.9= good, and >0.91= excellent (41). On the other hand, absolute reliability can be measured using standard error of measurement (SEM) (43). SEM can be calculated using the following formula: SEM = SD*square root of (1 – ICC) or from the square root of the mean square root term in a repeated measures ANOVA (43). The smaller the SEM, the more reliable the measurements (43). Bland and Altman’s limits of agreement is another way to analyse absolute reliability. Bland and Altman’s limits of agreement can be analysed using Bland-Altman plots, which is the individual subject differences between the tests’ plotted respective individual means (43). For Bland Altman plots interpretation of good agreement, the majority of points must rely within 95% limits of agreement with even distribution of points on both sides and a mean difference closer to zero (44).

Several studies have examined the reliability of the JPE test. Most of the studies in the literature have focused on assessing intra-rater reliability. For example, Artz et al. (45) conducted their intra-rater reliability investigation using the 3-Space Fastrak on asymptomatic participants, testing 25%, 50%, and 75% of THP in flexion only. Their within-day reliability was poor to moderate (ICC range: -0.81-0.66), and between-day reliability was poor to good (ICC range: -0.48-0.77). Kristjansson et al. (46) also carried their between-day intra-rater reliability on asymptomatic participants using the 3-Space Fastrak testing four tests of the JPE: NHP (ICC range: 0.35-0.44), THP (ICC range: 0.69-0.74), preset trunk rotation

(ICC range: 0.52-0.74), and the figure of eight relocation test (ICC: 0.67) after returning from right and left rotation. Lee et al. (47) carried out their within-day intra-rater reliability of asymptomatic participants testing the NHP and THP tasks after returning from flexion, extension, right rotation, left rotation, right side-bending, and left side-bending. Both tasks showed poor to good reliability. Pinsault et al. performed their within-day intra-rater reliability on asymptomatic participants using a laser pointer mounted on their heads, testing the NHP task after returning from right and left rotation. Their reliability was moderate to good (ICC range: 0.52-0.81).

With regard to reliability testing on people with neck pain, Roren et al. (38) recruited people with CNP to investigate the within-day reliability of the NHP task after returning from right and left rotation using a laser pointer and an Ultra-sound (US) device. Both devices showed moderate reliability (ICC range: 0.62-.068). Wibault et al. (35) recruited people with cervical radiculopathy testing within-day intra-tater reliability of the NHP task after returning from right and left rotation using a CROM device showing good reliability (ICC range: 0.79-0.85).

From the studies explored, it is clear that there are differences in the investigation of the reliability of the JPE measure. For example, all of the previously mentioned studies carried out their investigation in a sitting position, while two studies carried out their testing also in a standing position (45,48), showing moderate reliability, and in supine (34) showing moderate to good reliability. In addition, there were differences in the number of testing trials. Some used three trials (45,47), five trials (38), and ten trials (49) in their investigation. Further variations in testing procedures were movements tested, the assessed task (different JPE tasks), or the time interval between testing sessions. These differences in testing procedures make it difficult to draw a conclusion on what is the most reliable test to assess the reliability of the measure of JPE. Therefore, further assessment is required.

1.5.2 Validity

Validity refers to ‘the degree to which an instrument truly measures the construct(s) it purports to measure’ (50). Pearson's correlation (r) is a statistical test that can be used to analyse validity (51). It is a statistical measure of the strength of linear relationship between two variables (52) and it ranges between -1 to +1. The strength of the correlation increases from 0 to 1 with 0 means no correlation and 1 means very strong correlation (52). The following criteria can be used for validity interpretation: 0.1-0.39=weak, 0.4-0.69=moderate, 0.7-0.89=strong, 0.9-1=very strong (53). Roren et al. (38) correlated the laser pointer against a US device. They found a very strong correlation between the devices (r=0.94-0.95) testing right and left rotation of the NHP task using ten trials per movement. Chen and Treleaven (39) correlated the laser pointer against the 3-Space Fastrak using the conventional JPE test and the torsion JPE test. Their results showed a strong correlation for the conventional JPE test (r=0.87) and a moderate correlation for the torsion JPE test (r=0.67). Their study was limited to rotation, with six trials per movement, but was on asymptomatic and CNP participants. Variations in testing methods were also found for validity investigations, and similar to the reliability, it is difficult to conclude what methods are best to test the validity of the JPE test. Thus, further investigation is required.

1.5.3 Responsiveness

Responsiveness is a key attribute of an assessment tool/test intended to identify changes in a person's condition over a period of time (54). This feature has raised attention among clinicians and researchers because a change in measurement indicates a shift in the patient's clinical condition, a crucial aspect in interventional research. No study to date, to the knowledge of the researcher, has investigated the responsiveness of the JPE test. Responsiveness can be defined as the ability of an outcome measure to detect a change over time (55). Two types of responsiveness exist: internal and external responsiveness. Internal responsiveness can be measured by the effect size (Cohen's d) of pre-post differences using the formula Cohen's d= (M1-M2)/SDpooled, where M1 is the mean of baseline measurements, M2 is the mean of follow-up measurements, and SDpooled is the standard deviation of the two measurements (54,56). For interpretation, d=0.2 is considered a small effect, d=0.5 is a medium effect, and 0.8 is a large effect (54,56).

External responsiveness, which is a correlation of change in scores of two devices, and can be measured using the Pearson's product-moment correlation coefficient (r) where 0.1-0.39=weak, 0.4-0.69=moderate, 0.7-0.89=strong, 0.9-1=very strong (53).

1.5.4 Summary of the measurement properties of cervical JPE test

Knowledge of outcome measures' psychometric properties, including their reliability, validity, and responsiveness, is important as they reflect data accuracy and precision (40). Michiels et al. conducted a systematic review investigating the measurement properties of cervical sensorimotor control tests (57). In their 2012 review, they investigated the reliability and discriminative validity of tests. Although this systematic review did not use the now recommended Consensus-based Standards for the Selection of health Measurement Instrument (COSMIN) reporting guidelines (58), they reported that the NHP test showed fair to excellent reliability (ICC range: 0.35-0.87) while the THP showed poor to excellent reliability (ICC range: 0.01-0.9). Additionally, the JPE test was able to discriminate between people with and without CNP. Given the number of publications since this last review and the missing measurement properties in this review (criterion-related validity), a systematic review to synthesise the currently available evidence in relation to a range of measurement properties (reliability, measurement error, validity, and responsiveness) of the measure of cervical JPE for the assessment of people with and without neck pain is required.

1.6 Proprioception differences in people with and without neck pain

This section will present studies examining proprioceptive differences between people with and without neck pain conditions.

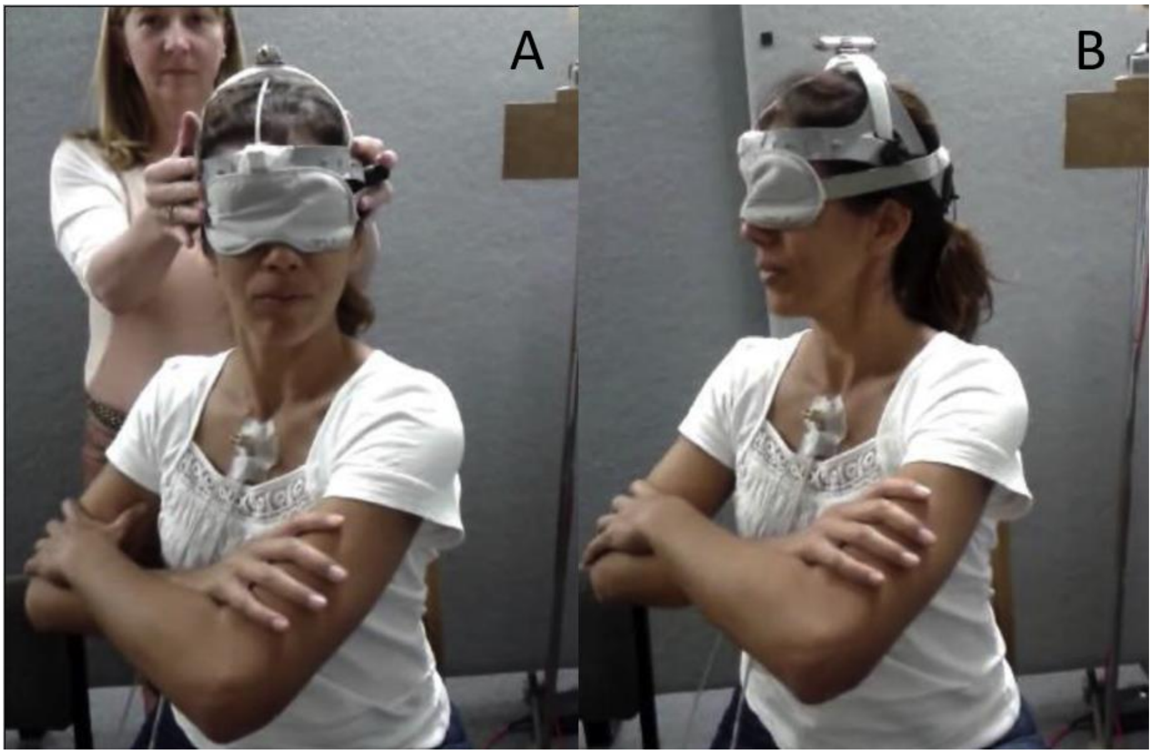
1.6.1 Chronic non-specific neck pain

Revel et al. (24) reported a significant difference in JPE between asymptomatic and CNP participants in flexion, extension, and right and left rotations ($P<0.01$). For the asymptomatic group, the mean error for horizontal movements was $3.5^{\circ}\pm0.8^{\circ}$ and $3.37^{\circ}\pm0.73^{\circ}$ for vertical repositioning, while it was $6.11^{\circ}\pm1.59^{\circ}$ for horizontal movements and $5.47^{\circ}\pm1.75^{\circ}$ for vertical movements in the neck pain group. Ten trials were used for the assessment of each movement. Overshooting of the target was reported (24), suggesting that participants were searching for additional feedback from the stretched antagonist muscles (24,59,60). Kristjansson et al. (61) carried out five cervicocephalic tests to evaluate sensorimotor impairment in people with neck pain (chronic or whiplash) and asymptomatic people. These tests were the NHP test, THP test, Preset trunk rotation test, figure-of-eight relocation test, and figure-of-eight movement test. Only the first test (NHP) showed between-group significant differences after returning from right and left rotation between the asymptomatic and CNP group ($P=0.001$). The other four tests did not show any significance between the groups. Using an electrogoniometer, Cheng et al. (62) reported significant differences in flexion and extension between CNP and asymptomatic participants ($P=0.03$). Other studies have failed to report any significance between asymptomatic and neck pain participants

(16,63–68). This could be due to differences in levels of pain intensity, study sample size, and testing methods.

Other forms of JPE tests have also been reported in the literature. Chen and Treleavan (39) investigated three types of JPE tests in CNP and asymptomatic people. These tests were: the Conventional test, the torsion test (Figure 1.3 (A)), and the Enbloc test (Figure 1.3 (B)). For the conventional test, participants were asked to rotate their heads to the right or left and then return to a neutral position (NHP test). For the trunk torsion test, the researcher gently held the participant's head while they rotated their trunk to the right or left and then returned to a neutral position. For the Enbloc test, the participants were asked to relocate their head and trunk after rotation to the right and left.

Figure 1. 3 A) Torsion JPE test, the head is still, and the trunk is stationary. B) Enbloc JPE test, the head and trunk are in rotation (39).



This study used the 3-Space Fastrak system, and a laser pointer fitted on the head and mid-sternum. The mean repositioning error of the conventional test was significantly different between both groups (*P*=0.04), but only for the laser pointer. The mean repositioning error for the trunk torsion test was significantly different between both groups for the laser pointer (*P*=0.02) and the 3-Space Fastrak (*P*=0.00). The Enbloc test did not show significance between groups using both testing tools.

1.6.2 Whiplash-associated disorders

De Pauw et al. (69) investigated sensorimotor disturbances in neck pain, WAD, and asymptomatic participants. Participants were asked to perform the THP test returning from flexion, extension, and right and left rotation. Ten trials were performed per movement. People with WAD had significantly higher repositioning errors in flexion and extension but not in rotation. Forty percent of the participants in the WAD group exceeded 37 points on the Tampa Scale of Kinesiophobia (TSK). Also, the WAD group reported higher disability levels in the neck disability index (NDI). The higher disability levels and fear of movements are suggested causes of this impaired proprioception (69). Feipel et al. (70) found similar results, where the whiplash group (79% grade III and 21% grade II) had significantly higher repositioning errors compared to asymptomatic participants.

With regard to dizziness in people with whiplash, Treleavan et al. (36) recruited 96 participants with Grade II whiplash, 9 participants with Grade III whiplash, and 44 asymptomatic participants. Participants in the whiplash group were divided further into two groups: whiplash with dizziness (WAD D) and whiplash with no dizziness (WAD ND). Participants completed the Northwick Park Neck Pain Questionnaire to record disability levels (71) and a specific questionnaire for dizziness of cervical origin. Participants performed three trials in extension, and right and left rotation. People with whiplash demonstrated greater repositioning error in extension and right and left rotation compared to the asymptomatic participants. Within the whiplash group, the WAD D demonstrated higher repositioning errors in right and left rotations when compared to the WAD ND group (Figure 1.4). Overshooting the target was also observed in extension, especially in the WAD group. As mentioned before, this overshooting may result from participants searching for feedback from the stretched antagonist muscles, similar to what Revel et al. (24) found in people with CNP.

Figure 1. 4. Differences in joint position error (°) between the control group, whiplash with dizziness (WAD D), and whiplash with no dizziness (WAD ND) (36).

Movement	Control	WAD ND	WAD D	WAD vs C *p* value	ND vs D *p* value	C vs ND *p* value
Ext	2.4 (0.3)	3.5 (0.4)	3.5 (0.3)	0.02	0.96	0.06
Rot L	2.0 (0.2)	2.8 (0.4)	3.9 (0.3)	0.001	0.06	0.09
Rot R	2.5 (0.2)	2.9 (0.4)	4.5 (0.3)	0.003	0.006	0.3

C = Control group; WAD = Total WAD group; WAD ND = WAD non-dizzy group; WAD D = WAD dizzy group; Ext = Extension; Rot L = Rotation left; Rot R = Rotation right.

Cervicogenic dizziness is defined as an impaired sensation and orientation of the head in space due to impaired afferent activity from the neck (72). Cervicogenic dizziness is predominant in people who have sustained a flexion-extension injury, those with severe cervical arthritis, those with herniated cervical discs, and people who have sustained head trauma (72). Micarelli et al. (73) investigated the differences in sensorimotor control between people with and without cervicogenic dizziness, where the latter had a significantly higher repositioning error after returning from flexion (p=0.009), extension (p=0.01), and right (p=0.008) and left rotation (p=0.006) when compared to asymptomatic people. In addition, people with cervicogenic dizziness demonstrated significantly higher scores on the Dizziness Handicap Inventory (DHI), TSK, and Hospital Anxiety and Depression Scale.

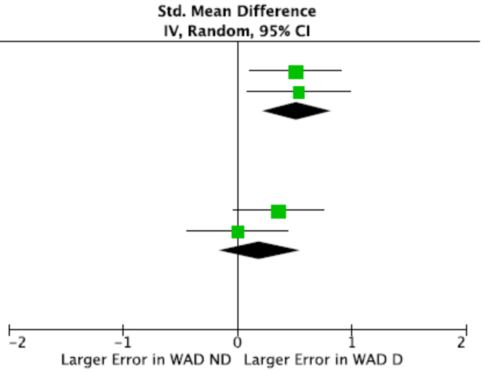
1.6.3 Summary of proprioception differences in people with and without neck pain

Four systematic reviews have evaluated the effect of neck pain on sensorimotor control (74–77). The pooled results by de Zoete et al. (74) found that people with neck pain typically have a repositioning error ranging from 2.2°-9.8° after cervical rotation, which differed significantly (p=0.04) when compared to asymptomatic participants. Stanton et al. (77) pooled the results of ten studies and found that people with neck had a higher repositioning error when compared to asymptomatic people. In the systematic review by Hesby et al. (75), five of the nine included studies reported significant differences in sensorimotor control between asymptomatic and neck pain participants. However, data were not pooled due to the heterogeneity of testing parameters and methods used in the reviewed studies. Similar results were also reported in a systematic review by de Vries et al. (76).

Regarding people with WAD, in a recent systematic review by Mazaheri et al. (78), 26 studies were included, and data on JPE was synthesised. Higher repositioning error for the NHP task following rotation to both sides and extension was found in people with whiplash compared to asymptomatic participants. Moreover, higher repositioning error was found in people with whiplash and dizziness complaints (WAD D) when compared to whiplash without dizziness complaints (WAD ND) but mainly in rotation (Figure 1.5). This systematic review concluded that people with whiplash, especially those with dizziness complaints, have higher sensorimotor disturbances when compared to controls.

Figure 1. 5. Forest plot demonstrating meta-analysis of absolute JPE when repositioning the head to neutral position from extension and rotation in WAD D versus WAD ND groups (78)

Study or Subgroup	WAD D Mean	SD	Total	WAD ND Mean	SD	Total	Weight	Std. Mean Difference IV, Random, 95% CI
3.1.1 HR_NHP Rotation								
Hill 2009	4.28	2.5	50	3	2.49	50	56.2%	0.51 [0.11, 0.91]
Treleaven 2003	4.2	2.63	76	2.85	2.02	26	43.8%	0.54 [0.09, 0.99]
Subtotal (95% CI)			**126**			**76**	**100.0%**	**0.52 [0.22, 0.82]**
Heterogeneity: Tau² = 0.00; Chi² = 0.01, df = 1 (P = 0.93); I² = 0%								
Test for overall effect: Z = 3.42 (P = 0.0006)								
3.1.2 HR-NHP Extension								
Hill 2009	3.61	2.12	50	2.84	2.12	50	54.2%	0.36 [−0.03, 0.76]
Treleaven 2003	3.5	2.62	76	3.5	2.04	26	45.8%	0.00 [−0.45, 0.45]
Subtotal (95% CI)			**126**			**76**	**100.0%**	**0.20 [−0.16, 0.55]**
Heterogeneity: Tau² = 0.02; Chi² = 1.41, df = 1 (P = 0.24); I² = 29%								
Test for overall effect: Z = 1.09 (P = 0.28)								

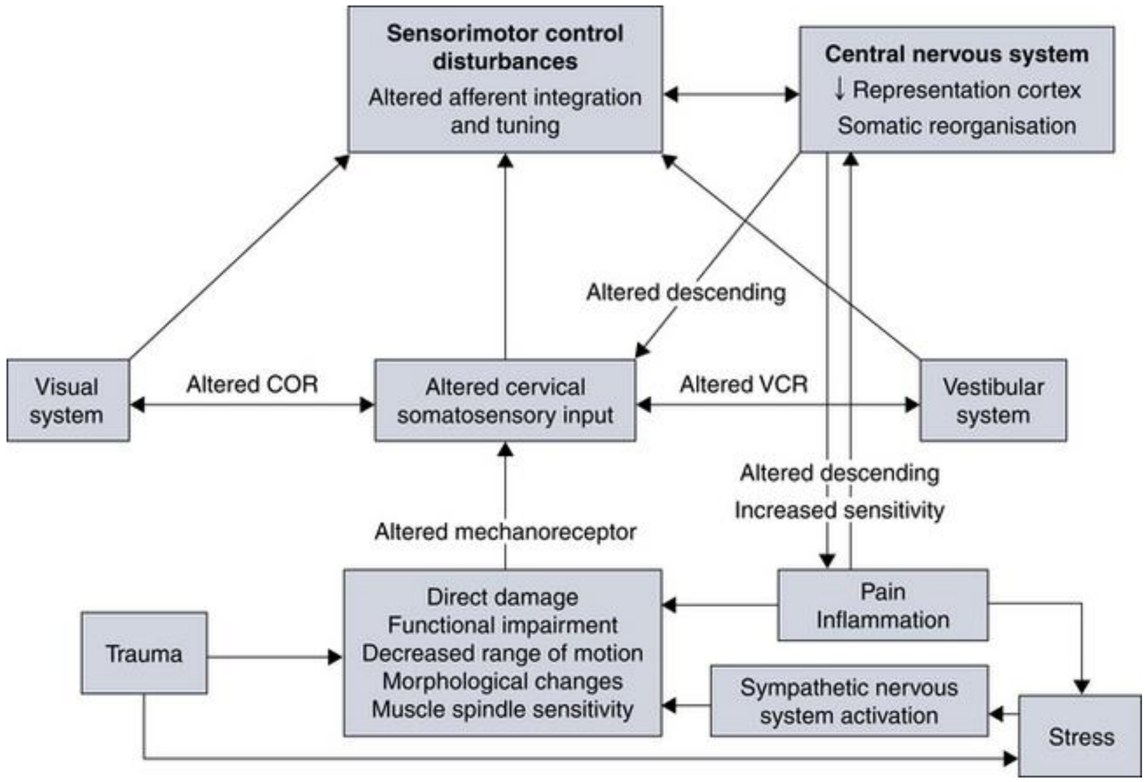


1.7 Mechanism underlying changes in proprioception in people with neck pain

The results from the studies reviewed in the previous section show that pain significantly influences the proprioceptive system (Figure 1.6). A few reasons could explain the pathophysiology of this disturbed proprioception. For example, pain can alter proprioception by disturbing the reflex activity and sensitivity of the gamma-muscle spindle system (26). This reflex is disturbed by the activation of the chemosensitive III and IV afferents. The effect of pain at various levels of the CNS leads to changes in the sensitivity of the muscle spindles leading to alterations in cortical representation and modulation of how afferent inputs are modulated and represented in the cortex (79).

In addition, changes in muscle coordination and the reduced specificity of neck muscles could also disturb proprioception. Those changes include the activation of superficial neck muscles and deactivation of deep neck muscles, which are highly dense in muscle spindles, thus affecting the discharge of muscle spindles, which affect afferent signals, leading to impaired proprioception (33). In people with WAD, the altered proprioception is suggested to be due to damaged mechanoreceptors of the neck due to trauma, pain, and inflammation (78).

Figure 1. 6. Mechanism of proprioceptive disturbances in neck disorders (80).



COR=cervico-ocular reflex. VCR=vestibulocollic reflex.

1.8 Proprioceptive rehabilitation

The clinical practice guidelines for CNP (81) recommend conservative treatment for people with neck pain and mobility/coordination deficits; this includes proprioceptive exercises. As described in the assessment section (section 1.4), JPS can be retrained using a laser pointer mounted on the patient's head and a target on a wall. The patient can begin by relocating the head to an NHP and then progress to relocating the head to different targets of the ROM (i.e., 20%, 40%, or 60%). Further progress in these exercises can be made in standing (29).

Strengthening the linkage between JPE test findings and clinical practice can significantly enhance the impact of this research. JPE testing helps identify proprioceptive deficits, which can play a critical role in many musculoskeletal conditions. JPE testing can serve as a valuable tool for tracking progress throughout rehabilitation, enabling treatment adjustments as needed. By applying JPE testing to specific patient populations such as people with CNP or WAD, JPE testing could inform more personalised and effective rehabilitation strategies, ultimately improving patient outcomes. Evidence from randomised controlled trials (RCTs) suggests that proprioceptive exercises for people with CNP improve repositioning errors and reduce pain. Revel et al. (82) randomised 60 participants with CNP into either a rehabilitation group (RG) or a control group (CG). Participants in the RG carried out eye-head coupling exercises. These exercises were as follows: In supine or sitting, the head of the participant was moved passively at a slow speed, and they were asked to maintain their gaze on a fixed target. Exercises were carried out in three steps in sitting and standing, and special goggles that limit peripheral vision were used. First, participants actively moved their heads, mainly in rotation, to follow a moving target. Second, participants were asked to maintain the head and eyes on a target while the therapist passively rotated the trunk. Third, participants were asked to memorise a target for a few seconds, and then they were asked to close their eyes and try to relocate their heads to this target as precisely as possible (82). Additionally, they had other exercises where participants were instructed to follow a moving target using alternatively slow pursuits and saccades in the horizontal plane. The rehabilitation program was carried out twice a week over eight weeks. In the RG, the mean repositioning accuracy before treatment were 7.5±3.7 (mean±SD) and after treatment were 5.5±2.6 (mean±SD) was highly significant ($p=0.0004$). When compared to the control group, repositioning accuracy increased significantly after the proprioception training intervention ($p=0.005$).

Additionally, Jull et al. (15) compared conventional proprioceptive training to craniocervical flexion (C-CF) exercise. Sixty-four participants with CNP were randomly assigned to the conventional proprioceptive training group or the C-CF exercise group.

Proprioceptive training interventions were carried out over six weeks. The C-CF exercise targets the deep cervical flexors (longus capitis and longus colli) rather than superficial neck flexors (sternocleidomastoid and anterior scalene). This exercise improves the coordination between superficial and deep neck flexors and reduces pain (15). Visual feedback gained from an air-filled pressure sensor was used so that participants could hold their inner ranges of C-CF while keeping the superficial flexors relaxed. The sensor was placed behind the neck to monitor the flattening of the cervical spine, which would indicate that the deep flexor muscles are active (15). The proprioceptive training exercises comprised head relocation practice, gaze stability, eye-follow, and eye/head coordination exercises. Repositioning accuracy after returning from right rotation, left rotation, and extension was measured before and after the proprioceptive intervention. JPE decreased significantly when returning from right rotation, left rotation, and extension for the proprioception training group ($p<0.001$) and the C-CF group ($p<0.05$), with the proprioceptive training group showing more error reduction in return from right rotation when compared to the C-CF exercise group ($p<0.05$).

Cervical movement sense (CMS) training is another form of cervical proprioceptive training. The patient moves the head (laser pointer) following different shapes, such as a double (ZZ) band or a figure of eight (F8). The patient can progress the exercises by increasing the speed; however, the laser must precisely trace the lines (29). This method (CMS) is effective in treating people with proprioceptive deficits. Treleaven et al. (83) recruited participants with CNP and were instructed to trace the ZZ figure four times a week for four weeks. This test showed a moderate to high effect size (Cohen's d=0.76). Although this measure has been used in trials as an outcome measure, its measurement properties is still lacking and requires to be investigated.

In summary, the variations observed in sensorimotor issues among patients experiencing neck pain imply the significance of crafting tailored rehabilitation programs designed for particular dysfunctions. Additionally, employing objective and quantifiable assessment methods to gauge the impacts of rehabilitation is vital. Both the JPS and CMS training can be used to rehabilitate people with proprioceptive deficits.

1.9 Conclusion

The measure of JPE is the most commonly used to assess cervical proprioception. It was able to discriminate between people with and without CNP, as has been reviewed in previous sections. However, different testing tools and methods exist, making it difficult for clinicians and researchers to decide which is the best method and tool to assess proprioception. Therefore, it is vital to summarise and appraise the literature to assess the methodological quality of the available studies in the literature in order to draw a conclusion on the best methods and tools to assess neck proprioception. Moreover, the responsiveness of the cervical JPE test was not reported in the literature and needs to be investigated. Figure 1.7 represents a flow diagram of the work carried out in the current Ph.D.

1.10 Aims

The overarching aim of this thesis is to evaluate the reliability, validity, and responsiveness of the measure of cervical JPE with a view of supporting its use in clinical and research practice.

Aim 1 (*Chapter 2*):

To appraise and summarise the existing literature on measurement properties of the measure of cervical JPE.

Objectives:

To conduct a systematic review of the measurement properties of the measure of cervical JPE in people with and without neck pain.

Aim 2 (Chapter 3):

To investigate the reliability, measurement error, and criterion validity of the measure of cervical JPE in people with and without neck pain.

Objective:

To carry out a reliability, measurement error, and criterion-related validity of the measure of cervical JPE in people with and without chronic neck pain.

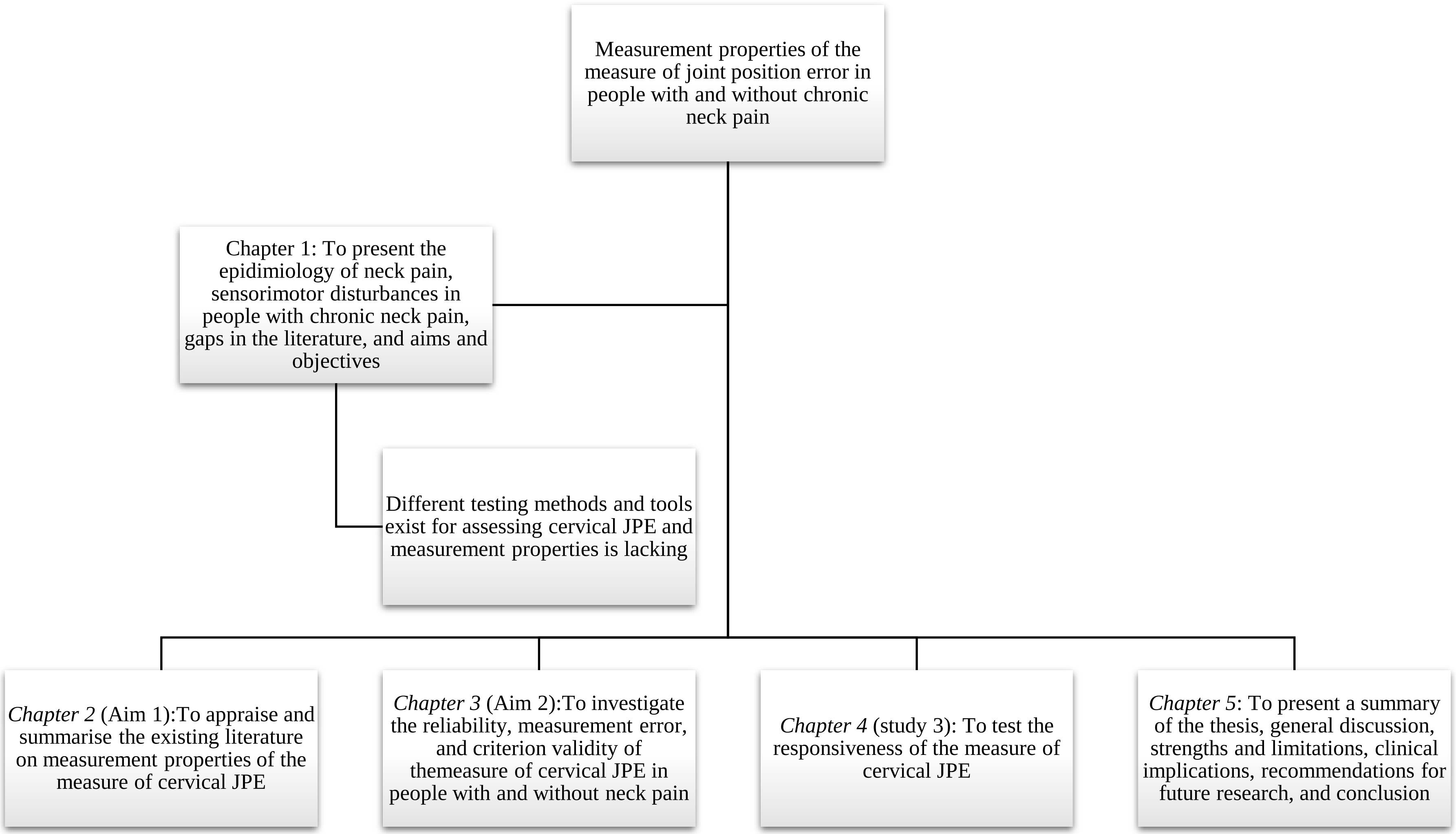
Aim 3 (*Chapter 4*):

To test the responsiveness of the measure of cervical JPE.

Objective:

To carry out a responsiveness study of the measure of cervical JPE after a 4-week of home-based proprioceptive training in people with CNP.

Figure 1. 7. A flow diagram of the planned work for the current Ph.D.



Chapter 2: Measurement properties of cervical joint position error in people with and without neck pain: a systematic review and narrative synthesis

This chapter reports content of a published manuscript by the thesis author (AlDahas et al. 2024). It includes verbatim text from published manuscript with changes employed for the purpose of this thesis.

Publication

AlDahas A, Heneghan NR, Althobaiti S, Deane JA, Rushton A, Falla D. Measurement properties of cervical joint position error in people with and without neck pain: a systematic review and narrative synthesis. BMC Musculoskeletal Disorders. 2024 Dec;25(1):1-9.

2.1 Abstract

Introduction: Proprioception can be impaired in people with neck pain. The cervical joint position sense test, which measures the JPE, is the most common test used to assess neck proprioception. The aim of this systematic review was to assess the measurement properties of this test for the assessment of people with and without neck pain.

Methods: This systematic review was registered prospectively on Prospero (CRD42020188715). It was designed using the COSMIN guidelines and reported in line with the PRISMA checklist. Two reviewers independently searched Medline, Embase, SportDiscus, and CINAHL Plus databases from inception to the 24th of July 2022 with an update of the search conducted until 14th of October 2023. The COSMIN risk of bias checklist was used to assess the risk of bias in each study. The updated criteria for good measurement properties were used to rate individual studies and then the overall pooled results. The level of evidence was rated by two reviewers independently using a modified GRADE approach.

Results: Fifteen studies were included in this review, 13 reporting absolute JPE and 2 reporting constant JPE. The measurement properties assessed were reliability, measurement error, and validity. The measurement of JPE showed sufficient reliability and validity, however, the level of evidence was low/very low for both measurement properties, apart from convergent validity of the constant JPE, which was high.

Conclusion: The measure of cervical JPE showed sufficient reliability and validity but with low/very low levels of evidence. Further studies are required to investigate the reliability and validity of this test as well as the responsiveness of the measure.

2.2 Introduction

As discussed in *Chapter 1,* several outcome measures have been used to assess cervical proprioception with the JPS test being the most common test to evaluate JPE (84). Knowledge of the psychometric properties of outcome measures, which includes their reliability, validity, and responsiveness, are important as they reflect data accuracy and precision (40). Michiels et al. carried out a systematic review investigating the measurement properties of cervical sensorimotor control tests (57). In their 2012 review, they investigated the reliability and discriminative validity of tests. Although this systematic review did not use the now recommended COSMIN reporting guidelines (58), they reported that the NHP test showed fair to excellent reliability (ICC range: 0.35-0.87) while the THP showed poor to excellent reliability (ICC range: 0.01-0.9). Additionally, the JPE test was able to discriminate between people with and without CNP.

Given the number of publications since this last review, in this current systematic review, the aim was to build upon this research to synthesise the currently available evidence in relation to a range of measurement properties (reliability, measurement error, validity, and responsiveness) of the measure of cervical JPE for the assessment of people with and without neck pain.

2.3 Design and methods

This systematic review was designed using the COSMIN risk of bias (RoB) guidelines for reliability and measurement error of outcome measurement instruments as well as the COSMIN methodology for systematic reviews of Patient-Reported

Outcome Measures (PROMs) (58,85) and is reported in accordance with the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) (86). The protocol was registered with PROSPERO on the 10th of July 2020 (CRD42020188715).

2.3.1 Deviations from the study protocol

The initial protocol described a systematic review of the measurement properties of proprioception tests for all regions of the spine. However, following an initial review of the literature and appreciation of the number of studies conducted in different spinal regions, the decision was made to focus on the measurement properties of cervical JPE only. Additionally, the original plan was to use the COSMIN RoB checklist for PROMs, however since publishing the protocol, the authors were made aware of the new COSMIN RoB checklist for reliability and measurement error of outcome measurement instruments. Thus, this new tool was used to assess RoB of reliability, measurement error, and criterion validity (85). The COSMIN RoB checklist for PROMs was used to assess construct and discriminative validity (87) as suggested in the manual for the COSMIN RoB checklist for reliability and measurement error of outcome measurement instruments.

2.3.2 Eligibility criteria

The following inclusion criteria are based on the Sample, Phenomena of Interest, Design, Evaluation, and Research type (SPIDER) guidelines (88).

- Sample: people with and without neck pain aged ≥18 years. Those with neck pain included regardless of the stage of their neck pain (e.g., acute, or chronic) or aetiology (e.g., non-specific or attributed to pathology).
- Phenomena of interest: cervical proprioception.
- Design: any study which investigated at least one of the domains (reliability, validity, responsiveness, and their sub-domains) of the COSMIN checklist and reported absolute error (AE) or constant error (CE) in degrees.
- Evaluation: any study that evaluated measurement properties of the measure of cervical JPE.
- Research type: quantitative research.

2.3.3 Exclusion criteria

Studies that included patients that had undergone cervical spine surgery and studies not written in English were excluded.

2.3.4 Information sources

The following databases were searched as recommended by the COSMIN guidelines for systematic reviews (58), from inception to the 24th July 2022 with an update of the search conducted until 14th of October 2023: MEDLINE, Embase, SportDiscus, and CINAHL plus. Manual searches were carried out for: The Spine Journal, European Spine Journal, Journal of Musculoskeletal Science and Practice, and the Journal of Orthopaedic and Sport Physical Therapy. Grey literature (Open Grey, ProQuest, and EThOS) was hand searched.

2.3.5 Search strategy

Following scoping searches and discussions with co-authors, the search strategy was developed, and a librarian was consulted. Search terms are provided in Table 2.1. Search syntax was translated to meet the requirements of each database.

Table 2. 1. MEDLINE syntax used in MEDLINE database.

Search terms	Neck pain OR neck dysfunction OR cervical pain OR cervical dysfunction **AND** Propriocept* OR movement sense OR kinesthes* OR repositioning OR repositioning error OR position sense OR motion perception OR active position sense OR passive position sense **AND** Reliability OR validity OR responsiveness OR reproducibility of results OR reproducib* OR reliab* OR valid* OR stability OR interrater OR interrater OR intrarater OR intrarater OR intra-rater OR intratester OR intra-tester OR interobserver OR inter-observer OR intraobserver OR intra-observer OR intertechnician OR inter-technician OR intratechnician OR intra-technician OR interexaminer OR inter-examiner OR intraexaminer OR intra-examiner OR intraclass correlation OR standard error of measurement OR sensitiv* OR responsive* OR minimal detectable concentration OR interpretab* OR small detectable change OR ceiling effect OR floor effect

2.3.6 Data management

Endnote software version X9 (Clarivate Analytics) was used to manage citations and bibliographies, and store articles found and eliminate duplicates.

2.3.6.1 Study selection

AA carried out the initial search of the databases, after that, two researchers (AA, SA) independently carried out the screening of potentially eligible studies. The screening and selection were carried out in two steps. Step 1: Abstracts and titles using the eligibility criteria. Step 2: Retrieve full text of potentially relevant studies to be screened. Studies were included if both reviewers had agreed on inclusion after screening the full text. In case of any disagreement, a third reviewer (DF) was consulted.

2.3.6.2 Data extraction and data items

Two researchers (AA, SA) independently carried out the data extraction from the included studies. Extracted data items were characteristics of the studies (study design and sample size), characteristics of the participants (age, gender, population), testing instrument, testing protocols, measurement properties (reliability, measurement error, validity, and responsiveness), and results. In case of any disagreement, a third reviewer (DF) was consulted.

2.3.6.3 Risk of bias assessment

Included studies were independently assessed by two reviewers (AA, SA) using the COSMIN RoB checklist for reliability and measurement error of outcome measurement instruments to assess RoB of reliability, measurement error, and criterion validity (85). The COSMIN RoB checklist for PROMs was used to assess construct and discriminative validity (87). Both checklists have four scores (very good, adequate, doubtful, and inadequate) (87) that assess measurement properties with regard to design and statistical methods. In case of any disagreement, a third reviewer (DF) was consulted.

2.3.6.4 Data synthesis

Data synthesis of the results was undertaken in accordance with COSMIN guidelines (58). After assessing the risk of bias, each study was rated using the updated criteria for good measurement properties as sufficient (+), insufficient (-), or indeterminate (?) (58), then, the overall results of each measurement property per outcome measure per population were rated against the criteria of a good measurement property as sufficient (+), insufficient (-), inconsistent (±), or indeterminate (?) (58). Table 2.2 presents the updated criteria for good measurement properties.

Table 2. 2. The updated criteria for good measurement properties (58,89).

Measurement property	Rating	Criteria
Reliability	Sufficient (+)	ICC or weighted Kappa ≥ 0.7
	Indeterminate (?)	ICC or weighted Kappa not reported
	Insufficient (-)	ICC or weighted Kappa < 0.70
Measurement error	Sufficient (+)	SDC or LoA < MIC
	Indeterminate (?)	MIC not defined
	Insufficient (-)	SDC or LoA > MIC
Hypothesis testing for construct validity	Sufficient (+)	The result is in accordance with the hypothesis
	Indeterminate (?)	No hypothesis defined (by the review team)
	Insufficient (-)	The result is not in accordance with the hypothesis
Criterion validity	Sufficient (+)	Correlation with gold standard ≥ 0.70 OR AUC ≥ 0.70
	Indeterminate (?)	Not all information for '+' reported
	Insufficient (-)	Correlation with gold standard < 0.70 OR AUC < 0.70
Responsiveness	Sufficient (+)	The result is in accordance with the hypothesis OR AUC ≥ 0.70
	Indeterminate (?)	No hypothesis defined (by the review team)
	Insufficient (-)	The result is not in accordance with the hypothesis7 OR AUC < 0.70

ICC=intraclass correlation coefficient, SDC= smallest detectable change, LoA= limits of agreement, MIC= minimal important change, AUC=area under curve.

The overall level of evidence for each outcome measure and its respective measurement property was then determined independently by two reviewers (AA, SA) using a modified Grading of Recommendations Assessment, Development, and Evaluation (GRADE) approach (90). Table 2.3 presents the modified GRADE approach used to rate the overall quality of the evidence. More information on how to downgrade the level of evidence can be found in the COSMIN user manual (90).

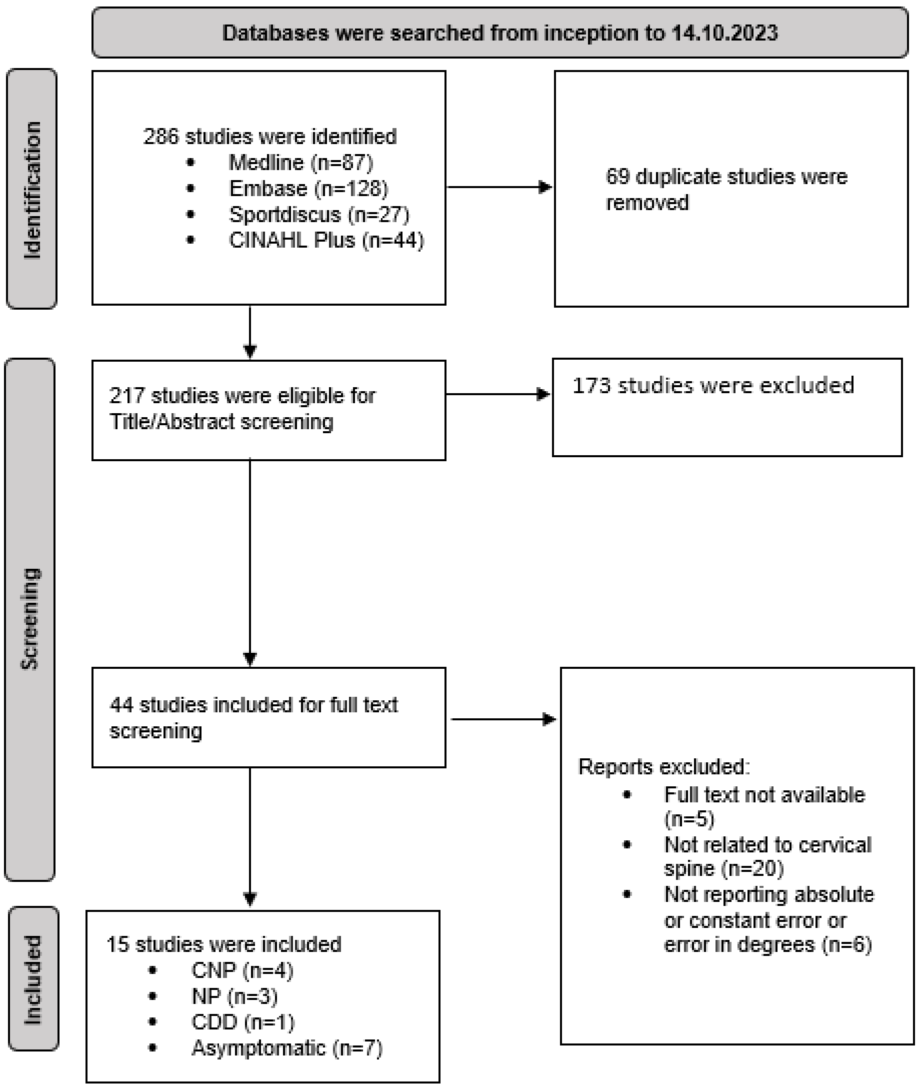
Table 2. 3. Modified GRADE approach used to rate the overall level of evidence (58).

Quality of evidence	**Lower if there is**
High	**Risk of bias**
Moderate	-1 Serious
Low	-2 Very serious
Very low	-3 Extremely serious
	Inconsistency
	-1 Serious
	-2 Very serious
	Imprecision
	-1 Sample size (n=50-100)
	-2 Sample size (*n* < 50)
	Indirectness
	-1 Serious
	-2 Very serious

2.4 Results

Fifteen studies were included four with CNP, three that did not specify the type of neck pain, one with cervicogenic disc disease (CDD), and seven studies that included participants without neck pain. There was a 100% agreement between raters (AA, SA) for the included studies. Search results are summarised in Figure 2.1 and Table 2.4 summarises the extracted data from the included studies.

Figure 2. 1. Prisma flow diagram of the study selection process (91).



CNP=chronic neck pain. NP=neck pain. CDD=cervicogenic disc disease. n=number of studies.

Table 2. 4. Data extracted from the studies included in this review.

Authors	Population and sample size	Age (mean or range)	Testing instrument	Testing position	Testing procedure	Property domain	Statistical test used	Results
Artz et al. (45)	Asymptomatic subjects: n=40, (within day n=21, between day n=19)	29.9 years	3-Space Fastrak	Sitting Standing	**Trials:** 3 trials. **Movements tested:** **THP:** 25%, 50%, 75% in flexion (randomised)	Reliability within-day and between-day intra-rater (at least 1 week apart)	ICC, SEM	**JPE:** **Sitting:** **Within-day** (ICC range: -0.81-0.66) **Between-day** (ICC range: -0.48-0.77). **SEM range(sitting):** **Within-day** (0.71-1.48) **Between-day** (0.72-0.99). **Standing:** **Within-day** (ICC range: -0.11-0.68) **Between-day** (ICC range: 0.09-0.58). **SEM range (standing):** **Within-day** (0.91-1.48) **Between-day** (0.82-1.22).
Kristjansson et al. (46)	Asymptomatic Subjects: n= 19 (12 females)	31.5 years	3-Space Fastrak	Siting	**Trials:** 3 trials each direction or test. **Movements tested:** **JPE:** Right rotation, left rotation	Reliability (Intra-rater between-day in the same week)	ICC (2,1)	**Reliability:** **JPE:** **NHP** (ICC range: 0.35-0.44) **THP** (ICC range: 0.69-0.74) **Preset trunk rotation** (ICC range: 0.52-0.74) **Figure of 8 relocation test** (ICC: 0.67)
Lee et al. (47)	Asymptomatic Subjects: n=20 (11 men)	21.9 years	Motion analysis system, CMS 70P	Sitting	**Trials:** 3 trials each direction. **Movements tested:** Flexion/extension, left/right rotation, left/right side-bending (not randomised)	Reliability (Intra-rater within day 10 minutes in between)	ICC (3, 1) SEM	**ICC range**: **NHP** (0.38-0.84) **THP** (-0.48-0.83) **SEM**: 0.3-4

Strimpakos et al. (48)	Asymptomatic Subjects: n=35 (17 males)	18-63 years	Zebris CMS20	Intra-rater: sitting, standing) Inter-rater (standing)	**<u>Trials:</u>** 3 trials. **<u>Movements tested:</u>** Flexion, right and left rotation, right and left side bending (not randomised)	Reliability (Intra-rater between day 3 occasion 1 week apart) and Inter-rater reliability, 15 minutes between assessors (10 subjects only)	ICC (1,1), SEM, Bland and Altman	**<u>Intra-rater</u>** **Sitting**: (ICC range: -0.01-0.35) **Standing**: (ICC range: 0.17-0.5) **<u>SEM</u>**: **Standing** (1.5-3) **Sitting** (1.5-3.5) **<u>Inter-rater</u>** **ICC range**: -0.2-0.64 **SEM**: 0.7-2.9
Pinsault et al. (49)	Asymptomatic subjects: n=44 (22 women)	21.7 years	Laser pointer	Sitting	**<u>Trials:</u>** 10 trials **<u>Movements tested:</u>** Right and left rotation	Reliability (intra-rater 1 hour apart)	ICC (2, 1), SEM, LoA	**<u>ICC range:</u>** (0.52-0.81) **<u>SEM</u>** (0.9) **<u>LoA</u>** (-2-2.2)
Kramer et al. (92)	Asymptomatic subjects: n=57 (30 male, 27 females)	18-64 years	Virtual 3D scene via head mounted display+3-Space Fastrak	Sitting	**<u>Trials:</u>** 8 trials in total **<u>Movements tested:</u>** Flexion, Extension, right and left rotation	Reliability (intrasession and intersession)	ICC (3, 1)	**<u>Intrasession</u>** <u>ICC: 0.63</u> **<u>Intersession:</u>** <u>ICC: 0.48</u>
Roren et al. (38)	Asymptomatic and CNP subjects: n=82 (41 each group)	Healthy: 30.5. CNP: 54.7 years	Revel visual technique US technique	Sitting	**<u>Trials:</u>** 10 trials each device (5 trials each movement) **<u>Movements tested:</u>** Right and left rotation	Reliability: Intra-rater within day 1 hr apart for both devices. Criterion validity (Revel visual technique vs US technique). Discriminative validity (healthy vs NP group)	Reliability: ICC, Bland and Altman agreement. Criterion validity: Pearson's correlation. Discriminative validity: Kappa agreement	**<u>ICC</u>**: **Revel visual system** (0.68) **US technique** (0.62). **<u>Bland and Altman agreement</u>**: **Revel technique** (-3.6-4.2) **US technique** (-3.8-5.6). **<u>Pearson's</u> <u>correlation range</u>**: 0.946-0.952. **<u>Kappa</u> <u>agreement</u>**: 0.65

Chen and Treleavan (39)	CNP subjects: n=25 Asymptomatic subjects: n=26	18-60 years	Fastrak, Laser pointer	Sitting	<u>**Trials:**</u> 6 trials each movement <u>**Movements tested:**</u> Right and left rotation	Criterion validity Discriminative validity Convergent validity	Pearson's correlation (criterion validity). Spearman's correlation (convergent validity). MANOVA (discriminative validity)	<u>**Discriminative validity**</u>: **Conventional Fastrak** (p=0.28) **Conventional Laser** (p=0.04) **Torsion Fastrak** (p=0.00) **Torsion Laser** (p=0.02) **Enbloc Fastrak (head)** (p=0.43) **Enbloc Fastrak (trunk)** (p=0.42). <u>**Criterion validity:**</u> **Conventional JPE** (r=0.87) **Torsion JPE** (r=0.67). <u>**Convergent validity:**</u> No correlation except Conventional Fastrak (r=0.51)
Wibault et al. (35)	CDD subjects: n=24 Asymptomatic subjects: n=12	CDD: 51 years Healthy: 42 years	Reliability: CROM device Validity: CROM device vs laser pointer	Sitting	<u>**Trials:**</u> Reliability: 3 trials each direction. Validity: 8 trials each direction. <u>**Movements tested:**</u> Reliability and validity: right and left rotation	Reliability: 24 subjects with CDD (Intra-rater within day 1 hour in between) Criterion validity: 12 healthy subjects	ICC (2,1) SEM	<u>**Reliability**</u>: **ICC range**: 0.79-0.85 **SEM range**: 1.4-2 <u>**Validity**</u>: **ICC range**: 0.43-0.91
Dugailly et al. (93)	Asymptomatic and CNP subjects. Validity group (n=17) Reliability group (n=5)	42 years	Laser+electrogonio meter	Sitting	<u>**Trials:**</u> 6 trials in each direction. <u>**Movements tested:**</u> Right and left rotation, flexion, extension (no evidence of randomisation)	Criterion validity Intra-rater reliability (1 week apart) Convergent validity	Spearman's correlation ICC Bland Altman (LoA)	<u>**ICC range:**</u> 90cm low speed: 0.22-0.47 90cm high speed: 0.58-0.79 180cm low speed: 0.52-0.75 180cm high speed: 0.8-0.86 <u>**Convergent validity:**</u> JPE vs disability (r=0.32) JPE vs pain intensity (r=0.03), JPE vs pain duration (r=0.14). LoA range: -9 to 9

Burke et al. (94)	Asymptomatic and NP subjects: n=50	NA	CROM, AL	Sitting	**Trials:** 3 trials in each direction for two devices (no randomisation). **Movements tested:** Right and left rotation	Reliability (intra and inter-rater reliability)	ICC (type C)	**ICC range:** Intra-rater CROM: 0.253-0.386 Intra-rater AL: 0.488-0.556 Inter-rater CROM: 0.717-0.773 Inter-rater AL: 0.589-0.75
Alahmari et al. (34)	NP and Asymptomatic subjects: NP: n=36 Asymptomatic: n=33	Healthy: 56 years. NP: 36 years	Digital inclinometer	NHP (sitting) THP (sitting and supine)	**Trials:** 3 trials in all tests and directions. **Movements tested:** NHP (extension) THP (50% of ROM in flexion, extension, right and left side bending, right and left rotation in a randomised order)	Intra-rater reliability, Inter-rater reliability (≤3 working days apart)	ICC (2.1.A) SEM	**Intra-rater reliability:** NHP (ICC range: 0.74-0.78) (SEM: 1.78-1.88) THP: (ICC range: 0.7-0.83) (SEM: 1.78-1.88) **Inter-rater reliability:** NHP (ICC range: 0.74-0.79) (SEM 1.79-1.87) THP (ICC range: 0.62-0.84) (SEM: 1.5-2.23)
Goncalves and Silva (95)	Asymptomatic vs CNP subjects: n=66 (33 each group)	Healthy: 43.6 years NP 43.5 years	Laser pointer on a helmet	Sitting	**Trials:** 6 trials each direction **Movements tested:** Right and left rotation	Reliability (Intra-rater within day and between day with 1-2 days in between) Construct validity	Reliability: ICC (2,1) SEM Validity: t-tests or Mann Whitney, Pearson correlation coefficient, Spearman's correlation coefficient.	**Chronic Neck pain:** **Within day ICC range:** HRNT: 0.9-0.93 TT: 0.88-0.9 HR30T: 0.73-0.79 F8T: 0.89-0.93 **Between day ICC range:** HRNT: 0.61-0.85 TT: 0.58-0.71 HR30T: 0.67-0.7 F8T: 0.66-0.85 **Asymptomatic:** **Within day ICC range:** HRNT: 0.79-0.89 TT: 0.75-0.87 HR30T: 0.78-0.83 F8T: 0.83-0.93 **Between day ICC range:** HRNT: 0.75-0.8 TT: 0.57-0.59 HR30T: 0.55-0.76 F8T: 0.8-0.83

								All tests between groups (NP vs healthy) were <0.05 but the HR30T. **Between test correlations ranged between 0.35 and 0.61 and correlations between proprioceptive tests and catastrophizing, fear of movement and disability were, in general, lower than 0.3.**
Nikkhoo et al. (96)	Asymptomatic (35 participants)	21.2	US MOCAP (CMS 10, Zebris)+IMU-based mobile devices	Sitting	**Trials:** 5 trials **Movements tested:** Flexion, extension, right and left rotation	Within-day and between-day intra-rater reliability (5-7 days in between) Measurement error Criterion validity	**Reliability:** ICC two-way mixed model, **Measurement error:** SEM **Validity:** Pearson's correlation	**Reliability:** **Within-day (US MOCAP)**: ICC range 0.83-0.93 **Between-day (US MOCAP)**: ICC range 0.69-0.85 **Within-day (IMU)**: ICC range 0.66-0.91 **Between-day (IMU)**: ICC range 0.63-0.76 **Validity:** **r range:** 0.74-0.83
Cid Et al. (97)	Asymptomatic (14 men, 14 women) NP (13 women)	24.4, 23.1, 26.6	Laser pointer	Sitting	**Trials:** 10 trials **Movements tested:** Right and left rotation	Within-day intra-rater reliability (at least 7 days in between)	**Reliability:** ICC (two-way mixed model)	**Reliability (NHP):** **NP:** ICC range 0.77-0.86 **Asymptomatic:** ICC range -0.16-0.5

CNP=chronic neck pain. NP=neck pain. n=number of subjects. NHP=neutral head position. THP=target head position. Wk=weighted kappa, ICC=intraclass correlation coefficient. SEM=standard error of measurement. LoA=limits of agreement. JPE=joint position error. CROM=cervical range of motion. HRNT=head repositioning to neutral. TT=torsion test. F8T=figure-of-eight test. HR30T=head repositioning to 30 degrees test. CDD=cervical disc disease. IMU=inertial measurement unit. r= Pearson's or Spearman's correlation.

2.4.1 Absolute joint position error for people with neck pain

2.4.1.1 Intra-rater reliability

For the NHP test, six studies investigated intra-rater reliability of absolute JPE. One study included participants with CDD (35) testing right and left rotation using a CROM device and 3 trials for their assessment in sitting position, however only the NHP test was reported. This study was rated as inadequate in the RoB checklist and sufficient in the updated criteria for good measurement properties. Three studies mentioned neck pain participants but failed to report type or duration of neck pain (34,94,97). Alahmari et al. (34) carried out their intra-rater reliability assessment for the NHP test, it was rated as inadequate in the RoB checklist and sufficient in the updated criteria for good measurement properties. Burke et al. (94) carried out their intra-rater reliability using two devices, the CROM and laser. Both were rated as inadequate in the RoB checklist and insufficient in the updated criteria for good measurement properties. Cid et al. (97) investigated the intra-rater reliability of the NHP, it was rated as inadequate in the RoB checklist and sufficient in the updated criteria for good measurement properties. Moreover, two studies included CNP participants (38,95), and tested both right and left rotation in sitting position. Roren et al. (38) included 5 trials in their assessment, and used a laser pointer and US device. Both parts were rated as inadequate in the RoB checklist and insufficient in the updated criteria for good measurement properties. Goncalves and Silva (95) carried out within-day and between-day intra-rater reliability investigations of different types of NHP tests: NHP, F8T relocation test, and torsion test (TT). All investigations for were rated as doubtful in RoB checklist and sufficient in the updated criteria for good measurement properties. Nine studies showed sufficient results and four studies showed insufficient results. Therefore, the overall rating was taken. The overall rating of the intra-rater reliability was rated as sufficient, but the quality of evidence was downgraded to very low due to inconsistency of results and risk of bias (multiple studies with doubtful/inadequate ratings and inconsistency of results) (Table 2.5).

For the THP test, two studies tested the intra-rater reliability of the THP test (34,95). Alahmari et al. (34) was rated as inadequate in the RoB checklist and sufficient in the updated criteria for good measurement properties. Goncalves and Silva (95) carried out a within-day and between-day testing. Both investigations were rated as doubtful in the RoB checklist and sufficient in the updated criteria for good measurement properties. The overall rating of the intra-rater reliability of the THP test was rated as sufficient, but the quality of evidence was downgraded to low due to risk of bias (multiple studies with doubtful/inadequate rating) (Table 2.5).

2.4.1.2 Inter-rater reliability

Only two studies investigated inter-rater reliability of the NHP test in this population, and both did not report type of neck pain. Alahmari et al. (34) was rated as inadequate in the RoB checklist and sufficient in the updated criteria for good measurement properties. Burke at al. (94) carried out their investigation using two devices the laser pointer and the CROM. Both were rated as inadequate in the RoB checklist and sufficient in the updated criteria for good measurement properties. A total of three investigation showing sufficient results. The overall rating was rated as sufficient, but the quality of evidence was downgraded to low due to risk of bias (multiple studies with inadequate ratings) (Table 2.5).

2.4.1.3 Measurement error

For the THP test, five studies investigated measurement error (34,35,38,94,95). GRADE was not possible to apply due to minimal important change (MIC) not provided (Table 5). For the THP test, two studies investigated measurement error (34,95). GRADE was not possible to apply as the minimal important change was not provided (Table 2.5).

2.4.1.4 Convergent validity

Two studies investigated the convergent validity in this population and were on CNP people. Chen and Treleaven (39) correlated three JPE tests (conventional, TT, Enbloc) with the NDI and the visual analogue scale (VAS). All parts were rated as adequate in the RoB checklist and insufficient in the updated criteria for good measurement properties, apart from the correlation of JPE conventional with VAS, which showed sufficient results. Goncalves and Silva (95) correlated four JPE tests (NHP, THP, TT, and F8T) against each other and against disability, pain catastrophising, and fear of movement questionnaires. All parts were rated as adequate in the RoB checklist. Correlation of the tests against the questionnaires were rated as insufficient in the updated criteria for good measurement properties, while correlation of tests against each other were rated as sufficient. Seventeen investigations showed insufficient results, and thirteen studies showed sufficient results. The overall rating was taken and rated as insufficient, and the quality of evidence was downgraded to low due to inconsistency of results (Table 2.5).

2.4.1.5 Discriminative validity

Three studies investigated the discriminative validity in people with CNP. Chen and Treleaven (39) used three tests (JPE conventional, TT, Enbloc), Goncalves and Silva (95) used four tests (NHP, THP, TT, F8T), and Roren et al. (38) used the NHP test. All investigation were rated as inadequate in the RoB checklist. All studies were rate as indeterminate in the updated criteria for good measurement properties due to improper statistical tests used for analysis, apart from the study by Roren et al. (38), which was rated as sufficient. Seven studies showed indeterminate results and one study showed sufficient results. The overall rating of the discriminative validity was rated as indeterminate, and the quality of evidence was downgraded to very low due to inconsistency of results and risk of bias (multiple studies with inadequate rating) (Table 2.5).

2.4.1.6 Criterion validity

The criterion validity was reported only in CNP population testing for only right and left rotation. Roren et al. (38) correlated the laser pointer against an US device in sitting position for the NHP test only. This study was rated as inadequate in the RoB checklist and sufficient in the updated criteria for good measurement properties. Chen and Treleavan (39) correlated the laser pointer against the 3-Space Fastrak for both the NHP and TT in sitting position. Both parts were rated as adequate in the RoB checklist. The conventional JPE was rated as sufficient, and the TT was rated as insufficient in the updated criteria for good measurement properties. Two investigations showed sufficient results and one showed insufficient results. The overall rating was rated as sufficient, and the quality of evidence was downgraded to low due to inconsistency of results (Table 2.5).

2.4.2 Absolute joint position error for asymptomatic people

2.4.2.1 Intra-rater reliability

A total of six studies investigated intra-rater reliability of the NHP test in this population. Kristjansson et al. (46) carried their investigation on four JPE tests: NHP, Preset trunk rotation, and F8T relocation test. All parts were rated as inadequate in the RoB checklist. The NHP and F8T investigations were rated as insufficient, and Present trunk rotation investigation was rated as sufficient in the updated criteria for good measurement properties. Strimpakos et al. (48) carried out their intra-rater investigation in sitting and standing. Both were rated as inadequate in the RoB checklist and insufficient in the updated criteria for good measurement properties. Pinsault et al. (49) was rated as doubtful in the RoB checklist and sufficient in the updated criteria for good measurement properties. Goncalves and Silva (95) carried out within-day and between day investigations for three NHP tests (NHP, TT, and F8T). All investigations were rater as doubtful in the RoB checklist. The between-day investigation of the TT was rated as insufficient, while the remaining investigations were rated as sufficient in the updated criteria for good measurement properties. Nikkhoo et al. (98) carried out within-day and between-day investigations using US MOCAP and IMU devices. All investigations were rated as doubtful in the RoB checklist and sufficient in the updated criteria for good measurement properties. Cid et al. (97) was rated as doubtful in the RoB checklist and insufficient in the updated criteria for good measurement properties. Eleven studies showed sufficient results, and six studies showed insufficient results. The overall rating was sufficient, and the quality of evidence was downgraded to very low due to inconsistency of results and risk of bias (multiple studies with doubtful/inadequate rating) (Table 2.5).

Regarding the THP test, three studies investigated the intra-rater reliability of this test in this population (45,46,95) Artz et al. (45) carried out within-day and between-day intra-rater reliability of THP test only in sitting and standing. All parts were rated as inadequate in the RoB checklist and insufficient in the updated criteria for good measurement properties, apart from the between-day assessment in sitting, which was rated as sufficient. Kristjansson et al. (46) was rated as inadequate in the RoB checklist and sufficient in the updated criteria for good measurement properties. Goncalves and Silva (95) carried out a within-day and between-day investigations, both investigation were rated as doubtful in the RoB checklist and sufficient in the updated criteria for good measurement properties. Four studies showed sufficient results and three studies showed insufficient results. The overall rating was rated as sufficient, but the quality of evidence was downgraded to very low due to risk of bias and inconsistency of results (Table 2.5).

2.4.2.2 Inter-rater reliability

Only one study investigated inter-rater reliability of the NHP test (48) in this population. This study was rated as inadequate in the RoB checklist and insufficient in the updated criteria for good measurement properties. The overall rating was insufficient, and the quality of evidence was downgraded to very low due to risk of bias and low imprecision (sample size <100) (Table 2.5).

2.4.2.3 Intra-session reliability

Only one study (92) investigated in intra-session reliability of the NHP test in this population. This study was rated as doubtful in the RoB checklist and insufficient in the updated criteria for good measurement properties. The overall rating was insufficient, and the quality of evidence was very low due to risk of bias and imprecision (sample size <100) (Table 2.5).

2.4.2.4 Inter-session reliability

Only one study (92) investigated in inter-session reliability of the NHP test in this population. This study was rated as doubtful in the RoB checklist and insufficient in the updated criteria for good measurement properties. The overall rating was insufficient, and the quality of evidence was very low due to risk of bias and imprecision (sample size <100) (Table 2.5).

2.4.2.5 Measurement error

For the NHP test, six studies investigated measurement error (45,46,48,49,95,98). GRADE was not possible to apply due to MIC no provided. For the THP test, three studies investigated measurement error (45,46,95). GRADE was not possible to apply as the minimal important change was not provided.

2.4.2.6 Criterion validity

Two studies investigated criterion validity in this population. Wibault et al. (35) was rated as doubtful in the RoB checklist and indeterminate in the updated criteria for good measurement properties. Nikkhoo et al. (96) was rated as adequate in the RoB checklist and sufficient in the updated criteria for good measurement properties. We were not able to take an overall rating as one study showed sufficient results, and the other one showed indeterminate results. Therefore, the overall rating was indeterminate, and no GRADE was applied due to inconsistency of results (Table 2.5).

Table 2. 5. Summary of measurement properties of the measure of absolute JPE.

Neutral head position (Neck Pain population)	**Summary or pooled results**	**Overall rating**	**Quality of evidence**
Intra-rater reliability	ICC: 0.58-0.93. Total sample size: 580	Sufficient	**Very low evidence for sufficient intra-rater reliability** • Nine studies showed sufficient results, 4 showed insufficient results (Inconsistent results). • Multiple studies with doubtful/inadequate rating (risk of bias). • No imprecision. • No indirectness.
Inter-rater reliability	ICC: 0.58-0.79. Total sample size: 169	Sufficient	**Low evidence for sufficient inter-rater reliability** • Three studies showed sufficient results. • Multiple studies with inadequate rating. • No inconsistency. • No imprecision. • No indirectness.
Measurement error	Total sample size: 736	Indeterminate	**Not possible to apply GRADE as the minimal important change was not provided.**
Convergent validity	Correlation (r<0.5). Total sample size: 1890	Insufficient	**Low evidence for insufficient convergent validity** • Thirteen studies showed sufficient results, 17 studies showed insufficient results (Inconsistent results). • Multiple studies with adequate rating (no risk of bias). • No indirectness. • No imprecision.
Discriminative validity	Total sample size: 496	Indeterminate	**Very Low evidence for indeterminate discriminative validity** • Seven studies were indeterminate and 1 study was sufficient (inconsistent results). • Multiple studies with inadequate rating. • No imprecision. • No indirectness.
Criterion validity	r=0.87-0.95. Total sample size: 184	Sufficient	**Low evidence for sufficient criterion validity** • Two studies were sufficient, 1 was insufficient (inconsistent results). • Multiple studies with adequate rating (no risk of bias). • No imprecision. • No indirectness.
Target head position (Neck Pain population)	**Summary of pooled results**	**Overall rating**	**Quality of evidence**

Intra-rater reliability	ICC: 0.67-0.83 Total sample size: 135	Sufficient	**Low evidence for sufficient intra-rater reliability** • Three studies showed sufficient results • Multiple studies with doubtful/inadequate rating • No imprecision • No indirectness
Inter-rater reliability	ICC: 0.58-0.84 Total sample size: 69	Sufficient	**Very low evidence of sufficient inter-rater reliability** • One study showed sufficient results • One study with inadequate rating (risk of bias) • Imprecision • No indirectness
Measurement error	Total sample size: 204	Indeterminate	**Not possible to apply GRADE as the minimal important change was not provided.**
Neutral head position (asymptomatic population)	**Summary or pooled results**	**Overall rating**	**Quality of evidence**
Intra-rater reliability	ICC: 0.52-0.93. Total sample size: 537	Sufficient	**Very low evidence of sufficient intra-rater reliability** • Eleven studies showed sufficient results, 6 showed insufficient results (inconsistent results). • Multiple studies with doubtful/inadequate rating (risk of bias). • No imprecision. • No indirectness.
Inter-rater reliability	ICC: -0.2-0.64 Total sample size: 35	Insufficient	**Very low evidence of insufficient inter-rater reliability** • One study showed insufficient results. • One study with inadequate rating (risk of bias). • Imprecision (sample size <100). • No inconsistency. • No indirectness.
Measurement error	Total sample size: 509	Indeterminate	**Not possible to apply GRADE as the minimal important change was not provided.**
Intra-session reliability	ICC: 0.63 Total sample size: 57	Insufficient	**Very low evidence of insufficient intra-session reliability** • One study with doubtful rating (risk of bias) • Imprecision • No inconsistency • No indirectness
Inter-session reliability	ICC: 0.48 Total sample size: 57	Insufficient	**Very low evidence of insufficient intra-session reliability** • One study with doubtful rating (risk of bias) • Imprecision • No inconsistency • No indirectness
Criterion validity	Total sample size: 71	Inconsistent	**Not possible to apply GRADE due to inconsistency of results** • One study showed indeterminate results and one showed sufficient results.

Target head position (asymptomatic population)	Summary of pooled results	Overall rating	Quality of evidence
Intra-rater reliability	ICC: -0.48-0.83 Total sample size: 165	Sufficient	**Very low evidence of sufficient intra-rater reliability** • Four studies showed sufficient results, three showed insufficient results (inconsistency of results) • Multiple studies with doubtful/inadequate rating (risk of bias) • No indirectness • No imprecision
Measurement error	Total sample size: 165	Indeterminate	**Not possible to apply GRADE as the minimal important change was not provided.**

2.4.3 Constant joint position error for asymptomatic people

2.4.3.1 Intra-rater reliability

Two studies investigated the intra-rater reliability of the NHP test. Lee et al. (47) was rated as inadequate in the RoB checklist and sufficient in the updated criteria for good measurement properties. Dugailly et al. (93) carried out four intra-rater reliability investigation of the NHP test; low and fast speeds at 90cm and 180cm from a target. All four parts were rated as inadequate in the RoB checklist. Only the low speed at 90cm was rated as insufficient, while the remaining three were rated as sufficient in the updated criteria for good measurement properties. Four studies showed sufficient result, one study showed insufficient results. The overall rating was sufficient, and the quality of evidence was downgraded to very low due to inconsistency of results, risk of bias (multiple studies with inadequate ratings), and imprecision (sample size <100) (Table 2.6).

For the THP test, only one study investigated the intra-rater reliability of this test (47). This study was rated as inadequate in the RoB checklist and sufficient in the updated criteria for good measurement properties. The overall rating was sufficient, but the quality of evidence was downgraded to very low due to risk of bias and imprecision (sample size <100) (Table 2.6).

2.4.3.2 Measurement error

For the NHP test, two studies investigated the measurement error in this population (47,93). GRADE was not possible to apply due to MIC not provided (Table 6). For the THP, only one study investigated measurement error (47). GRADE was not possible to apply as the minimal important change was not provided (Table 2.6).

2.4.3.3 Convergent validity

One study by Dugailly et al. (93) correlated the JPE test against disability questionnaire, pain duration, and pain intensity. All parts were rated as adequate in the RoB checklist and insufficient in the updated criteria for good measurement properties. The overall rating was insufficient, and the quality of evidence was high due to multiple studies with adequate ratings (no risk of bias) (Table 2.6).

2.4.3.4 Criterion validity

The criterion validity was reported only once by Dugailly et al. (93). This study was rated as doubtful in the RoB checklist and indeterminate in the updated criteria for good measurement properties. The overall rating was indeterminate, and the quality of evidence was downgraded to very low due to risk of bias and imprecision (sample size <50) (Table 2.6).

Table 2. 6. Summary of measurement properties of the measure of constant JPE.

Neutral head position (asymptomatic population)	**Summary or pooled results**	**Overall rating**	**Quality of evidence**
Intra-rater reliability	ICC: 0.38-0.86 Total sample size: 40	Sufficient	**Very low evidence of sufficient intra-rater reliability** • Four studies showed sufficient results and 1 showed insufficient results (inconsistency) • Multiple studies with inadequate rating (risk of bias). • Imprecision (sample size <100).

			• No indirectness.
Measurement error	Total sample size: 40	Indeterminate	**Not possible to apply GRADE as the minimal important change was not provided.**
Convergent validity	r=0.03-0.32 Total sample size: 213	Insufficient	**High evidence for insufficient convergent validity** • Multiple studies with adequate rating (no risk of bias). • No inconsistency of results • No imprecision. • No indirectness.
Criterion validity	Total sample size: 17	Indeterminate	**Very Low evidence for indeterminate criterion validity** • One study with doubtful rating (risk of bias). • Imprecision (sample size <50). • No indirectness.
Target head position (asymptomatic population)	**Summary of pooled results**	**Overall rating**	**Quality of evidence**
Intra-rater reliability	ICC: -0.47-0.83 Total sample size: 20	Sufficient	**Very low quality of evidence for sufficient intra-rater reliability** • One study showed sufficient results • One study with inadequate rating (risk of bias) • Imprecision • No inconsistency • No indirectness
Measurement error	Total sample size: 20	Indeterminate	**Not possible to apply GRADE as the minimal important change was not provided.**

2.5 Discussion

This is the first systematic review to synthesise and appraise the measurement properties of cervical JPE in people with and without neck pain using the COSMIN checklist. Our search yielded 8 studies that included neck pain participants and 7 in which asymptomatic participants were included. Absolute and constant errors were reported in this review since they are recommended when assessing JPE (99). The large range of testing procedures used in the studies reviewed highlight the lack of any consensus in the literature on how best to assess JPE. A key factor contributing to this may be the heterogeneity of neck pain participants recruited for the reviewed studies, each with different clinical features. Given these differences in testing procedures and the vast range in types of neck pain, it is difficult to draw any general conclusions on the gold standard for testing the measurement properties of cervical JPE.

Similar to other systematic reviews, the current systematic review highlighted several issues with the quality of the included studies (100,101). Most of the included studies in this review were rated as inadequate or doubtful in the RoB checklist with an overall quality of the evidence being low to very low, apart from the convergent validity of the constant JPE, which was high. This was due to a failure in adhering to COSMIN guidelines when carrying out investigations of measurement properties of outcome measures. For example, according to COSMIN, the time-interval should be long enough to prevent recall bias, and short enough to ensure that the patients have not been changed on the construct to be measured (58). When assessing the RoB for reliability and measurement error, there are no guidelines for the time-interval between sessions, therefore, this section was rated as doubtful. Other issues highlighted were statistical tests used for validity investigations. COSMIN recommends Pearson’s or Spearman’s correlation for validity assessment, which the criterion validity in the constant JPE did not use. Therefore, some of the included studies were rated as indeterminate in the updated criteria for good measurement properties. A further limitation in the included studies was when the model of the ICC used for reliability assessment was not stated. When using the RoB checklist for reliability and measurement error (85), if a study used ICC and reported the model used, it should be rated as very good; if the study used ICC but failed to report the model, then it should be rated as inadequate. Three studies failed to report the ICC model used (38,45,93), thus, they were rated as inadequate in the RoB checklist. Reporting the ICC model is important because the model used and the type of coefficient will impact on the magnitude of the ICC (102). Failure to report the ICC model will affect the study’s generalisability and interpretation of the results. Inclusion of a replicable measure of response stability will aid the interpretation of results and comparison between studies.

Another issue in the current review was the inconsistency of results for the criterion validity of absolute JPE in the asymptomatic population. This inconsistency was probably due to differences in statistical tests used for validity assessment and variations in testing protocols. For example, Wibault et al. (35) correlated the CROM device against a laser pointer after returning from right and left rotation using three trials per movement in their assessment. They used the ICC for their validity assessment, which is not recommended by COSMIN, and thus were rated as indeterminate in the updated criteria for good measurement properties. Nikkhoo et al. (96) correlated the US MOCAP against IMUs after returning from flexion, extension, and bilateral rotation using five trials per movement. This study was rated as sufficient in the updated criteria for good measurement properties. Therefore, it was not possible to draw an overall rating for this measurement property due to inconsistency of the results and it was rated as indeterminate. The convergent validity on the other hand was rated as high. This was due to no risk of bias in the included studies; however, it did not show sufficient results. Sample size was another issue that affected the overall rating of an outcome measure. When applying the modified GRADE approach, sample size should be ≥ 100. However, the total sample size of the inter-rater reliability of absolute JPE in the asymptomatic population was 62 participants; this led to downgrading the overall evidence to one level. Similarly, the criterion validity of constant JPE was downgraded to two levels due to sample size <50. In addition, the wording around reliability studies was challenging as several studies did not report the word ‘’reliability’’ in the title of the study, affecting the quality of the study.

Furthermore, the current systematic review highlighted gaps in the literature when testing the measurement properties of the measure of cervical JPE. First, the testing position. Most of the included studies carried out their investigations in sitting. Only two studies carried out their investigation in sitting as well as standing (45,48). However, these two studies did not include any neck pain patients, and only asymptomatic participants were recruited. In addition, they reported only constant JPE, failing to report absolute JPE. A second gap was the lack of investigation of inter-rater reliability of constant JPE in people with neck pain. The third gap we uncovered was regarding the criterion validity of absolute JPE. Although this property was investigated twice, it was limited to right and left rotation. Lastly, the domain of responsiveness was not reported in our systematic review. The evident gaps in the existing literature created a demand for the empirical research conducted in the following chapters of this thesis.

2.5.1 Methodological considerations

This is the first systematic review to summarise and appraise the evidence of measurement properties of the cervical JPE measure using COSMIN guidelines. Two raters carried out the study selection, data extraction, the risk of bias checklist, and the GRADE approach minimising bias, which is considered a strength of this systematic review. Additionally, we included studies that have reported absolute and constant errors, which is recommended when testing cervical proprioception (99). Prospective registration with PROSPERO is another strength of this review. A potential limitation is that the principle of lowest rating counts when using the COSMIN risk of bias checklist, thus underestimating the overall quality of the study, and potentially downgrading the overall quality of the evidence.

Although the COSMIN checklist is a useful resource for assessing the quality of health measurement instruments, it does come with certain limitations. Its detailed and extensive structure can be difficult and time-consuming to apply, particularly for individuals who lack expertise in measurement properties, and its dependence on subjective interpretation can result in inconsistent evaluations. Additionally, the checklist places significant emphasis on psychometric aspects like reliability and validity, which may lead to the neglect of other critical factors such as feasibility and clinical practicality. In addition, the current systematic review included studies with CNP, studies that did not specify type of neck pain, and studies with CDD. This might affect the studies generalisability to other neck pain populations, especially people with WAD and cervicogenic dizziness as both populations exhibit proprioceptive deficits. Further, when applying the ROB checklist on the included studies, the lowest rating counts, which have led to most of the studies being rated as inadequate, thus, the overall quality of evidence was downgraded. Although this approach was strictly in line with COSMIN recommendations, it underestimated the overall quality of evidence.

A further limitation would the methodological challenges and biases when rating the included studies. For example, there were no guidelines to differentiate between within-day or between-day reliability testing, so rating those sub-domains of reliability testing is all subjective and was based on agreements between researchers rating the included studies. Also, when there were inconsistency of results and the modified GRADE approach to be applied, there were no guidelines on how many levels the level of evidence should be downgraded, and it was based on agreement between the raters whether to downgrade by one or two levels. These subjectivities will lead to inconsistencies between researchers thus, potentially leading to different conclusions about the overall quality of evidence.

2.5.2 Recommendations for future research

Additional research is clearly warranted to assess the measurement properties of the measure of JPE in people with and without neck pain. Another recommendation is to report both absolute and constant errors in future research. Also, assessing the measurement properties of the measure of JPE in standing in addition to sitting is recommended, as well as reporting absolute and constant error for both. Responsiveness of the measure of JPE was not investigated, which we recommend investigating in future research.

2.6 Conclusion

Conclusions about the measurement properties of the measure of cervical JPE were difficult to draw due to lack of consensus on testing procedures and tools used. The next chapter aims to carry out high-quality research to overcome the risk of bias in the included studies and to address the gaps highlighted in this review.

Chapter 3: Reliability, measurement error, and validity of cervical joint position error in people with and without chronic neck pain

This chapter reports content of a published manuscript by the thesis author (AlDahas et al. 2023). It includes verbatim text from published manuscript with changes employed for the purpose of this thesis.

Publication

AlDahas A, Devecchi V, Deane JA, Falla D. Measurement properties of cervical joint position error in people with and without chronic neck pain. Plos one. 2023 Oct 12;18(10):e0292798.

3.1 Abstract

Background: People with CNP often present with impaired neck proprioception. The most widely used clinical test for assessing neck proprioception is cervical JPS which measures JPE. This clinical test is typically performed using a laser pointer to examine the accuracy of returning to a NHP or THP following active neck movements. The aim of this study was to determine the measurement properties of JPE using a laser pointer when tested in people with and without CNP under a variety of different testing conditions (i.e., different movement directions, sitting versus standing, NHP versus THP).

Methods: Forty-three participants (23 asymptomatic and 20 with CNP) underwent neck proprioception testing, returning to a NHP and THP in both sitting and standing positions (six trials for each test). A laser pointer was secured on the participant's forehead and inertial measurement unit (IMU) sensors were placed beneath the laser pointer and at the level of the spinous process of the seventh cervical vertebra. Both the absolute and the constant JPE were assessed.

Findings: For the asymptomatic participants, good reliability (ICC: 0.79) was found only for right rotation of the THP task in sitting. In standing, good reliability (ICC: 0.77) was only found in flexion for the THP task. In standing, good reliability (ICC: 0.77) was only found for right rotation of the THP for the absolute JPE and left rotation (ICC: 0.85) for the constant error of the NHP task. In those with CNP, when tested in sitting, good reliability was found for flexion (ICC: 0.8) for the absolute JPE and good reliability (ICC range: 0.8-0.84) was found for flexion, extension, and right rotation for the constant JPE. In standing, good reliability (ICC range: 0.81-0.88) was found for flexion, and rotation for the absolute JPE. The constant JPE showed good reliability (ICC: 0.85) for right rotation and excellent reliability (ICC: 0.93) for flexion. Validity was weak to strong (r range: 0.26-0.83) and moderate to very strong (r range: 0.47-0.93) for absolute and constant error respectively, when tested in sitting. In standing, the validity was weak to very strong (0.38-0.96) for the absolute JPE and moderate to very strong (r range: 0.54-0.92) for the constant JPE.

Conclusion: The reliability of the measure of JPE when tested in sitting and standing in both groups showed good reliability, but not for all movements. The results of the current study also showed that the laser pointer correlated well with the Noraxon IMUs, but not for all movements. The results of the current study support the use of the JPE using a laser pointer in clinical and research settings.

3.2 Introduction

In a clinical environment, neck proprioception is commonly assessed with a laser pointer mounted on the patient's head combined with a wall target (37). Although the measure of JPE is commonly used in clinical practice and in research, there is still insufficient knowledge of the measurement properties of this test, including the reliability, validity, and responsiveness of the measure. Some studies have assessed the measurement properties of the JPE assessed using a laser pointer (e.g. (38,49,93–95,103)). However, a variety of testing protocols were used for the assessment of the reliability of the JPE test in terms of movements tested, type of error assessed (absolute versus), type of JPE task, and testing position. For example, Goncalves and Silva (95), investigated the NHP and THP tests but in right and left rotation only. Pinsault et al. (49) evaluated the NHP task in asymptomatic participants and evaluated both absolute and variable errors whereas Roren et al. (38), tested the reliability of the NHP task after returning from right and left rotation analysing absolute error only. Jorgensen et al. (103) positioned the laser at the back of the participants' heads, while the previously mentioned studies mounted the laser on their forehead. All the previously mentioned studies were limited to testing of right and left rotation. Meanwhile, Dugailly et al. (93) tested flexion, extension, and right and left rotation in five asymptomatic participants at low and high movement speeds and included only the constant error in their analysis. Also, the number of testing trials was not standardised between studies. All previous studies tested JPE in a sitting position, and no study was identified testing the reliability of the JPE test in standing position using a laser pointer, however, two studies were identified testing the measurement properties of the JPE test in a standing using other tools (45,48). Overall, it is evident that a more comprehensive evaluation is required to establish the reliability of the JPE when tested in different movement directions, different testing positions and when considering both absolute and constant error. There is also limited research testing the criterion-related validity of the JPE test using a laser pointer in sitting. Studies that have tested this measurement property were limited to tests of right and left rotation (35,39), while Dugailly et al. (93) tested rotation as well as flexion and extension. In addition, no study has investigated the criterion-related validity of the JPE using a laser pointer measured in standing.

Based on the apparent need to evaluate the measurement properties of the JPE in both people with and without CNP in a range of different movement directions, testing positions (sitting and standing), and conditions (NHP and THP), the aims of this study were as follows: 1. to determine the reliability of the JPE test when assessed to a NHP and THP following active neck flexion, extension, and right and left rotation in people with and without CNP when performed in sitting and standing positions, 2. to determine the criterion-related validity of the JPE test when assessed to a NHP and THP following active neck flexion, extension, and right and left rotation in asymptomatic people when performed in sitting and standing positions, 3. to compare the JPE between groups, and 4. to compare JPE when tested in sitting and standing positions.

3.3 Methods

3.3.1 Study design

A between-day test-retest (intra-rater) reliability and criterion-related validity study was carried out on people with and without CNP. The COSMIN guidelines of study designing checklist (104) was used to report this study. Testing was carried out by a single rater who has experience in COSMIN guidelines for reporting studies of measurement properties and received extensive training on measuring JPE using a laser pointer and IMUs. The study was carried out in a motion analysis laboratory at the Centre of Precision Rehabilitation for Spinal Pain (CPR) Spine, University of Birmingham, United Kingdom. The study received full ethical approval from the ethics committee at the University of Birmingham (ERN_21-0618). All participants provided written informed consent. Data collection was carried out from December 2021 to May 2022.

Participants identities and personal information were stored in a locked room at the University, and no one has access to their information.

3.3.2 Participants

All participants were recruited from the staff and student population at the University of Birmingham, United Kingdom. A circular email was sent to all students at the school of Sport, Exercise, and Rehabilitation Sciences along with the participant's information sheet. Also, flyers were distributed all over the campus at the University of Birmingham with details about the study and contact information in case anyone is interested in taking part of the study. People who showed interest in taking part of the study were screened via health questionnaire to ensure their eligibility for the study. People with CNP who showed interest in the study were further asked to fill the NDI questionnaire and the pain scale (NRS) to ensure their eligibility for the CNP group. After that, people who were eligible for the study were asked to attend the first session where they were asked to sign a consent form prior to the investigation.

3.3.3 Inclusion and exclusion criteria

An inclusion criterion for both groups was adults aged between 18-55 years with a restriction on the upper limit to limit potential degenerative changes of the spine with older age (105). Asymptomatic participants had to be free of neck pain. People with CNP had to have experienced neck pain for at least 3 months (39) with at least mild pain (≥4 out of 10 on a (NRS)) (106) or at least 10 out of 100 on the NDI (39). The NRS is a reliable and valid self-administered questionnaire to measure the level of pain intensity (107). The NDI is a reliable and valid method to measure disability in people with neck pain (108). Exclusion criteria for both groups were neck surgery, vestibular disorders, and Covid-19 related symptoms in the last 14 days according to the requirements of the University of Birmingham.

3.3.4 Testing procedure

Testing of the asymptomatic participants was spread over four testing days to minimise fatigue during testing and to reduce learning effects. Testing in sitting always took place before testing in standing. The NHP test was carried out first followed by the THP test, but the order of tested movements was randomised using the following website (https://www.random.org/lists/). The first session consisted of reliability session 1 and validity testing in sitting. The second session consisted of reliability session 1 and validity testing in standing. After 14 days, as recommended by COSMIN, the participants were asked to come for two additional testing days for reliability testing in sitting (session 3) then standing (session 4). In each testing session, the order of tested movements was randomised to minimise learning effects.

People with CNP were asked to attend two testing sessions only. They carried out the NHP test only to reduce fatigue and potential changes in their pain intensity due to repeated testing. CNP participants were tested in the same way as asymptomatic participants, testing in sitting always took place before standing but the order of tested movements was randomised. Testing sessions were arranged as follows: the first session consisted of reliability testing in sitting and standing and the second session consisted of reliability testing in sitting and standing. The second session took place 14 days after day 1, as recommended by COSMIN.

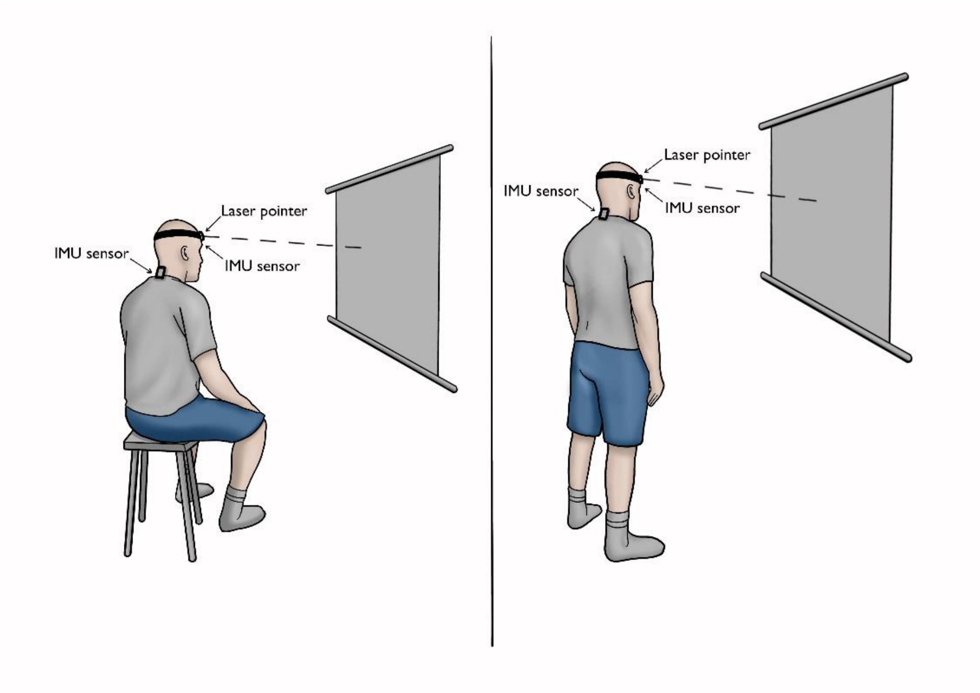
All participants were instructed not to perform any strenuous exercise or activity during the period between testing sessions that could potentially aggravate their pain or lead to fatigue.

At the beginning of the first session, participants with CNP were asked to complete the DHI questionnaire, and TSK questionnaire. Asymptomatic participants completed the TSK questionnaire only. People with CNP also completed the TSK and the DHI questionnaires in session 2 to determine whether there was any change between sessions. The DHI is a questionnaire that is sub-grouped into three domains (functional, emotional, and physical) that assesses dizziness over 25 items (109); DHI scores range from 0 to 100 (110). DHI scores can be further sub-divided according to the sub-groups of the questionnaire into 28 points for physical, 36 points for functional, and 36 points for emotional (111). The TSK is a questionnaire that contains 17 items that assess the person's fear of movement and movement-related behaviour (112); TSK scores range from 17-68, where higher scores mean higher degrees of Kinesiophobia (112).

A laser pointer specifically designed for clinical testing of proprioception (Tracker ^{TM}, USA) was fixed on the participant's forehead and additionally, IMUs (Research PRO IMU, Noraxon, USA) with a sampling rate of 100 Hz were used simultaneously with the laser pointer to investigate the criterion-related validity of the two testing tools. The IMUs by Noraxon are reliable and valid for measuring body kinematics (113). One IMU sensor was fitted on the forehead beneath the laser pointer via double-sided tape and one sensor was fitted over the neck at the level of the seventh cervical spinous process. Prior to data collection, the IMUs were calibrated, and the starting position was set at 0°.

The participant sat/stood in a comfortable position in front of an A2-sized paper that was positioned 90 cm in front of them at eye level (Figure 3.1). Tests of JPE to a NHP and a THP were carried out. During the NHP tests, participants were asked to stay in a neutral position for a few seconds then the rater marked this position on the paper as the starting position (NHP). The participant moved their head away from the start position in their full range of motion at a comfortable pace and then attempted to reposition the head back to the starting point as accurately as possible, whereas for the THP, the participant was asked to reposition the head to a target position (approximately mid-range) predetermined visually by the investigator (AA).

Figure 3. 1. An illustration of the testing procedure performed in sitting and standing.



For all JPE tests performed, flexion, extension, right rotation, and left rotation were tested in a random order in both sitting and standing. Participants performed one familiarisation trial with their eyes open and after that, they were asked to close their eyes, perform the active movement and repeat the movement six times; six trials have been recommended to assess spinal proprioception (26,114). They were instructed to keep their eyes closed during all six repetitions. A one-minute rest was given after each trial. The movement was evaluated in the primary plane only.

3.4 Data analysis

The difference between the starting position (zero) and the point of return in the plane of movement was measured in centimetres (37–39) and then converted to degrees using this formula angle=$\tan^{-1}$ [error distance/90 cm] (38). The average of the six trials was calculated and taken forward for data analysis. Both absolute and constant errors were determined. The absolute error was defined as the mean of total deviation from the target ignoring the positive and negative values

(99). The constant error was defined as the mean of total deviation from the target considering positive and negative values (99).

To analyse the IMU data, the two waveforms of cervical flexion/extension and right rotation/left rotation were exported from myoRESEARCH software (Noraxon, USA) to MATLAB where they were analysed with customised script. The waveform referring to the primary plane of movement was considered. The starting position was visually identified from the angle and velocity waveforms, and it was recognised by the steady position just before starting the movement. The return position was considered as the one at the end of the recording. The JPE was then computed as the difference between the start and return position. Both absolute and constant JPE were computed as previously described.

3.5 Statistical analysis

G*Power (version 3.1.9.4) was used to determine the required sample size for the evaluation of reliability and validity. The sample size for the reliability analysis was determined based on a 0.05 significance level, true reliability exceeding 0.7, and power of 0.8, resulting in a required sample of ≥19 participants (115). For validity, a sample of ≥13 participants is required to detect a correlation of 0.7, with a level of significance 0.05, and power of 0.8 (116). Therefore, a target of at least 20 participants was set for each group accounting for possible dropouts.

Data analysis was carried out using SPSS (version 27, IBM). The Shapiro-Wilk test was used to assess the normality of data distribution. Since the data were not normally distributed, the Mann Whitney U test was used to analyse the difference in JPE between people with and without CNP and between sitting and standing positions. Also, the Mann Whitney U test was used to analyse any differences in the demographic data between the asymptomatic and the CNP group. Significance was set at ($p \leq 0.05$). For the reliability analysis, the ICC, SEM, and Bland Altman limits of agreement were assessed. The two-way mixed model ICC (3, K) with absolute agreement and average measure was used for analysis. The following criteria was used for ICC interpretation: <0.5= poor, 0.5-0.74= moderate, 0.75-0.9= good, and >0.91= excellent (41). The ICC is highly suitable for reliability studies because it measures the consistency or agreement between raters, testing sessions, or repeated measurements, which are central to reliability assessment. It captures both within-subject variability and between-subject variability, providing a more complete evaluation of reliability. Additionally, it is sensitive to both random and systematic errors, making it a robust and flexible tool for quantifying agreement in a wide range of research contexts.

The SEM was obtained from the repeated measure analysis of variance (ANOVA) as the square root of the mean square residual using the following formula SEM =$\sqrt{\sigma}$ 2 residual (50). For Bland Altman plots interpretation of good agreement, the majority of points must rely within 95% limits of agreement with even distribution of points on both sides and a mean difference closer to zero (117).

For criterion validity, the two-tailed Pearson’s product-moment correlation coefficient (r) was used. The following criteria was used for validity interpretation; 0.1-0.39=weak, 0.4-0.69=moderate, 0.7-0.89=strong, 0.9-1=very strong (53). Pearson's correlation coefficient is well-suited for criterion validity studies because it assesses the strength and direction of the linear relationship between a new measurement tool and an established gold standard.

3.6 Results

Twenty-three asymptomatic participants (8 men, 15 women) and 20 people with CNP (8 men, 12 women) participated. The demographic data of the participants are summarised in Table 3.1. Statistical analysis showed no significant differences between the groups in terms of their age, height, and weight however, the TSK scores were significantly greater in those with CNP compared to asymptomatic controls.

Table 3. 1. Participant demographic data presented as means and standard deviations.

	Asymptomatic	CNP	P-value for group difference
Gender	8 males, 15 females	8 males, 12 females	-
Age, mean (SD)	25.66 (6.85)	25.9 (4.75)	P=0.64
Height (cm), mean (SD)	170.13 (7.47)	162.48 (26.01)	P=0.15
Weight (kg), mean (SD)	68.56 (15.98)	78.61 (29.07)	P=0.45
TSK, mean (SD)	32.69 (7.8)	40.1 (5.9)	P=0.001*
NDI, mean (SD)	-	27.6 (6.34)	-
NRS, mean (SD)	-	4.05 (1.87)	-
DHI, mean (SD)	-	25.7 (15.01)	-

TSK=Tampa Scale of Kinesiophobia. NDI=Neck Disability Index. NRS=Numerical Rating Scale. DHI=Dizziness Handicap Inventory. CNP=chronic neck pain. The Mann-Whitney U test was used to assess significance. *= P-value ≤0.05.

There was one dropout from the asymptomatic group due to Covid-19 related symptoms, thus data for tests performed in standing are presented for 22 asymptomatic and 20 people with CNP. Fifteen asymptomatic participants and 19 people with CNP completed the reliability study whereas for validity analysis, data for 15 asymptomatic participants were included in sitting data analysis and 14 in standing data analysis due to technical difficulties with one recording. There was no difference in the Tampa Scale of Kinesiophobia (p=0.44) and the Dizziness Handicap Inventory (p=0.95) questionnaires between sessions 1 and 2 in those with CNP.

3.6.1 Differences in JPE between people with and without chronic neck pain

In sitting, there was a significant difference between groups in absolute JPE for flexion, extension, and left rotation (Table 3.2), while JPE for right rotation was not significant between groups. No differences were observed between groups for the constant error apart from the constant JPE in left rotation (Table 3.2).

Table 3. 2. Differences in absolute and constant JPE between asymptomatic participants and people with CNP when tested in sitting.

Absolute error, mean (SD)				Constant error, mean (SD)			
Movement	**Asymptomatic**	**CNP**	**P-value**	**Movement**	**Asymptomatic**	**CNP**	**P-value**
Flexion	2.09 (0.63)	4.3 (3.33)	0.001*	**Flexion**	-0.02 (1.78)	0.73 (5.18)	0.84
Extension	2.23 (0.82)	4.8 (2.69)	0.001*	**Extension**	1.13 (2.23)	1.28 (4.9)	0.78
Right rotation	2.46 (2.02)	3.53 (2.36)	0.072	**Right rotation**	0.84 (2.53)	0.47 (4.06)	0.3
Left rotation	1.86 (0.96)	3.68 (2.11)	0.001*	**Left rotation**	-0.14 (1.81)	-2.62 (3.07)	0.002*

*= P-value ≤0.05. CNP=chronic neck pain

When tested in standing, there was a significant difference in the absolute JPE for flexion, extension, and right rotation (Table 3.3), while JPE following left rotation was not significant between groups. No differences were observed between groups for the constant JPE (Table 3.3).

Table 3. 3. Differences in absolute and constant JPE between asymptomatic participants and people with CNP when tested in standing.

Absolute error, mean (SD)				Constant error, mean (SD)			
Movement	**Asymptomatic**	**CNP**	**P-value**	**Movement**	**Asymptomatic**	**CNP**	**P-value**
Flexion	2.07 (1.14)	4.93 (3.12)	0.001*	**Flexion**	-0.16 (1.9)	1.15 (5.44)	0.42
Extension	2.19 (0.92)	4.06 (2.68)	0.001*	**Extension**	0.94 (1.66)	-0.04 (4.63)	0.096
Right rotation	1.96 (1.18)	3.41 (2.18)	0.013*	**Right rotation**	0.92 (1.64)	0.19 (3.92)	0.19
Left rotation	2.34 (1.6	3.06 (1.91)	0.13	**Left rotation**	-0.27 (2.28)	0.37 (3.06)	0.48

*= P-value ≤0.05. CNP=chronic neck pain.

3.6.2 Differences in JPE between sitting and standing

For the asymptomatic participants, there was no significant difference in JPE between sitting and standing for both the absolute and constant errors (Table 3.4). In people with CNP, there was only a significant difference in JPE between sitting and standing positions for the constant error of left rotation (Table 3.5) thus the measures were largely the same regardless of the testing position.

Table 3. 4. Differences in JPE when tested in sitting and standing positions for the asymptomatic participants.

Absolute error, mean (SD)				Constant error, mean (SD)			
Movement	**Sitting**	**Standing**	**P-value**	**Movement**	**Sitting**	**Standing**	**P-value**

Flexion	2.09 (0.63)	2.07 (1.14)	0.33	**Flexion**	-0.02 (1.78)	-0.16 (1.9)	0.82
Extension	2.23 (0.82)	2.19 (0.92)	0.96	**Extension**	1.13 (2.23)	0.94 (1.66)	0.76
Right rotation	2.46 (2.02)	1.96 (1.18)	0.48	**Right rotation**	0.84 (2.53)	0.92 (1.64)	0.48
Left rotation	1.86 (0.96)	2.34 (1.6)	0.45	**Left rotation**	-0.14 (1.81)	-0.27 (2.28)	0.63

Table 3. 5. Differences in JPE when tested in sitting and standing positions for the participants with CNP.

Absolute error, mean (SD)				**Constant error, mean (SD)**			
Movement	**Sitting**	**Standing**	**P-value**	**Movement**	**Sitting**	**Standing**	**P-value**
Flexion	4.37 (3.33)	4.93 (3.12)	0.41	**Flexion**	0.73 (5.18)	1.15 (5.44)	0.75
Extension	4.8 (2.69)	4.06 (2.68)	0.37	**Extension**	1.28 (4.9)	-0.04 (4.63)	0.26
Right rotation	3.53 (2.36)	3.41 (2.18)	0.97	**Right rotation**	0.47 (4.06)	0.19 (3.92)	0.84
Left rotation	3.68 (2.11)	3.06 (1.91)	0.27	**Left rotation**	-2.62 (3.07)	0.37 (3.06)	0.003*

*= significance (P-value ≤0.05).

3.6.3 Reliability

For the asymptomatic group, the absolute error for the NHP task when performed in sitting showed poor to moderate reliability (ICC range: 0.4-0.66) with a SEM range of 0.46°-0.91° and poor to good reliability (ICC range: -0.27-0.79) for the THP task with a SEM range of 0.53°-1.22° (Table 3.6). For the constant error, poor to good reliability (ICC range: 0.28-0.76) was observed with a SEM range of 0.8°-1.76° for the NHP task and poor to good reliability (ICC range: 0.08-0.77) with a SEM range of 0.93°-1.77° for the THP task (Table 3.6).

Table 3. 6. Reliability analysis of JPE measured from asymptomatic participants performing the NHP and THP tasks in sitting.

Movement	**Absolute error ICC (95% CI)**	**SEM**	**Constant error ICC (95% CI)**	**SEM**
Flexion (NHP)	0.4 (-0.88-0.8)	0.84	0.28 (-1.31-0.76)	1.76
Extension (NHP)	0.66 (0.08-0.8)	0.91	0.52 (-0.18-0.83)	1.57
Right rotation (NHP)	0.56 (-0.37-0.85)	0.57	0.71 (0.17-0.9)	0.8
Left rotation (NHP)	0.64 (-0.12-0.88)	0.46	0.76 (0.29-0.92)	0.86
Flexion (THP)	-0.18 (03.1-0.62)	0.76	0.77 (0.29-0.92)	0.93
Extension (THP)	0.04 (-2.27-0.69)	1.22	0.26 (-1.34-0.75)	1.8
Right rotation (THP)	0.79 (0.26-0.93)	0.53	0.62 (-0.16-0.87)	1.51

Lefty rotation (THP)	-0.27 (-3.36-0.58)	1.24	0.08 (-1.87-0.7)	1.77

ICC=Intraclass correlation coefficient. CI=Confidence interval. SEM=Standard error of measurement. NHP=neutral head position. THP=target head position. SEM=standard error of measurement

When the tests were performed in standing, the absolute JPE showed moderate reliability (ICC range: 0.5-0.74) for the NHP task with a SEM range of 0.48°-0.76° and poor to good reliability (ICC range: 0.21-0.77) for the THP task with a SEM range of 0.51°-1.38° (Table 3.7). The constant JPE showed poor to good reliability (ICC range: 0.21-0.85) with a SEM range of 0.72°-1.11° for the NHP task and poor to moderate reliability (ICC range: 0.23-0.6) for the THP task with a SEM range of 0.92°-1.55° (Table 3.7).

Table 3. 7. Reliability analysis of JPE measured from asymptomatic participants performing the NHP and THP tasks in standing.

Movement	Absolute error ICC (95% CI)	SEM	Constant error ICC (95% CI)	SEM
Flexion (NHP)	0.68 (0.01-0.89)	0.5	0.67 (0.02-0.89)	1.01
Extension (NHP)	0.5 (-0.4-0.83)	0.76	0.74 (0.3-0.92)	1.03
Right rotation (NHP)	0.5 (-0.52-0.83)	0.6	0.21 (-1.58-0.74)	1.11
Left rotation (NHP)	0.74 (0.22-0.91)	0.48	0.85 (0.56-0.95)	0.72
Flexion (THP)	0.33 (-1.1-0.78)	1.38	0.55 (-0.37-0.85)	1.55
Extension (THP)	0.21 (-1.49-0.74)	1.07	0.6 (-0.1-0.86)	0.92
Right rotation (THP)	0.77 (0.3-0.92)	0.51	0.23 (-1.23-0.74)	1.42
Lefty rotation (THP)	0.42 (-0.86-0.81)	0.58	0.6 (-0.22-0.86)	1.03

ICC=Intraclass correlation coefficient. CI=Confidence interval. SEM=Standard error of measurement. NHP=neutral head position. THP=target head position.

For those with CNP when tested in sitting, the absolute JPE showed poor to good reliability (ICC range: 0.43-0.8) and a SEM range of 0.59°-2.34° and poor to good reliability (ICC range: -0.09-0.82) with a SEM range of 2.09°-3.43° for the constant error (Table 3.8). In standing, the absolute JPE showed poor to good reliability (ICC range: 0.19-0.87) with a SEM range of 0.98°-2.64° and moderate to excellent reliability (ICC range: 0.52-0.93) with a SEM range of 1.82°-4° for the constant error (Table 3.9). The Bland Altman limits of agreement can be found in Appendix 2.3.

Table 3. 8. Reliability analysis of JPE measured from people with CNP when performing the NHP task in sitting.

Movement	Absolute error ICC (95% CI)	SEM	Constant error ICC (95% CI)	SEM
Flexion	0.8 (0.48-0.92)	2.02	0.84 (0.59-0.93)	2.73
Extension	0.43 (-0.51-0.78)	2.34	0.8 (0.5-0.92)	2.66
Right rotation	0.57 (-0.11-0.83)	1.65	0.82 (0.53-0.93)	2.09
Left rotation	0.51 (-0.24-0.81)	0.59	-0.09 (-1-0.51)	3.43

ICC=Intraclass correlation coefficient. CI=Confidence interval. SEM=Standard error of measurement.

Table 3. 9. Reliability analysis of JPE measured from people with CNP performing the NHP task in standing.

Movement	Absolute error ICC (95% CI)	SEM	Constant error ICC (95% CI)	SEM
Flexion	0.88 (0.69-0.95)	1.38	0.93 (0.81-0.97)	1.82
Extension	0.19 (-1.08-0.69)	2.64	0.52 (-0.19-0.81)	4
Right rotation	0.81 (0.53-0.92)	1.22	0.85 (0.61-0.94)	2.17
Left rotation	0.87 (0.67-0.95)	0.98	0.6 (-0.03-0.84)	2.43

ICC=Intraclass correlation coefficient. CI=Confidence interval. SEM=Standard error of measurement.

3.6.4 Criterion validity

When tested in sitting, the absolute JPE showed weak to strong correlations (r range: 0.39-0.83) between measures for the NHP task and weak to moderate correlations (r range: 0.26-0.69) for the THP task. For the constant JPE, the NHP task showed moderate to very strong correlations (r range: 0.55-0.93) and moderate correlations (r range: 0.47-0.68) for the THP task (Table 3.10).

For the tests performed in standing, the absolute JPE showed strong to very strong correlations (r range: 0.73-0.95) for the NHP task and weak to very strong correlations (r range: 0.38-0.96) for the THP task. For the constant JPE, strong to very strong correlations (r range: 0.78-

0.94) between measures were observed for the NHP task and a moderate to strong correlations (r range: 0.54-0.83) were observed for the THP task (Table 3.10).

Table 3. 10. Criterion-validity analysis performed for the JPE measured from asymptomatic participants for the NHP and THP tasks.

Movement	Sitting (n=15)		Standing (n=14)	
	Absolute error	Constant error	Absolute error	Constant error
Flexion (NHP)	0.65	0.73	0.95	0.94
Extension (NHP)	0.39	0.55	0.75	0.92
Right rotation (NHP)	0.83	0.93	0.73	0.78
Left rotation (NHP)	0.57	0.65	0.89	0.92
Flexion (THP)	0.26	0.68	0.45	0.54
Extension (THP)	0.4	0.57	0.96	0.64
Right rotation (THP)	0.34	0.55	0.6	0.83
Left rotation (THP)	0.69	0.47	0.38	0.54

NHP=Neutral head position. THP=Target head position.

3.7 Discussion

This study investigated the measurement properties (reliability and criterion validity) of the cervical JPE test when performed in sitting and standing in people with and without CNP. Both absolute and constant errors were included in the analysis. The results show that the JPE is reliable, but not for all movements. In addition, the JPE measurements assessed with a laser pointer correlated well with the measurements taken by the IMUs but again, not for all movements. JPE was significantly higher in people with CNP when compared to asymptomatic participants when tested in both sitting and standing, but mainly for the measurement of the absolute error. In most tasks there was no significant difference between the JPE measured in sitting and standing, apart from the constant JPE measured following left rotation.

3.7.1 Differences in JPE between people with and without chronic neck pain

In the current study when tested in sitting, the absolute JPE for the asymptomatic participants 2.09°-2.46° and 3.53°-4.8° for the CNP group; significant between group differences were observed for flexion, extension, and left rotation. In standing, the absolute JPE for the asymptomatic participants was 1.96°-2.34° and 3.06°-4.93° for CNP group; significant between group differences were observed for flexion, extension, and right rotation. Errors ranging from ≥3°-4° have been suggested as a threshold for indicating proprioceptive deficits on the cervical position sense test (79). Pooled results from a previous systematic review by de Zoete et al. (74) found that people with idiopathic neck pain repositioned their head with an error 2.2°-9.8°, while asymptomatic participants repositioned the head with an error 1.66°-5.1°. Thus the results of the current study are in line with previous studies that have reported some differences in JPE when comparing asymptomatic people to those with non-traumatic neck pain (24,62,118,119).

Some studies have noted differences depending on the movement direction tested. For instance, Kristjansson et al. (119) reported significant group differences in JPE following active rotation, Revel et al. (24) reported significant between group differences for flexion, extension, right and left rotation, Cheng et al. (62) reported significant between group differences for flexion and extension, and Rix and Bagust (118) reported significant between group differences for flexion only. In the current study, significant between group differences were observed for the absolute error when tested in sitting for flexion, extension, and left rotation with right rotation almost reaching statistical significance. Whilst all of these studies evaluated JPE in sitting, it should be noted that several differences exist between studies including the number of trials, the equipment used to assess JPE, the type of neck pain complaint (e.g., WAD, non-specific neck pain) and the level of patient reported pain and disability.

No previous studies have compared JPE between people with and without CNP when tested in standing. In the current study, we observed a significant between group difference in the absolute

JPE for flexion, extension, and right rotation when tested in standing, while JPE following left rotation was not significant between groups. No differences were observed between groups for the constant JPE. thus overall, between group differences were largely the same regardless of whether testing performed in sitting or standing.

When comparing withing group differences between sitting and standing positions, we showed no significant difference in JPE between the testing positions for either group apart from left rotation in those with CNP participants which showed a significant difference for the constant error in standing. Kim and Shin (120) investigated differences of JPE in sitting versus standing when returning from flexion, extension, and lateral flexion but only in asymptomatic people. They reported a significant difference in JPE between sitting and standing but only after returning from extension only. The authors argued that during sitting, the neck extensors are more active than in standing and concluded that this may have led to a significant difference between testing positions. Overall, however, it seems that major differences in JPE do not exist when testing is conducted in sitting versus standing.

3.7.2 Reliability of JPE when assessed in sitting

The Bland Altman LoA plots showed that most points lied between the 95% CI indicating that there was no systematic bias. This was anticipated as the rater took extensive training on the tools used.

In the asymptomatic participants, when performing the NHP task, the absolute error after returning from flexion showed poor reliability (ICC: 0.4) while extension, right and left rotation showed moderate reliability (ICC range: 0.56-0.66). Goncalves and Silva (95) performed the NHP task but only returning from right and left rotation showing good reliability (ICC range: 0.75-0.8), which is superior to our results. Pinsault et al. (49) also tested the reliability of the NHP and showed moderate to good reliability (ICC range: 0.52-0.81) for the absolute error. Our results are similar to those reported by Roren et al. (38) where they showed moderate reliability (ICC: 0.68) for right and left rotation. However, they assessed within-day intra-rater reliability while we examined between-day intra-rater reliability. For THP, only one previous study was identified which is the one by Goncalves and Silva (95) which tested the reliability of the THP after returning from right and left rotation only showing moderate to good reliability (ICC range: 0.55-0.76) while in the current study, the reliability was poor to good (ICC range: -0.27-0.79).

In the current study we also examined the reliability of the constant error for the NHP and THP tasks. Only one earlier study which tested the reliability of constant JPE after returning from flexion, extension, and right and left rotation was identified (93). In this study, asymptomatic participants performed the tasks at fast and slow speeds and at 90cm and 180cm distances from the target. When comparing their results obtained with the target at 90cm distance and for movement performed at a slow speed (i.e., comparable to the task performed in our study), JPE following rotation, flexion, and extension showed poor reliability (ICC range: 0.22-0.47). Our results were higher than this at least for extension (ICC: 0.52), and right and left rotation (ICC range: 0.71-0.76). Several differences between the studies exist including sample size (n=5 versus n=15 in the current study) and the position of the laser pointer. When considering the results for people with CNP, good reliability (ICC: 0.8) was observed for flexion, whereas extension showed poor reliability (ICC: 0.43) and right and left rotation showed moderate reliability (ICC range: 0.51-0.57). Goncalves and Silva (95) also examined people with CNP but examined right and left rotation only showing moderate to good (ICC range: 0.61-0.8) reliability.

Interestingly, the reliability of JPE was better when testing our participants with CNP than for the asymptomatic group. This could potentially be explained by fatigue due to more extensive testing of the asymptomatic participants especially since previous studies have confirmed the detrimental effect of fatigue on neck proprioception in the cervical spine (121,122). Boredom during data collection may have also impacted on the results (93). Overall, the wide range of reliability results, which spanned from poor to good, needs to be considered when interpreting changes in JPE e.g., after an intervention.

3.7.3 Reliability of JPE when assessed in standing

To the best of our knowledge, this is the first study to test the measurement properties of the JPE test using a laser pointer when tested in standing. In asymptomatic participants, the reliability of the measure was moderate (ICC range: 0.5-0.74) and poor to good (ICC range: 0.21-0.77) for the absolute and constant errors respectively for the NHP test. For the THP, the reliability was poor to good (ICC range: 0.21-0.77) and poor to moderate (ICC range: 0.23-0.6) for the absolute and constant error respectively. For those with CNP participants, the reliability was poor to good (ICC range: 0.19-0.88) and moderate to excellent (ICC range:0.52-0.93) for the absolute and constant error respectively for the NHP test. Similar results have been reported by Strimpakos et al. (48) albeit using a motion analysis device and not a laser pointer. Time-interval and the number of testing trials are methodological flaws that existed in the study by Strimpakos et al. (48). Time-interval in their reliability investigation was one week, which is not recommended by COSMIN guidelines (58), which may also indicate that there was a learning effect by the participants. Number of testing trials in their investigation was three per flexion, bilateral rotation, and bilateral bending, however, at least 6 trials are recommended when testing proprioception (123). When comparing the results of the reliability investigation in sitting vs standing in CNP participants (Table 8 and 9), the results in standing were superior to sitting. The participants sat in a comfortable position of their choosing instead of strictly upright sitting, which may have caused an increase in the activity of the neck muscles during sitting position (120), thus affecting the results.

3.7.4 Standard error of measurement

The closer the measurement error is to zero the more reliable the measure is. In the asymptomatic people, in sitting, the measurement error of the absolute NHP showed less error than the absolute THP. Similarly, in standing, the absolute JPE showed less measurement error when compared to absolute THP. In people with CNP, the measurement error was relatively high when compared to asymptomatic participants. This was expected as people with CNP exhibit proprioceptive deficits. In sitting, the absolute JPE showed an error of 0.59°-2.34°. This was low if compared to absolute JPE in standing (0.98°-2.64°).

Alahmari et al. (34) showed a measurement error of 1.78°-1.88° and 1.45°-2.45° for NHP and THP tasks respectively, which is lower than the measurement error in the current study. This can be explained by the movements tested and the population recruited for the study. Extension NHP was assessed in sitting only, whereas THP was assessed after returning from 50% of flexion, extension, bilateral lateral flexion, and bilateral rotation were evaluated in sitting and supine. In the current study we evaluated flexion, extension, and bilateral rotation in sitting and standing and we reported absolute and constant errors also. In their study, the time interval between testing sessions was ≤ 3 working days while in the current study it was 1 week. During this time, pain symptoms could have changed which could affect the results. Lower measurement errors were also reported by Goncalves and Silva (95) for NHP and THP tasks, however, their assessment was limited to the assessment of right and left rotation only.

3.7.5 Criterion validity

The goal here was to assess the criterion validity of the measure of cervical JPE by determining how closely the new tool's (laser pointer) results align with the criterion (IMUs), and Pearson's correlation provides a clear, interpretable measure of this association. It captures both the magnitude and direction of the relationship, helping to quantify how well the new tool mirrors the criterion. One would argue that this is concurrent validity not criterion validity. Concurrent validity investigation is to correlate a new test with a criterion test, while criterion validity is investigating the same test (JPE test) but correlating the results from two different tools (new tools vs gold standard), which was carried out in this study.

There was a wide range of correlation seen between the measures of JPE with the laser pointer versus the IMUs with correlations ranging from only weak to very strong correlation. The limits of agreement plots revealed that most points were between the 95% CI indicating no systematic bias.

The results obtained when validity was assessed in the sitting position are comparable with previous studies. Roren et al. (38) compared the laser pointer with an ultrasound technique testing only right and left rotation. Their results showed very strong levels of validity (r=0.95), but only for the absolute error. Chen and Treleavan (39) correlated the laser pointer measure to the 3-Space Fastrak when testing right and left rotation. Their results showed strong levels of validity (r=0.87) and only for the absolute error. Wibault et al. (35) compared a laser pointer to a CROM device when testing right and left rotation in people with cervical radiculopathy. Their results revealed moderate to very strong validity (ICC: 0.43-0.91). However, importantly these previous studies only investigated the absolute JPE to a NHP following right and left rotation. In contrast, the current study has considered JPE following flexion, extension, right and left rotation for both NHP and THP tests and considered both absolute and constant error, and as a result has revealed more variability in the degree of validity. This variability of correlations is suggested to be from the differences in standard deviation between the two testing devices. The higher the standard deviation, the higher the variability in the results. Another factor that could explain this variability is the human error as the error obtained from the laser is measured by hand, which is subject to error, and it is being compared to a gold standard. Sample size, time taken for data collection, and fatigue are all possible reasons for these differences in correlations.

3.7.6 Methodological considerations

This research was carried out following COSMIN guidelines (87), which is considered a strength of this study. The average of 6 trials was used to assess cervical proprioception as recommended previously (123). However, the large number of trials and tests could have led to fatigue and may have affected the results. The testing in this study was carried out by one tester only which is a further limitation of this study. Recruitment challenges were a further limitation of the study. This study was carried out immediately after Covid-19 lockdowns which made it difficult to recruit participants due to strict health and risk assessment along with social distancing and possibility of dropping from the study. These limitations might affect the studies generalisability to other age populations. Also, the pain and disability levels were around normal in the CNP. Moreover, repositioning errors in in the CNP group were also around normal (3˚-4˚) which is considered a limitation as this implies little proprioceptive deficits in those recruited. This must be addressed in the future by screening the participants and include people with higher pain, disability, and repositioning error.

The between-day test retest was chosen over the within-day test retest because of the relevance of repeat testing over several days when assessing patients with neck pain and due to lack of guidelines on time-intervals in reliability sessions. COSMIN recommends that time-interval should be long enough to prevent recall bias, and short enough to ensure that the patients have not been changed on the construct to be measured. Therefore, between-day test retest is more suitable design. Between-day reliability testing offers several advantages over within-day testing, particularly in assessing long-term stability. It evaluates the consistency of measurements across different days, reflecting real-world conditions where repeated measurements often occur over time. This method reduces the influence of learning or fatigue effects that may arise in within-day testing, providing a more accurate assessment of reliability. Additionally, between-day testing captures natural daily variability, offering a more comprehensive evaluation and improving the generalisability of the results to real-life scenarios where conditions fluctuate across days. The main drawback of between-day reliability testing is that it introduces greater potential for external factors, such as changes in environment, participant mood, or health, affecting the results and making it harder to control the confounding variables. It also requires more time and resources, as participants need to return for testing on different days, which can pose logistical challenges and increase the risk of participant dropout. Additionally, between-day testing may not be as effective at capturing short-term consistency, which is important for measurements that are expected to remain stable over brief intervals.

3.8 Conclusion

This study indicates that the JPE test could be used to differentiate between people with and without CNP. When performed using a laser pointer, the JPE test showed to be reliable and valid but not all movements. The responsiveness domain remains to be investigated, which will be carried out in the next chapter.

Chapter 4: Responsiveness of the cervical joint position error test to detect changes in neck proprioception following four weeks of home-based proprioceptive training

This chapter reports content of a published manuscript by the thesis author (AlDahas et al. 2024). It includes verbatim text from published manuscript with changes employed for the purpose of this thesis.

AlDahas A, Devecchi V, Deane JA, Falla D. Responsiveness of the cervical joint position error test to detect changes in neck proprioception following four weeks of home-based proprioceptive training. PlosOne. 2024 April.

4.1 Abstract

Introduction: Assessing proprioception using a head mounted laser to assess JPE is a reliable and valid measure. However, the responsiveness of this measure has not been assessed.

Objective: To assess the responsiveness of the measure of cervical JPE after a 4-week home-based neck proprioceptive training intervention in people with CNP.

Design: An observational study to assess the responsiveness of the measure of cervical JPE.

Methods: The JPE test was assessed in people with CNP before and after 4 weeks of neck proprioception training. JPE was assessed as participants performed neck joint position sense tests for flexion, extension, right rotation, and left rotation in sitting and standing which were performed in a random order. Both the absolute and constant JPE were assessed. The intervention consisted of neck repositioning exercises as well as movement sense exercises. Cohen's d effect size was used to assess the internal responsiveness of the JPE test. The Pearson's correlation was used to assess the change of scores of the laser pointer and measures from the IMUs (external responsiveness).

Results: After 4 weeks of proprioception training, JPE assessed in sitting reduced from 2.69°-3.57° to 1.88°-1.98° for flexion, extension, and right rotation with large effect sizes (Cohen's d range: 1.25-2.00). For left rotation, JPE reduced from 3.23° to 1.9°, and the effect size was close to being large (Cohen's d: 0.79). When assessed in standing, JPE reduced from 3.49°-4.52° to 1.5°-2.33° with large effect sizes (Cohen's d range: 0.89-1.25) for flexion, extension, right rotation, and left rotation. Large effect sizes were not observed for the constant JPE when assessed in either sitting or standing. The assessment of the external responsiveness revealed weak correlations between the change of scores obtained from the laser pointer and the IMUs for all movements, apart from the constant JPE in sitting for left rotation, which showed a strong correlation (r=0.7).

Conclusion: The results of this study showed that the measure of the JPE has sufficient internal responsiveness, however, the external responsiveness was inadequate. Further research is advised.

Key words: Joint position sense, neck pain, proprioception, rehabilitation.

4.2 Introduction

Cervicocephalic kinaesthesia is the ability to perceive both movement and the location of the head in space and in relation to the trunk and is therefore vital for normal function (26,33,124).. Cervical kinesthesia is vitally dependent on sensory input from the, neck muscles (especially in the sub-occipital muscles), ligaments, and joints (124). In a clinical environment, cervical kinesthesia can be assessed by evaluating head repositioning accuracy (HRA) measuring JPE. JPE can be used to measure the ability of the individual to reposition their head back to its NHP or to a THP (34). Revel et al. (24) was the first to describe the assessment of neck proprioception (i.e., cervicocephalic kinesthesia) using a laser pointer mounted on the head and revealed differences in proprioceptive acuity between people with and without CNP after returning from neck flexion, extension, and right and left rotation. Further work followed and there is now clear evidence from a systematic review of the literature that neck proprioception can be impaired in people with CNP, specifically WAD (78), especially those with the symptom of dizziness (78).

RCTs have shown that neck proprioception training is beneficial for people with CNP and can reduce proprioceptive deficits. For example, Revel et al. (82) combined oculomotor training with proprioception training (head repositioning tasks) over a period of ten weeks and demonstrated that neck repositioning accuracy and ROM improved significantly when compared to a control group. Jull et al. (15) compared the effect of six weeks of proprioception exercises versus craniocervical flexion exercise and showed that both programs led to improvements in repositioning sense. However, participants allocated to the proprioception training group showed greater improvements compared to the craniocervical flexion training group when HRA was assessed for right rotation. Moreover, in a double-blinded RCT by Saadat et al. (125), it was found that proprioception training combined with traditional physical therapy interventions was more effective than traditional physical therapy treatment alone in improving cervical JPE.

For an outcome measure to be used in clinical settings, it must be affordable, safe, simple to administer, and able to be used within an operational time frame (126). Moreover, outcome measures need to be reliable, valid, and responsive to detect a change (126). The use of a laser pointer mounted on the participant's head to assess cervical proprioception is reliable and valid as demonstrated in *Chapter 3* (127). Responsiveness of the measure, which is the ability of an outcome measure to detect a change over time (55), has not been examined before. In order to assess the effectiveness of a particular intervention, establishing the responsiveness of clinical tests used to evaluate outcomes is crucial (126). Therefore, the aim of this study was to assess the internal and external (relative to measures obtained from IMUs) responsiveness of the cervical JPE test measured in people with CNP using a laser pointer and a wall target. We hypothesised that the measure of cervical JPE would demonstrate sufficient levels of responsiveness which would support its use in the clinical assessment of neck proprioception.

4.3 Methods

4.3.1 Study design

This is a responsiveness study of the measure of cervical JPE following a period of 4-weeks of neck proprioception training for people with CNP. COSMIN guidelines of study designing checklist (104) was used to report this study. Before and after the intervention, testing was carried out by a single rater (AA) who was aware of the COSMIN guidelines for reporting studies of measurement properties and has received extensive training on data collection and analysis of cervical JPE. The study was carried out in a motion analysis laboratory at the CPR Spine, University of Birmingham, United Kingdom from September to

December 2022. The study received full ethical approval from the ethics committee at the University of Birmingham (ERN_22-0269). All participants provided written informed consent.

4.3.2 Participants

Participants were recruited from the staff and student population at the University of Birmingham. Participants were initially screened via email through a health screening questionnaire to insure their eligibility for the study. G*Power (version 3.1.9.4) was used to determine the required sample size for this study. The sample size was determined based on a 0.05 significance level, a moderate to high effect size, and a power of 80%. Therefore, a sample size of seventeen participants was required.

4.3.3 Inclusion and exclusion criteria

Participants had to be aged 18-55 years to limit potential degenerative changes of the spine with older age (105) and presenting with neck pain for at least 3 months (39) with at least mild pain (≥4 out of 10) on the NRS (106) or at least 5 out of 50 on the NDI (39). The NRS is a reliable and valid self-administered questionnaire to measure pain intensity (107). The NDI is a reliable and valid method to measure perceived disability in people with CNP (108). The exclusion criteria included history of neck trauma, neck surgery, vestibular disorders, and Covid-19 related symptoms in the last 14 days.

4.3.4 Testing procedure

At the beginning of the first session, participants were asked to complete the DHI and the TSK questionnaires. The DHI is a questionnaire that is sub-grouped into three domains (functional, emotional, and physical) that assesses dizziness over 25 items (109). The DHI scores range from 0 to 100 (110); DHI scores can be further subdivided according to the sub-groups of the questionnaire into 28 points for physical, 36 points for functional, and 36 points for emotional (111). The TSK contains 17 items that assess the person's fear of movement and movement-related behaviour (112); scores range from 17-68, where higher scores mean higher degrees of Kinesiophobia (112). Pre and post training participants carried out the NHP task in sitting and standing with 15-minute rest intervals. Testing in sitting took place before standing and the order of tested movements was randomised using the following website (https://www.random.org/lists/). Active neck movements tested included flexion, extension, right rotation, and left rotation.

A laser pointer specifically designed for clinical testing of proprioception (https://www.concussionlab.com) was fixed on the participant's forehead. The participant sat/stood in a comfortable position in front of an A2-sized paper, positioned 90cm in front of them at eye level (Figure 1.2). A test of repositioning to a NHP was then carried out. Participants were asked to stay in a neutral position for few seconds then the rater marked this position on the wall target as the starting position (i.e., NHP). The participant moved their head away from the start position to full range and then attempted to reposition the head back to the starting point as accurately as possible. The speed of their movements was not controlled, and they were simply asked to move at a comfortable pace.

Participants performed one familiarisation trial with their eyes open and subsequently, they were asked to close their eyes, perform each active neck movement and to repeat each movement six times, since six trials have been recommended to assess spinal proprioception (26,114). Participants were instructed to keep their eyes closed across the full six repetitions. A one-minute rest was given between each movement direction. JPE was evaluated in the primary plane of movement only. The difference between the starting position (zero) and the returning point in the plane of movement was measured in centimetres (37–39) and then converted to degrees using this formula angle=$\tan^{-1}$ [error distance/90 cm] (38). The average of the six trials was calculated and taken forward for data analysis. Both AE and CE were determined. AE is the mean of total deviation from the target ignoring the positive and negative values (99) whereas CE is the mean of total deviation from the target considering positive and negative values (99).

After that, participants rested for 15 minutes before repeating the same procedure but with measurements taken from IMUs (Noraxon Research PRO IMU, Noraxon, USA) with a sampling rate of 100 Hz. (113). One IMU sensor was fitted on the forehead via double-sided tape and one sensor was fitted over the neck at the level of the seventh cervical spinous process. Prior to data collection, the IMUs were calibrated, and the starting position was set at 0°. The IMUs by Noraxon are reliable and valid for measuring body kinematics (113). To analyse the IMU data, the two waveforms of neck flexion/extension and right rotation/left rotation were exported from myoRESEARCH software (Noraxon, USA) to MATLAB where they were analysed with customised script. The waveform referring to the primary plane of movement was considered. The starting position was visually identified from the angle and velocity waveforms, and it was recognised by the steady position just before starting the movement. The return position was considered as the one at the end of the recording. The JPE was then computed as the difference between the start and return position in degrees. Both absolute and constant JPE were computed.

4.3.5 Proprioception training

After the first testing session, participants were instructed on how to conduct four exercises, and they were given a laser pointer for home use. Participants were instructed to perform the exercises for a period of four weeks and each exercise was to be carried out twice a day, three times a week. The specific duration of training was chosen as four weeks as this duration of proprioception training has been shown to be effective in previous research (124). Each exercise was carried out in both sitting and standing. This home-based training was monitored by contacting the participants once a week via email. Also, they were instructed to contact the investigator whenever they want and if they felt any adverse effects such as increased pain, headache, or dizziness. However, there were no compliance checks and general monitoring the exercise was only through emails. This was to ensure that their training was running smoothly without adverse effects or symptoms. After four weeks of training, the participants were asked to attend a follow-up measurement session the following day or as early as possible (not greater than five days). The same testing procedure was carried out as in the first session.

The training intervention consisted of head repositioning exercises (82) as well as movement sense exercises (128,129). For the head repositioning exercises, the participants performed the NHP task for the first two weeks then progressed to THP tasks afterwards. The movement sense exercises consisted of three exercises: tracing lines of ZZ bands, different shaped circles, and different arrow patterns. For the different circle sizes exercise, participants progressed in training from tracing bigger circles to smaller ones. A detailed description of the exercises can be found in supplementary file 1.

4.4 Statistical analysis

Data analysis was carried out using SPSS (version 29.0.1, IBM). As recommended by COSMIN (90), the effect size (Cohen's d) of pre-post differences was used to measure the internal responsiveness of the measure of JPE using the formula Cohen's d= (M1-

M2)/SDpooled, where M1 is the mean of baseline measurements, M2 is the mean of follow-up measurements, and SDpooled is the standard deviation of the two measurements (54,56). For interpretation, d=0.2 is considered a small effect, d=0.5 is a medium effect, and 0.8 is a large effect (54,56). A further sub-analysis was carried out only for participants that had an absolute JPE of $\geq 3^{\circ}$ since an error of $\geq 3^{\circ}$ to 4° can indicate a proprioceptive deficit (79). The Pearson's product-moment correlation coefficient (r) was used to analyse the external responsiveness (correlation of change in scores of the laser pointer and the IMUs) of the measure of JPE for each movement. The following criteria was used for interpretation; 0.1-0.39=weak, 0.4-0.69=moderate, 0.7-0.89=strong, 0.9-1=very strong (53). The Shapiro-Wilk test was used to assess the normality of the distribution of the questionnaires. Since the data were not normally distributed, the Wilcoxon Signed Rank Test was carried out to investigate changes in pain intensity (NRS), disability (NDI), fear of movement (TSK), and dizziness (DHI), and repositioning error before and after the intervention. The level of significance (P-value) was set at 0.05.

4.5 Results

Nineteen participants (8 males, 11 females) with CNP took part in this study with an age (mean and standard deviation (SD)) of 27.73 (6.20) years, height of 172.21 (9.40) cm, and weight of 73.72 (15.76) kg. After 4 weeks of proprioception training, significant reductions in NDI, NRS, and TSK scores were observed. There was no significant change on the DHI (Table 4.1). The minimal clinically important change for the NDI is a decrease of 10.5 points and for the NRS is a decrease of 4.3 points (130). In the current study, the NDI post intervention decreased by 10.86 points, which is clinically significant. The change in pain intensity based on the NRS however, did not reach a minimal clinically important change. Regarding the TSK, a decrease of 4 points is considered clinically significant (131) and this was not obtained post intervention.

Table 4. 1. Mean, standard deviation, and range of the scores for patient reported outcome measures assessed at baseline and after the four-week training intervention.

Questionnaire (score range)	Baseline (Mean, (SD), Range)	Follow-up (Mean, (SD), Range)	P-value
NDI (0-100)	28.75 (8.75), 18-50	17.89 (8.01), 4-32	0.001*
NRS (0-10)	4.7 (1.7), 2-7	3.39 (1.99), 0.5-7	0.01*
TSK (17-68)	36.6 (5.51), 30-48	34.73 (6.85), 24-49	0.02*
DHI (0-100)	20.73 (9.38), 6-38	19.26 (9.75), 0-36	0.45

NDI=Neck Disability Index. NRS=Numerical Rating Scale. TSK=Tampa Scale of Kinesiophobia. DHI=Dizziness Handicap Inventory. *=statistically significant (P-value ≤0.05).

When assessed in sitting, after 4 weeks of proprioception training, the absolute JPE significantly reduced in all of the movements tested, apart from right rotation which was not significant (P=0.07) (Table 4.2). Similar changes were also seen for all movements when the absolute JPE was assessed in standing (Table 4.3). In contrast, the constant JPE did not change regardless of whether it was assessed either in sitting or standing (Tables 4.2 and 4.3).

When using the laser pointer, the Cohen's d effect size for the measure of absolute JPE assessed in sitting showed that there was a large effect following four weeks of proprioceptive training and this was evident for relocation from neck flexion, extension, right rotation, with the measure from left rotation approximating large effect size (Cohen's d= 0.79) (Table 4.2). Large effect sizes were also found for absolute JPE when assessed in standing following active neck flexion, extension, right rotation, and left rotation (Table 4.3). In contrast, large effect sizes were not observed for the constant JPE when assessed in either sitting or standing (Tables 4.2 and 4.3). A sub-analysis established that for participants with an absolute JPE of ≥3°. Following the proprioception training intervention, the absolute JPE, assessed in sitting, showed a significant reduction when assessed in flexion, extension, and left rotation, while right rotation was not significant (P=0.27) (Table 4.4). When assessed in standing, a significant reduction in absolute JPE was seen for all movement directions (Table 4.4). Large effect sizes (Cohen's d) were observed for the absolute JPE in all movement directions both in sitting and standing (Table 4.4).

Table 4. 2. Mean and standard deviation of the absolute and constant JPE measured in sitting at baseline and at the follow-up session using a laser pointer. Cohen's d effect sizes demonstrate the internal responsiveness of the measures.

Error type	**Absolute error**		**P-value**	**Effect size (Cohen's d)**	**Constant error**		**P-Value**	**Effect size (Cohen's d)**
JPE	**Baseline Mean° (SD°)**	**Follow-up Mean° (SD°)**			**Baseline Mean° (SD°)**	**Follow-up Mean° (SD°)**		
Flexion	3.57 (1.59)	1.98 (0.93)	0.003*	1.25	-0.33 (3.58)	-0.84 (1.7)	0.46	0.19
Extension	5.17 (2.54)	1.88 (0.75)	<0.001*	2.008	0.76 (5.31)	-0.04 (1.7)	0.35	0.23
Right rotation	2.69 (1.91)	1.91 (1.69)	0.07	2.75	-0.54 (3.23)	0.06 (2.31)	0.74	-0.22

Left rotation	3.23 (2.06)	1.9 (1.27)	0.01*	0.79	-0.3 (4.07)	-0.28 (2.04)	0.87	-0.005

JPE=joint position error. *=statistically significant (P-value ≤0.05).

Table 4. 3. Mean and standard deviation of the absolute and constant JPE measured in standing at baseline and at follow-up session using a laser pointer. Cohen's d effect sizes demonstrate the internal responsiveness of the measures.

Error type	**Absolute error**		**P-value**	**Effect size (Cohen's d)**	**Constant error**		**P-value**	**Effect size (Cohen's d)**
JPE	**Baseline Mean° (SD°)**	**Follow-up Mean° (SD°)**			**Baseline Mean° (SD°)**	**Follow-up Mean° (SD°)**		
Flexion	4.52 (2.8)	2.1 (1.00)	0.002*	1.27	0.29 (5.13)	-1.18 (1.78)	0.17	0.43
Extension	3.96 (1.85)	2.33 (1.77)	0.009*	0.89	-0.67 (3.74)	0.63 (2.67)	0.13	-0.4
Right rotation	3.53 (1.7)	1.67 (1.31)	<0.001*	1.23	-0.35 (3.79)	0.42 (1.92)	0.39	-0.27
Left rotation	3.49 (2.49)	1.5 (0.67)	<0.001*	1.25	-1.05 (3.84)	-0.53 (1.12)	0.71	-0.2

JPE=joint position error. *=statistically significant (P-value ≤0.05).

Table 4. 4. Mean and standard deviation of the absolute JPE measured in sitting and standing at baseline and at follow-up session for a subgroup of participants with ≥3◦ of absolute JPE using a laser pointer. Cohen's d effect sizes demonstrate the internal responsiveness of the measures.

Position	**Sitting**		**P-value**	**Effect size (Cohen's d)**	**Position**	**Standing**		**P-value**	**Effect size (Cohen's d)**
JPE	**Baseline Mean° (SD°)**	**Follow-up Mean° (SD°)**			**JPE**	**Baseline Mean° (SD°)**	**Follow-up Mean° (SD°)**		
Flexion (n=12)	4.36 (1.48)	1.68 (0.45)	0.002*	2.75	**Flexion (n=10)**	6.61 (2.35)	2.33 (1.22)	0.007*	2.39
Extension (n=15)	5.94 (2.66)	1.64 (0.62)	<0.001*	2.6	**Extension (n=12)**	4.85 (1.79)	2.61 (2.07)	0.02*	1.15

Right rotation (n=4)	5.95 (1.62)	3.36 (3.07)	0.27	1.1	**Right rotation (n=12)**	4.44 (1.45)	1.8 (1.53)	0.002*	1.76
Left rotation (n=9)	4.62 (2.19)	1.71 (0.73)	0.008*	1.98	**Left rotation (n=7)**	6.29 (2.01)	1.57 (0.69)	0.01*	3.48

JPE=joint position error. n=number of participants. *=statistically significant (P-value ≤0.05).

Table 4. 5. Correlation of changed scores between the laser pointer and the IMUs measured in sitting and standing for the absolute and constant JPE to evaluate the external responsiveness of the measure.

	Absolute error		**Constant error**	
	Sitting (r)	**Standing (r)**	**Sitting (r)**	**Standing (r)**
Flexion	-0.07	0.08	-0.20	-0.20
Extension	0.19	0.20	0.11	0.59
Right rotation	0.008	0.42	0.05	0.27
Left rotation	0.35	0.43	0.70	0.44

r=Person's product-moment correlation coefficient

The external responsiveness of the absolute JPE, when assessed in sitting, showed weak correlations (r range: -0.07-0.35) with measures obtained from the IMUs, while when assessed in standing, there were weak to moderate correlations (r range: 0.08-0.43). For the constant JPE, there were weak to strong correlations (r range -0.2-0.7) for the measures assessed in sitting and weak to moderate correlations (r range -0.2-0.59) when assessed in standing (Table 4.5).

4.6 Discussion

Responsiveness is a fundamental characteristic of any outcome measure in research, mainly when the objective is to detect changes over time (54). The ability to gauge changes in clinical status is particularly relevant in interventional studies, where researchers seek to evaluate the effectiveness of interventions. In this context, the present study utilised Cohen's d effect size to assess the internal responsiveness of the measure of JPE, following recommendations by the COSMIN framework. Specifically, the study investigated the responsiveness of the JPE measure following a 4-week home-based proprioception training intervention for individuals with CNP. The study also assessed the correlation of change of scores obtained from the laser pointer and IMUs in order to assess the external responsiveness of this clinical measure. Internal responsiveness is defined as the ability of an outcome measure to detect clinically meaningful changes over a period of time, ensuring in accurate evaluation of treatment effectiveness (132). External responsiveness on the other hand, evaluates the ability of an outcome measure to detect a change relative to an external criterion (i.e., gold standard) (132). Evaluating responsiveness ensures that outcome measures capture meaningful changes. It aids in determining whether the measure appropriately captures improvements or deteriorations in health status, supporting patient-centred treatment and collaborative decision-making.

Overall, the change scores in JPE collectively suggest the clinical significance of the improvements observed in individuals with CNP. This is evident as the mean absolute JPE values after the 4-week proprioceptive training, were within the range of ≤3-4° and a range exceeding this typically signifies a deficit in neck proprioception (79). Revel et al. (82) previously conducted a study to evaluate the beneficial effects of proprioception training for individuals with CNP. Their study reported a notable improvement of 2° in mean repositioning error after ten weeks of training. Our findings closely align with the mean repositioning error improvements of 1.75° when assessed in sitting and 1.97° when assessed in standing for absolute JPE.

Proprioception exercises require fine control of neck movements. The CNP participants in the current group carried out extensive training of neck relocation exercises as well as movement sense exercises consisting of fine neck movements as they performed tracing circles, ZZ bands and other shapes. The improvement in proprioception could be attributed to multiple mechanisms including reduced nociception, improved muscle coordination and reduced muscle inhibition although the exact mechanisms of improvement cannot be determined from the current study.

It is important to note that our intervention was shorter (4 weeks) but was administered with a higher dose of training compared to other studies. Revel et al. (82) carried out their treatment twice a week for a period of 8 weeks. Jull et al. (15) carried out their training also twice a week but for a period of 6 weeks. The current duration of treatment was in line with a previous study by

Humphreys and Irgen (124). The dosage of treatment in the current study was almost similar to their dosage of treatment. Their training dosage consisted of 14 treatment sessions per week, however their exercises consisted of proprioceptive training as well as upper limb exercises. In the current study, our training dosage per week was 12 sessions. In the current protocol, participants were instructed to do 4 exercises twice a day in sitting and twice in standing three times per week for a period of 4 weeks. We believe that shorter but extensive training period is often better because it promotes efficiency, keeping patients focused on essential skills without overwhelming them. It also reduces costs and minimises disruptions to work.

The results of the current study also explored the broader impact of this 4-week proprioception training intervention as participants showed a significant reduction in neck pain intensity, decreased disability, and decreased fear of movement following the proprioception training intervention. Revel et al. (82) and Jull et al. (15) reported similar positive trends, including reduced pain and disability levels in individuals with CNP following periods of proprioception training. The findings of the current study are also in line with a systematic review by Wilhelm et al. (133) which found that neck exercises were beneficial for reducing pain and disability regardless of exercise dosage. Similar results for people with CNP were also reported in another systematic review (134). It should be noted however that although the change in the NDI score exceeded the minimal clinically important change, change for pain intensity (NRS) and Kinesiophobia (TSK) did not, even though the changes were statistically significant. The participants enrolled in this study had mild -moderate pain intensity on average and only few had high levels of Kinesiophobia which likely explains this.

For internal responsiveness, there was a large effect size for absolute JPE when assessed in sitting, particularly following active neck flexion, extension, and right rotation. The effect size for left rotation approximated a large effect size. In standing, a similar pattern emerged, with a large effect size found for the measure of absolute JPE for all movement directions. Large effect sizes were not observed for constant JPE when assessed in sitting or standing. This was expected and highlighted in previous research as the sum of the testing trials leads to an error closer to zero due to positive (overshooting) and negative (undershooting) values (127). Besides cervical JPE, other tests can be used to evaluate the effects following a proprioception training intervention. One study assessed the effect of proprioception training on neck proprioception, using a different cervical outcome measure, the clinical cervical movement sense test (CCMST) (83). Treleaven et al. (83) assessed the responsiveness of this cervical outcome measure after four weeks of proprioception training. Their intervention consisted of tracing a line with a laser pointer as accurately as possible or moving from one point to another. Their results showed a moderate effect size (Cohen's d=0.76) after training four times per week over the four-week period. In contrast, our results for internal responsiveness of the absolute JPE show larger effect sizes when tested in both sitting and standing.

However, the current study found inadequate external responsiveness of the measure. In sitting, the absolute JPE showed weak correlation after returning from flexion, extension, right rotation and left rotation. The absolute JPE in standing showed weak correlation after returning from flexion and extension, while right rotation and left rotation showed moderate correlation. The constant JPE when performed in sitting showed weak correlation after returning from flexion, extension, and right rotation, while on the other hand, left rotation showed strong correlation. In Standing, the constant JPE showed weak correlation after returning from flexion and right rotation and moderate correlation after returning from extension and left rotation. This can be explained by the limitations in data collection as the data collection from both devices were not taken simultaneously leading to larger variabilities in the data. Also, another reason could be from the IMUs as sometimes the machine crashes and requires to be restarted, or the signal is lost from the sensors which requires to be removed from the participant head of neck and inserted back into the charger for reconnection. Removing and attaching the sensor might have led to some variabilities, thus affecting the results. It is worth noting that fatigue may have also influenced data collection, as prior research has indicated that fatigue can disrupt cervical proprioception (121,122) and extensive testing was carried out in this study.

4.7 Study limitations

Performance bias is a limitation in the current study; only one therapist carried out the baseline assessment, administered the proprioception intervention, followed up with the participants, and carried out the follow up assessment. Given that this is not a clinical trial and rather was a study on the responsiveness of a measure, this was deemed acceptable. The population of participants included in our study were primarily young adults, which may affect the study's generalisability to other age populations. The sample size was determined based on an a priori established sample size calculation and as a result, the study was sufficiently powered to address the research question. Nevertheless, future studies should aim to corroborate these findings in larger and more diverse populations. As mentioned above, data collection to assess the change of scores obtained from the laser pointer and the IMUs were not carried out simultaneously, thus might have affected the results leading to weak correlation, which may be considered as a limitation in this study.

Home-based treatment offers several advantages, including convenience, flexibility, and cost-effectiveness, as it allows patients to receive care in the comfort of their homes, eliminating the need for travel and clinic visits. This is especially beneficial for individuals with mobility issues or those who live far from healthcare facilities. It also reduces the risk of exposure to illnesses, particularly in times like the COVID-19 pandemic. However, it has some limitations, such as the lack of direct supervision, which can lead to improper execution of exercises or missed signs of deterioration. Additionally, and the absence of immediate feedback from professionals can hinder progress. Maintaining motivation and accountability can also be challenging without the structure of regular clinic visits, and inconsistent monitoring may prevent timely adjustments to the treatment plan.

4.8 Conclusion

The cervical JPE test showed good internal responsiveness after 4 weeks of home-based proprioception training intervention. However, the external responsiveness in this current study showed poor results, and therefore, we recommend to re-assess the external responsiveness of the measure of cervical JPE using the same current design, however, data collection from both devices must be taken simultaneously similar to the criterion validity investigation in *Chapter 3*.

Chapter 5: General discussion

5.1 Summary of Findings

The main goal of this thesis was to assess the measurement properties of the cervical JPE test in people with and without CNP. *Chapter 1* provided an overview on the epidemiology of CNP and physical impairments in people with CNP, with specific focus on proprioception. This included an exploration of methods used to assess cervical proprioception, an examination of measurement properties of the cervical JPE test, and a review of intervention programmes. Notably, gaps in the existing literature were identified regarding the cervical JPE test's measurement properties which provided the basis for the research conducted within this thesis.

In *Chapter 2*, a systematic review was conducted to summarise and appraise the literature regarding the measurement properties of the cervical JPE test in people with and without neck pain (135). A search was carried out in Medline, Embase, SportDiscus, and CINAHL plus databases from inception to the 14th of October 2023. Included studies were: 4 with CNP, 3 did not specify the type of neck pain, 1 with cervicogenic disc disease, and 7 included asymptomatic people. The AE and CE were included for the analysis of the JPE test. The results indicated generally low/very low levels of evidence when modified GRADE was applied apart from the convergent validity of the constant JPE, which was high. Gaps in methods for testing the measurement properties of the cervical JPE test along with risk of bias in the included studies were highlighted. Overall conclusions about the measurement properties of the cervical JPE test was difficult to draw due to lack of consensus on testing procedures and tools used.

Chapter 3 addressed the limitations highlighted in the systematic review (*Chapter 2*), which involved investigating intra-rater reliability, measurement error, and criterion validity of the cervical JPE test in people with and without CNP (127). The AE and CE for the NHP and THP tests were analysed in people with and without CNP in both sitting and standing. Asymptomatic participants performed both NHP and THP tasks, whereas CNP participants performed only the

NHP task. In sitting, asymptomatic participants showed poor to moderate reliability for the absolute NHP test and poor to good reliability for the absolute THP test. The constant NHP showed poor to good reliability and the constant THP showed poor to good reliability. When tested in standing, asymptomatic participants showed moderate reliability for the absolute NHP and poor to good reliability for the absolute THP. The constant NHP showed poor to good reliability and the constant THP showed poor to moderate reliability. In people with CNP, when tested in sitting, absolute NHP showed moderate to good reliability and poor to good reliability was found for the constant NHP. In standing, absolute NHP showed poor to good reliability and constant NHP showed moderate to excellent reliability. The criterion-validity was only tested in asymptomatic people; in sitting, the absolute NHP showed weak to strong correlations, while the absolute THP showed weak to moderate correlations. In sitting, the constant NHP showed moderate to very strong correlations and the constant THP showed moderate correlations. In standing, the absolute NHP showed strong to very strong correlations and the absolute THP showed weak to very strong correlations. In standing, the constant NHP showed strong to very strong correlations and the constant THP showed moderate to strong correlation. This study also assessed the ability of the JPE test to discriminate between people with and without CNP and found that there were significant between group differences for the absolute JPE after returning from flexion, extension, and left rotation when tested in sitting. There were also significant between group differences when tested in standing for the absolute JPE after returning from flexion, extension, and right rotation. The constant JPE showed no significance between the groups for all movements, apart from left rotation in sitting for the constant JPE, which was significant between the groups. In addition, the study also assessed the repositioning error between testing positions (sitting versus standing) and showed no significance between the testing positions for all movements, except for the left rotation of the constant JPE in people with CNP, which was significant. In summary, this test showed to be reliable and valid but not for all movements. It was also able to discriminate between people with and without CNP. The responsiveness of this test was investigated in the next study.

In *Chapter 4*, attention turned to examining the responsiveness of the JPE test following a 4-week proprioception intervention, which was also a gap highlighted in the systematic review presented in *Chapter 2*. The study assessed the ability of the cervical JPE test to detect a change over a period of time following proprioception training. Participants attended two assessments sessions, before and after 4 weeks of proprioception training, which consisted of head repositioning (NHP and THP tasks) and movement sense exercises carried out in sitting and standing. Levels of pain, disability, fear of movement, and dizziness were also assessed before and after the proprioception training intervention. Cohen's d effect size was used to assess the internal responsiveness of the JPE test whereas Pearson's correlation was used to assess the external responsiveness of the JPE test by correlating the change of score obtained from both the laser pointer and the IMUs.

The study found promising results for the internal responsiveness of the measure. In sitting, the study showed large effect sizes after returning from flexion, extension, right rotation, and left rotation for the absolute JPE. In standing, large effect sizes were also observed for flexion, extension, right rotation, and left rotation. The constant JPE did not reveal large effect for all movements in either sitting or standing. On the other hand, there were poor correlations of the change of scores between the laser pointer and the IMUs (poor external responsiveness). Levels of pain (NRS), disability (NDI), and fear of movement (TSK) decreased significantly after 4 weeks of proprioception training intervention supporting the appropriateness of the intervention.

The final chapter (*Chapter 5*) provides a comprehensive summary, drawing conclusions, delineating the strengths and weaknesses of the research, discussing clinical implications, and recommendations for future research based on the thesis findings.

5.2 Measurement properties of the cervical JPE test

A myriad of testing tools and methods have been used to assess the measurement properties of cervical JPE. For example, in asymptomatic participants, Artz et al. (45) carried out their intra-rater reliability of the THP task, only testing 25%, 50%, and 75% of flexion in sitting and standing. Again in asymptomatic people, Kristjansson et al. (46) carried out intra-rater reliability of four JPE tests (NHP, THP, Preset trunk rotation, and F8T relocation test) after returning from right and left rotation when tested in sitting. Lee et al. (47) tested the intra-rater reliability of NHP and THP tasks after returning from flexion, extension, bilateral side-bending, and bilateral rotation. Various testing procedures and tools have also been used when testing people with neck pain. Roren et al. (38) tested the intra-rater reliability of the NHP task in people with CNP using a laser pointer and US device after returning from right and left rotation only. In contrast, Alahmari et al. (34) tested JPE in a NHP task after returning from extension only and a THP task after returning from 50% flexion, extension, bilateral side-bending, and bilateral rotation. Testing was carried out in sitting and supine positions.

For the assessment of validity, various testing procedures and tools also have been used. Roren et al. (38) tested the laser pointer against a US device for the NHP task whereas Chen and Treleavan (39) tested the laser pointer against a 3-Space Fastrak. Both studies included people with CNP.

A systematic review was carried out to summarise and appraise the available literature regarding the measurement properties of the cervical JPE test in people with and without neck pain (135) (*Chapter 2*). In this review, the aim was to draw an overall conclusion on the best method to test the measurement properties in this population and identify gaps where further research is needed to establish the measurement properties of the cervical JPE test. The review included studies that have reported absolute and constant errors only. In this study, an overall conclusion regarding the measurement properties of the cervical JPE test could not be drawn as the overall quality of evidence was low/very low for all measurement properties, apart from the convergent validity of constant JPE in asymptomatic participants, which was high. The evidence was downgraded due to the risk of bias, inconsistency of results, and low sample size (imprecision). Thus, it was evident that further high-quality studies assessing the measurement properties of the JPE in people with and without neck were required.

In *Chapter 3*, the measurement properties (intra-rater reliability, measurement error, and criterion-related validity) of the cervical JPE test were investigated in people with and without CNP, and testing was carried out in sitting and standing (136). The NHP and THP tasks were investigated in asymptomatic participants, while people with CNP performed the NHP task only. The reliability results were sufficient (ICC ≥0.7) but not for all movements. The validity results were sufficient (r≥0.7) but again not for all movements. However, when examining Bland and Altman plots, all movements (for both reliability and validity) showed good results as all the points lay between the 95% confidence interval, and the means were closer to zero. In *Chapter 3*, the conclusion was that the cervical JPE test, using a laser pointer, is a reliable and valid outcome measure for clinical settings but not for all movements.

Zhang et al. (137) recruited 28 asymptomatic participants (16 women, 12 men) to investigate intra-rater reliability and validity of the cervical JPE test after returning from flexion, extension, right and left rotation, and right and left lateral bending. The devices and methods in their study were similar to those described within this thesis; JPE was measured using head mounted laser and WitMotion sensors which were placed beneath the laser pointer. Movements tested were flexion, extension, right and left rotation, and right and left side bending. However, participants were asked to perform the THP only (50% of ROM) and only the absolute JPE was calculated. Their results were superior to the results reported in *Chapter 3*. The laser pointer showed moderate reliability (ICC range: 0.51-0.71) for flexion, right side bending, and left rotation, while the results in *Chapter 3* for the THP showed poor to good reliability (ICC range: -0.27-0.79) for flexion, extension, right and left rotation. The validity in the study by Zhang et al. (137) also was superior. Their results showed moderate to good correlations (ICC: 0.614) while the current results showed weak to moderate correlations (r range: 0.26-0.69). Note that in this thesis the measurement properties of the cervical JPE test were tested in sitting as well as standing, on people with and without CNP, both the absolute and constant JPE were calculated. Their study used only 3 trials for assessing each movement while in the current work, 6 trials were used. The time-interval between sessions in their study was 7 days, while in the current study it was 14 days as recommended by COSMIN. These differences in the methods and number of trials and tasks likely explain the differences in the results.

Using a CROM device, Reddy et al. (138) investigated the intra-rater reliability of the JPE test on asymptomatic participants. They assessed the NHP task after returning from rotation and THP task after returning from 65% of flexion, extension, bilateral side bending, and bilateral rotation. The time-interval for their study was 48 hours. In their study, NHP showed good reliability (ICC: 0.83), while in the current work, rotation showed moderate reliability (ICC range: 0.5-0.74). In their study, THP test showed moderate to excellent reliability (ICC range: 0.66-0.93), while in the current work it showed poor to good reliability (ICC range: 0.21-0.77). They only calculated the absolute JPE, while in contrast, in the current work, the absolute as well as the constant JPE were calculated where the latter showed poor to moderate reliability (ICC range: 0.23-0.6).

In this thesis, the additional testing of the measurement properties of the cervical JPE test in people with and without CNP in standing was a strength of the work since testing in this position has not been assessed extensively in the literature. In this thesis, cervical JPE was investigated in standing after returning from flexion, extension, right rotation, and left rotation. Moreover, absolute and constant errors were calculated and 6 trials per movement were used in the investigation. Strimpakos et al. (48) tested the reliability of the JPE test in standing after returning from 30° flexion, and 20° rotation and side flexion. Their results showed poor to moderate reliability (ICC range: 0.15-0.68), while in this thesis (*Chapter 3*), the THP in standing was superior to the results by Strimpakos et al. (48) as it showed poor to good reliability (ICC range: 0.21-0.77). Their results were only for absolute JPE, while in this thesis both absolute and constant JPE were tested. The constant JPE in our study showed poor to good reliability (ICC range: 0.21-0.85) for the NHP task and poor to moderate reliability (ICC range: 0.23-0.6) for the THP task.

In *Chapter 4*, the ability of the cervical JPE test to detect a change after a 4-week home-based proprioception intervention (responsiveness) was carried out. The intervention consisted of repositioning tasks and movement sense tasks. Previous research has shown that repositioning tasks (15,82) and movement sense tasks (83) are useful for the rehabilitation of people with CNP. This was the first study to assess the responsiveness of the cervical JPE test. In the literature, RCTs investigating the effect of proprioception training on people with proprioceptive deficits showed positive results. Only one study that included movement sense exercises was identified; however, the measure of responsiveness was for another proprioception outcome measure (CCMST), and it showed a medium to large effect size (Cohen's d= 0.76) (83). The results for the internal responsiveness of cervical JPE (*Chapter 4*) showed a large effect size for all movements for the absolute JPE when assessed in sitting and standing. Additionally, the results confirmed a significant decrease in the NDI, NRS, and TSK following the intervention. The external responsiveness, in contrast, showed a weak correlation of the change of scores when correlating the laser pointer with the IMU measures of JPE. One explanation could be that measurements from the laser pointer and the IMUs were not carried out simultaneously during data collection, which likely affected the results. In the previous study (*Chapter 3*), sufficient correlations (r≥0.7) were found between the two devices when carried out simultaneously, but not for all movements.

In *Chapters 3 and 4*, a combination of AE and CE was used to analyse cervical JPE. Previous studies have used AE (61,139), CE (24,47), variable error (VE) (48), and root mean square error (RMSE) (47). Hill et al. (99) investigated error properties and their ability to discriminate between people with and without WAD and those with and without dizziness complaints. They analysed the repositioning accuracy using AE, CE, VE, and RMSE. Both AE and CE have been defined earlier in this thesis (*Chapter 3*). VE is defined as the square root of the mean of the differences between the raw error and the calculated CE, and RMSE is defined as the square root of the sum of the CE squared and the VE squared (99). The movements analysed in that study were extension, left rotation, and right rotation. The AE and RMSE could not detect the target's overshooting and undershooting, which led to non-significant changes after returning from extension. In contrast, AE detected changes in repositioning error when comparing AE to CE. At the same time, CE could not do so when values were scattered over and under the target, leading to a mean error closer to zero. Moreover, VE was unable to detect differences between the groups. Therefore, a combination of AE/RMSE and CE seems more suitable to analyse repositioning errors in people with sensorimotor impairments (99). Given these results, both AE and CE calculations were used to analyse repositioning errors in this thesis (*Chapter 3 and 4*).

5.3 Proprioception differences between people with and without CNP

In *Chapter 3*, significant differences in repositioning errors were demonstrated between people with and without CNP (127). These differences were mainly observed only for the AE when tested in both sitting and standing. The CE did not show significant differences between the groups apart from left rotation when tested in sitting. This was expected due to overshooting and undershooting the target, which leads to means closer to zero, which was previously highlighted by Hill et al. (99). Previously, Revel et al. (24) used CE and found significant differences between people with and without CNP after returning from flexion, extension, and bilateral rotation. Differences in sample size and the number of trials could be the reason for this variability in the results. On the other hand, the current thesis showed that the AE could differentiate between people with and without CNP after returning from flexion, extension, and left rotation in sitting and after returning from flexion, extension, and right rotation in standing. The AE was more able to detect differences between groups as it has no directional bias and is a mean of all errors around the return point, disregarding positive and negative values. A systematic review by De Vries et al. (114) included 14 studies that compared proprioception between people with and without neck pain (4 were on traumatic neck pain). The systematic review concluded that people with neck pain had higher repositioning errors than asymptomatic people. Moreover, all studies that calculated repositioning errors over at least six trials showed significantly higher errors in people with neck pain when compared to people without. This confirms the methodology in the current thesis as six trials were used to calculate repositioning error. Another systematic review and Meta-Analysis by Stanton et al. (77) found that people with CNP perform significantly worse on the NHP task when compared to asymptomatic individuals, which was also demonstrated in this thesis when measures were conducted in both sitting and standing (127). Another systematic review found greater JPE in people with neck pain than asymptomatic individuals (75). Kristjansson et al. (61) investigated proprioception differences between people with and without neck pain using five cervicocephalic relocation tests using a 3-Space Fastrak device. Only the cervical JPE test (NHP task) was able to significantly differentiate between people with and without neck pain. Moreover, only the absolute JPE was reported in their study.

To conclude, based on the findings of previous research and on the findings of the current thesis, the use of the NHP task and reporting the absolute JPE are more likely to detect proprioceptive differences between people with and without neck pain.

5.4 Quality of studies carried out in this Ph.D. thesis

The systematic review (*Chapter 2*) was registered with PROSPERO and reported using PRISMA guidelines (86). COSMIN RoB checklist for reliability and measurement error of outcome measurement instruments, as well as the COSMIN methodology for systematic reviews of PROMs, were used to assess the RoB of the included studies in this review (58,85). *Chapters 3 and 4* studies received full ethical approval from the Ethics Committee at the University of Birmingham, United Kingdom. They were reported using COSMIN checklist guidelines for designing measurement property studies (87).

The quality of the reliability and measurement error study (*Chapter 3*) would be rated as Adequate in the RoB checklist if the COSMIN risk of bias checklist to assess the quality of studies on reliability and measurement error of PBOMs studies was applied (85). First, participants were health screened before the start of the study to make sure they fit the inclusion criteria then they were asked to repeat the NRS, NDI, TSK, and DHI questionnaires (CNP group) before the start of the second session to make sure that participants were stable and there were no changes in their condition. Second, the time interval (a main methodological flaw highlighted in *Chapter 2*) between the testing sessions was appropriate. For the asymptomatic participant, the time interval was 14 days following the COSMIN manual; however, for CNP participants, the time interval was reduced to 7 days as the neck pain condition might worsen. An appropriate statistical test (ICC) was used, which was also recommended by COSMIN. Randomisation was applied, a power calculation was carried out, and a number of 6 trials per movement to assess JPE was performed.

Regarding the validity testing (*Chapter 3*), an appropriate statistical test (Pearson's correlation) was applied, power calculation was also applied, and correlation of the laser pointer with another device (IMUs by Noraxon) was carried out, which is what COSMIN recommends. The responsiveness study (*Chapter 4*) was also carried out following COSMIN guidelines. An appropriate statistical test (Cohen's d effect size) was used to assess internal responsiveness and an appropriate statistical test (Pearson’s correlation) was used to assess the external responsiveness, and power calculation was also carried out. Thus, effort in this thesis has been made to limit biases raised in the systematic review in *Chapter 2*.

5.5 Study limitations

The studies in *Chapters 3 and 4* spanned the period of COVID-19 lockdowns, making participant recruitment, laboratory bookings, and data collection challenging to say the least. Muscle fatigue emerged as a potential limitation, impacting the results reported in this thesis. The repetitive nature of the tests, conducted in both sitting and standing positions with each movement repeated six times, could have induced muscle fatigue, potentially affecting repositioning errors. The included participants in *Chapters 3 and 4* were younger adults, this could influence the study's generalisability to other age populations. In addition, the study's external validity might also be affected. The level of pain and disability in people with CNP in *Chapters 3 and 4* were mild, this might limit how well the results apply to other pain levels. Moreover, the results of the current study might not be applied to other neck pain populations such as WAD, cervicogenic headache or dizziness, or people with cervical radiculopathy due to cause of pain, severity of pain, and levels of physical impairments presented. Another limitation that needs to be considered here is the external responsiveness in *Chapter 4* as the data obtained from the laser pointer and the IMUs was not carried out simultaneously, thus, it might have affected the results, and this requires further investigation.

5.6 Clinical implications

The Ph.D. thesis effectively addressed its aims by focusing on the assessment of the measurement properties of the cervical JPE test in individuals with and without CNP using a laser pointer. *Chapter 3* provided evidence that the JPE test demonstrated good reliability and validity, although with variations across different movements, and it effectively distinguished between individuals with and without CNP. In *Chapter 4*, the thesis demonstrated the internal responsiveness of the test by detecting changes after a four-week proprioception training intervention. Collectively, the findings of this thesis emphasise the utility of cervical JPE as a measure for researchers and clinicians, showcasing its applicability in assessing cervical proprioception using a laser pointer, both in sitting and standing.

5.7 Recommendations for future research

Recommendations for future research would be to re-assess the measurement properties of the THP test alone using the same guidelines in *Chapter 3*, as it is believed that fatigue might have affected the test results. We also recommend assessing the inter-rater reliability of the measure of cervical JPE. In addition, we recommend to re-assess the external responsiveness of the measure of cervical JPE using a laser pointer and IMUs with collecting the data simultaneously from both devices. Also, we recommend recruiting participants with higher repositioning error as the included participants in *Chapters 3 and 4* had a repositioning error around 3˚-4˚, which resembles an error that asymptomatic participants exhibit. Therefore, for future research, we recommend screening the participants prior to include them in the study. Future research could also be carried out to investigate the difference between people with and without dizziness complaints in people with idiopathic neck pain. Also, we recommend investigating the measurement properties of the measure of cervical JPE on different neck pain populations.

5.8 Conclusion

In this Ph.D. thesis, the cervical JPE test demonstrated good measurement properties. While its reliability and validity were established, it should be noted that these characteristics were observed selectively for specific movements. Bland Altman plots, however, indicated overall reliability and validity across all movements, with most points falling within the 95% confidence interval. Moreover, the findings highlighted the test's internal responsiveness, as evidenced by its ability to detect changes over time. On the other hand, the external responsiveness was poor which requires further investigation. Considering these results, the cervical JPE test, using a laser pointer, emerges as an applicable test to be used by clinicians and researchers, whether administered in a sitting or standing.

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Appendix 1. 1 Study 1 Publication

AlDahas *et al. BMC Musculoskeletal Disorders* (2024) 25:44
https://doi.org/10.1186/s12891-023-07111-4

BMC Musculoskeletal Disorders

RESEARCH Open Access

Measurement properties of cervical joint position error in people with and without neck pain: a systematic review and narrative synthesis

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Abstract

Introduction Proprioception can be impaired in people with neck pain. The cervical joint position sense test, which measures joint position error (JPE), is the most common test used to assess neck proprioception. The aim of this systematic review was to assess the measurement properties of this test for the assessment of people with and without neck pain.

Methods This systematic review was registered prospectively on Prospero (CRD42020188715). It was designed using the COSMIN guidelines and reported in line with the PRISMA checklist. Two reviewers independently searched Medline, Embase, SportDiscus, and CINAHL Plus databases from inception to the 24th July 2022 with an update of the search conducted until 14th of October 2023. The COSMIN risk of bias checklist was used to assess the risk of bias in each study. The updated criteria for good measurement properties were used to rate individual studies and then the overall pooled results. The level of evidence was rated by two reviewers independently using a modified GRADE approach.

Results Fifteen studies were included in this review, 13 reporting absolute JPE and 2 reporting constant JPE. The measurement properties assessed were reliability, measurement error, and validity. The measurement of JPE showed sufficient reliability and validity, however, the level of evidence was low/very low for both measurement properties, apart from convergent validity of the constant JPE, which was high.

Conclusion The measure of cervical JPE showed sufficient reliability and validity but with low/very low levels of evidence. Further studies are required to investigate the reliability and validity of this test as well as the responsiveness of the measure.

Keywords Neck pain, Proprioception, Sensorimotor, Position sense, Position error, Measurement properties

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Appendix 1. 2 Study 1 Construct validity risk of bias checklist

Construct validity – Risk of bias

Score: V= very good; A = adequate; D = doubtful; I = inadequate; N= not applicable

9. Hypotheses testing for construct validity

9a. Comparison with other outcome measurement instruments (convergent validity)

1 Is it clear what the comparator instrument(s) measure(s)?

2 Were the measurement properties of the comparator instrument(s) adequate?

3 Was the statistical method appropriate for the hypotheses to be tested?

4 Were there any other important flaws?

TOTAL *Lowest score of items 1-4*

Goncalves and Silva (HRNT vs Disability)			Goncalves and Silva (HRNT vs pain catastrophising)			Goncalves and Silva (HRNT vs fear of movement)			Goncalves and Silva (TT vs Disability)		
rater 1	**rater 2**	**Consensus**	**rater 1**	**rater 2**	**Consensus**	**rater 1**	**rater 2**	**Consensus**	**rater 1**	**rater 2**	**Consensus**
V	V	V	V	V	V	V	V	V	V	V	V
V	V	V	V	V	V	V	V	V	V	V	V
V	V	V	V	V	V	V	V	V	V	V	V

A (sample size)	V	A	A (sample size)	V	A	A (sample size)	V	A	A (sample size)	V	A
A	V	A	A	V	A	A	V	A	A	V	A

Goncalves and Silva (TT vs pain catastrophising)			Goncalves and Silva (TT vs fear of movement)			Goncalves and Silva (HR30T vs Disability)			Goncalves and Silva (HR30T vs pain catastrophising)		
rater 1	**rater 2**	**Consensus**	**rater 1**	**rater 2**	**Consensus**	**rater 1**	**rater 2**	**Consensus**	**rater 1**	**rater 2**	**Consensus**
V	V	V	V	V	V	V	V	V	V	V	V
V	V	V	V	V	V	V	V	V	V	V	V
V	V	V	V	V	V	V	V	V	V	V	V
A (sample size)	V	A	A (sample size)	V	A	A (sample size)	V	A	A (sample size)	V	A
A	V	A	A	V	A	A	V	A	A	V	A

Goncalves and Silva (HR30 T vs fear of movement)			Goncalves and Silva (F8T vs Disability)			Goncalves and Silva (F8T vs pain catastrophising)			Goncalves and Silva (F8T vs fear of movement)		
rater 1	**rater 2**	**Consensus**	**rater 1**	**rater 2**	**Consensus**	**rater 1**	**rater 2**	**Consensus**	**rater 1**	**rater 2**	**Consensus**
V	V	V	V	V	V	V	V	V	V	V	V
V	V	V	V	V	V	V	V	V	V	V	V
V	V	V	V	V	V	V	V	V	V	V	V

A (sample size)	V	A	A (sample size)	V	A	A (sample size)	V	A	A (sample size)	V	A
A	V	A	A	V	A	A	V	A	A	V	A

Goncalves and Silva (HRNT vs TT)			Goncalves and Silva (HRNT vs HR30T)			Goncalves and Silva (HRNT vs F8T)			Goncalves and Silva (TT vs HRNT)		
rater 1	**rater 2**	**Consensus**	**rater 1**	**rater 2**	**Consensus**	**rater 1**	**rater 2**	**Consensus**	**rater 1**	**rater 2**	**Consensus**
V	V	V	V	V	V	V	V	V	V	V	V
V	V	V	V	V	V	V	V	V	V	V	V
V	V	V	V	V	V	V	V	V	V	V	V
A (sample size)	V	A	A (sample size)	V	A	A (sample size)	V	A	A (sample size)	V	A
A	V	A	A	V	A	A	V	A	A	V	A

Goncalves and Silva (TT vs HR30T)			Goncalves and Silva (TT vs F8T)			Goncalves and Silva (HR30T vs HRNT)			Goncalves and Silva (HR30T vs TT)		
rater 1	**rater 2**	**Consensus**	**rater 1**	**rater 2**	**Consensus**	**rater 1**	**rater 2**	**Consensus**	**rater 1**	**rater 2**	**Consensus**
V	V	V	V	V	V	V	V	V	V	V	V
V	V	V	V	V	V	V	V	V	V	V	V
V	V	V	V	V	V	V	V	V	V	V	V

A (sample size)	V	A	A (sample size)	V	A	A (sample size)	V	A	A (sample size)	V	A
A	V	A	A	V	A	A	V	A	A	V	A

Goncalves and Silva (HR30T vs F8T)			Goncalves and Silva (F8T vs HRNT)			Goncalves and Silva (F8T vs TT)			Goncalves and Silva (F8T vs HR30T)		
rater 1	**rater 2**	**Consensus**	**rater 1**	**rater 2**	**Consensus**	**rater 1**	**rater 2**	**Consensus**	**rater 1**	**rater 2**	**Consensus**
V	V	V	V	V	V	V	V	V	V	V	V
V	V	V	V	V	V	V	V	V	V	V	V
V	V	V	V	V	V	V	V	V	V	V	V
A (sample size)	V	A	A (sample size)	V	A	A (sample size)	V	A	A (sample size)	V	A
A	V	A	A	V	A	A	V	A	A	V	A

Chen and Treleavan (JPE conventional vs VAS)			Chen and Treleavan (JPE Torsion vs VAS)			Chen and Treleavan (JPE Enbloc vs VAS)			Chen and Treleavan (JPE conventional vs NDI)		
rater 1	**rater 2**	**Consensus**	**rater 1**	**rater 2**	**Consensus**	**rater 1**	**rater 2**	**Consensus**	**rater 1**	**rater 2**	**Consensus**
V	V	V	V	V	V	V	V	V	V	V	V
V	V	V	V	V	V	V	V	V	V	V	V
V	V	V	V	V	V	V	V	V	V	V	V

A (sample size)	A (sample size)	A	A (sample size)	A (sample size)	A	A (sample size)	A (sample size)	A	A (sample size)	A (sample size)	A
A	A	A	A	A	A	A	A	A	A	A	A

Chen and Treleavan (JPE Torsion vs NDI)			Chen and Treleavan (JPE Enbloc vs NDI)			Dugailly (JPE vs disability)			Dugailly (JPE vs pain intensity)			Dugailly (JPE vs pain duration)		
rater 1	**rater 2**	**Consensus**	**rater 1**	**rater 2**	**Consensus**	**rater 1**	**rater 2**	**Consensus**	**rater 1**	**rater 2**	**Consensus**	**rater 1**	**rater 2**	**Consensus**
V	V	V	V	V	V	V	V	V	V	V	V	V	V	V
V	V	V	V	V	V	V	V	V	V	V	V	V	V	V
V	V	V	V	V	V	V	V	V	V	V	V	V	V	V
A (sample size)	A (sample size)	A	A (sample size)	A (sample size)	A	A (sample size)	A (sample size)	A (sample size)	A (sample size)	A (sample size)	A (sample size)	A (sample size)	A (sample size)	A (sample size)
A	A	A	A	A	A	A	A	A	A	A	A	A	A	A

9b. Comparison between subgroups (discriminative or known-groups validity)

5 Was an adequate description provided of important characteristics of the subgroups?

6 Was the statistical method appropriate for the hypotheses to be tested?

7 Were there any other important flaws?

TOTAL *Lowest score of items 5-7*

Goncalves and Silva (HRNT)			Goncalves and Silva (TT)			Goncalves and Silva (HR30T)			Goncalves and Silva (F8T)		
rater 1	**rater 2**	**Consensus**	**rater 1**	**rater 2**	**Consensus**	**rater 1**	**rater 2**	**Consensus**	**rater 1**	**rater 2**	**Consensus**
V	V	V	V	V	V	V	V	V	V	V	V
I	I	I	I	I	I	I	I	I	I	I	I
D (sample size)	V	D	D (sample size)	V	D	D (sample size)	V	D	D (sample size)	V	D
I	I	I	I	I	I	I	I	I	I	I	I

Roren et al.			Chen and Treleavan (JPE Conventional)			Chen and Treleavan (JPE Torsion)			Chen and Treleavan (JPE Enbloc)		
rater 1	**rater 2**	**Consensus**	**rater 1**	**rater 2**	**Consensus**	**rater 1**	**rater 2**	**Consensus**	**rater 1**	**rater 2**	**Consensus**
V	V	V	V	V	V	V	V	V	V	V	V
V	V	V	I	I	I	I	I	I	I	I	I
I (No. of trials, speed of testing)	I (No. of trials, speed of testing)	I	A (sample size)	A (sample size)	A	A (sample size)	A (sample size)	A	A (sample size)	A (sample size)	A
I	I	I	I	I	I	I	I	I	I	I	I

Appendix 1. 3 Study 1 Criterion validity risk of bias checklist

Score: V= very good; A = adequate; D = doubtful; I = inadequate; N= not applicable
1- Were patients stable in the time between the repeated measurements on the construct to be measured?
2- Was the time interval between the repeated measurements appropriate?
3- Were the measurement conditions similar for the repeated measurements – except for the condition being evaluated as a source of variation?
4- Did the professional(s) administer the measurement without knowledge of scores or values of other repeated measurement(s) in the same patients?
5- Did the professional(s) assign scores or determine values without knowledge of the scores or values of other repeated measurement(s) in the same patients?
6- Were there any other important flaws in the design or statistical methods of the study?
7- For continuous scores: was an intraclass correlation coefficient (ICC) calculated?
8- Kappa calculated; the weighting scheme was described, and matches the study design and the data
9- For dichotomous/nominal scores: was Kappa calculated for each category against the other categories combined?
Total (lowest score)

Chen and Treleavan (JPE conventional)			Chen and Treleavan (JPE torsion)			Dugailly et al.			Roren et al.		
Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus
A	A	A	A	A	A	A	A	A	A	A	A
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
A	A	A	A	A	A	A	A	A	A	A	A
A	A	A	A	A	A	A	A	A	A	A	A
A	A	A	A	A	A	A	A	A	A	A	A
A (sample size)	A	A (sample size)	A (sample size)	A	A (sample size)	D (sample size)	D	D (sample size)	I (No. of trials, speed of testing)	I	I
V (correlation calculated	V	V (correlation calculated	V (correlation calculated	V	V (correlation calculated	V (correlation calculated	V	V (correlation calculated	V (correlation calculated	V	V (correlation calculated
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
A	A	A	A	A	A	D	D	D	I	I	I

Wibault et al.			Nikkhoo et al.		
Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus

A	A	A	A	A	A
NA	NA	NA	NA	NA	NA
A	A	A	A	A	A
A	A	A	A	A	A
A	A	A	A	A	A
D (sample size)	D	D (sample size)	A (sample size)	A	A (sample size)
V (correlation calculated	V	V (correlation calculated	V (correlation calculated	V	V (correlation calculated
NA	NA	NA	NA	NA	NA
NA	NA	NA	NA	NA	NA
D	D	D	A	A	A

Appendix 1. 4. Study 1 Reliability and measurement error risk of bias checklist

Reliability

Score: V= very good; A = adequate; D = doubtful; I = inadequate; N= not applicable
1- Were patients stable in the time between the repeated measurements on the construct to be measured?
2- Was the time interval between the repeated measurements appropriate?
3- Were the measurement conditions similar for the repeated measurements – except for the condition being evaluated as a source of variation?
4- Did the professional(s) administer the measurement without knowledge of scores or values of other repeated measurement(s) in the same patients?
5- Did the professional(s) assign scores or determine values without knowledge of the scores or values of other repeated measurement(s) in the same patients?
6- Were there any other important flaws in the design or statistical methods of the study?
7- For continuous scores: was an intraclass correlation coefficient (ICC) calculated?
8- Kappa calculated; the weighting scheme was described, and matches the study design and the data
9- For dichotomous/nominal scores: was Kappa calculated for each category against the other categories combined?
Total (lowest score)

Alahmari et al. (Intra NHP)			Alahmari et al. (inter NHP)			Alahmari et al. (Intra THP)			Alahmari et al. (inter THP)		
Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus
A	A	A	A	A	A	A	A	A	A	A	A
D (3 days)	D	D (3 days)	D (3 days)	D	D (3 days)	D (3 days)	D	D (3 days)	D (3 days)	D	D (3 days)
A	A	A	A	A	A	A	A	A	A	A	A
A	A	A	A	A	A	A	A	A	A	A	A
A	A	A	A	A	A	A	A	A	A	A	A
I (No. of trials	I	I (No. of trials	I (No. of trials	I	I (No. of trials	I (No. of trials	I	I (No. of trials	I (No. of trials	I	I (No. of trials
V	V	V	V	V	V	V	V	V	V	V	V
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
I	I	I	I	I	I	I	I	I	I	I	I

Artz et al. (JPE) within day sitting			Artz et al. (JPE) between day sitting			Artz et al. (JPE) within day standing			Artz et al. (JPE) between day standing		
Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus
A	A	A	A	A	A	A	A	A	A	A	A
D	D	D	D	D	D	D	D	D	D	D	D
A	A	A	A	A	A	A	A	A	A	A	A
A	A	A	A	A	A	A	A	A	A	A	A
A	A	A	A	A	A	A	A	A	A	A	A
I (No. of trials, did not report ICC model)	I	I (No. of trials, did not report ICC model)	I (No. of trials, did not report ICC model)	I	I (No. of trials, did not report ICC model)	I (No. of trials, did not report ICC model)	I	I (No. of trials, did not report ICC model)	I (No. of trials, did not report ICC model)	I	I (No. of trials, did not report ICC model)
A	V	A	A	A	A	A	A	A	A	A	A
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
I	I	I	I	I	I	I	I	I	I	I	I

Burke et al. (intra CROM)			Burke et al. (Intra AL)			Burke et al. (Inter CROM)			Burke et al. (Inter AL)		
Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus
A	A	A	A	A	A	A	A	A	A	A	A
D	D	D	D	D	D	D	D	D	D	D	D
A	A	A	A	A	A	A	A	A	A	A	A

A	A	A	A	A	A	A	A	A	A	A	A
A	A	A	A	A	A	A	A	A	A	A	A
I (age not provided and No of trials)	I	I (age not provided and No of trials)	I (age not provided and No of trials)	I	I (age not provided and No of trials)	I (age not provided and No of trials)	I	I (age not provided and No of trials)	I (age not provided and No of trials)	I	I (age not provided and No of trials)
V	V	V	V	V	V	V	V	V	V	V	V
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
I	I	I	I	I	I	I	I	I	I	I	I

Goncalves and Silva (within day HRNT)			**Goncalves and Silva (within day TT)**			**Goncalves and Silva (within day HR30T)**			**Goncalves and Silva (within day F8T)**		
Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus
A	A	A	A	A	A	A	A	A	A	A	A
D	D	D	D	D	D	D	D	D	D	D	D
A	A	A	A	A	A	A	A	A	A	A	A
A	A	A	A	A	A	A	A	A	A	A	A
A	A	A	A	A	A	A	A	A	A	A	A

V	V	V	V	V	V	V	V	V	V	V	V
V	V	V	V	V	V	V	V	V	V	V	V
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
D	D	D	D	D	D	D	D	D	D	D	D

Goncalves and Silva (between day HRNT)			**Goncalves and Silva (between day TT)**			**Goncalves and Silva (between day HR30T)**			**Goncalves and Silva (between day F8T)**		
Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus
A	A	A	A	A	A	A	A	A	A	A	A
D	D	D	D	D	D	D	D	D	D	D	D
A	A	A	A	A	A	A	A	A	A	A	A
A	A	A	A	A	A	A	A	A	A	A	A
A	A	A	A	A	A	A	A	A	A	A	A

V	V	V	V	V	V	V	V	V	V	V	V
V	V	V	V	V	V	V	V	V	V	V	V
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
D	D	D	D	D	D	D	D	D	D	D	D

Kristjansson et al. 2001 (NHP)			**Kristjansson et al. 2001 (THP)**			**Kristjansson et al. 2001 (preset trunk rotation)**			**Kristjansson et al. 2001 (Fo8 relocation test)**		
Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus
A	A	A	A	A	A	A	A	A	A	A	A
D	D	D	D	D	D	D	D	D	D	D	D
A	A	A	A	A	A	A	A	A	A	A	A
A	A	A	A	A	A	A	A	A	A	A	A
A	A	A	A	A	A	A	A	A	A	A	A

I (sample size and No. of trials)	I	I (sample size and No. of trials)	I (sample size and No. of trials)	I	I (sample size and No. of trials)	I (sample size and No. of trials)	I	I (sample size and No. of trials)	I (sample size and No. of trials)	I	I (sample size and No. of trials)
V	V	V	V	V	V	V	V	V	V	V	V
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
I	I	I	I	I	I	I	I	I	I	I	I

Lee et al. (NHP)			**Lee et al. (THP)**			**Pinsault et al.**			**Strimpakos et al. (intrarater sitting)**		
Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus
A	A	A	A	A	A	A	A	A	A	A	A
D	D	D	D	D	D	D	D	D	D	D	D
A	A	A	A	A	A	A	A	A	A	A	A
A	A	A	A	A	A	A	A	A	A	A	A
A	A	A	A	A	A	A	A	A	A	A	A

I (No. of trials, no randomisation, sample size)	I	I (No. of trials, no randomisation, sample size)	I (No. of trials, no randomisation, sample size)	I	I (No. of trials, no randomisation, sample size)	V	V	V	I (No. of trials, no randomisation)	I	I (No. of trials, no randomisation)
V	V	V	V	V	V	V	V	V	V	V	V
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
I	I	I	I	I	I	D	D	D	I	I	I

Strimpakos et al. (interrater)			**Wibault et al.**			**Roren (Intrarater within day Revel visual technique)**			**Roren (Intrarater within day US technique)**		
Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus
A	A	A	A	A	A	A	A	A	A	A	A
D	D	D	D	D	D	D	D	D	D	D	D
A	A	A	A	A	A	A	A	A	A	A	A
A	A	A	A	A	A	A	A	A	A	A	A
A	A	A	A	A	A	A	A	A	A	A	A

I (No. of trials, no randomisation)	I	I (No. of trials, no randomisation)	I (No. of trials)	I	I (No. of trials)	I (No. of trials, speed of testing, did not report ICC model)	I	I (No. of trials, speed of testing, did not report ICC model)	I (No. of trials, speed of testing, did not report ICC model)	I	I (No. of trials, speed of testing, did not report ICC model)
V	V	V	A	A	A	V	V	V	V	V	V
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
I	I	I	I	I	I	I	I	I	I	I	I

Nikkhoo (within day intra US MOCAP)			**Nikkhoo (between day intra US MOCAP)**			**Nikkhoo (within day intra IMU)**			**Nikkhoo (between day intra IMU)**		
Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus
A	A	A	A	A	A	A	A	A	A	A	A
D	D	D	D	D	D	D	D	D	D	D	D
A	A	A	A	A	A	A	A	A	A	A	A
A	A	A	A	A	A	A	A	A	A	A	A
A	A	A	A	A	A	A	A	A	A	A	A

A (sample size)	A	A (sample size)	A (sample size)	A	A (sample size)	A (sample size)	A	A (sample size)	A (sample size)	A	A (sample size)
V	V	V	V	V	V	V	V	V	V	V	V
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
D	D	D	D	D	D	D	D	D	D	D	D

Strimpakos et al. (intrarater standing)			**Cid et al.**			**Kramer et al. (intrasession)**			**Kramer et al. (intersession)**		
Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus
A	A	A	A	A	A	A	A	A	A	A	A
D	D	D	D	D	D	D	D	D	D	D	D
A	A	A	A	A	A	A	A	A	A	A	A
A	A	A	A	A	A	A	A	A	A	A	A
A	A	A	A	A	A	A	A	A	A	A	A

I (No. of trials, no randomisation)	I	I (No. of trials, no randomisation)	V	V	V	I (no randomisation, NO. of trials)	I	I (no randomisation, NO. of trials)	I (no randomisation, NO. of trials)	I	I (no randomisation, NO. of trials)
V	V	V	V	V	V	V	V	V	V	V	V
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
I	I	I	D	D	D	D	D	D	D	D	D

Dugailly et al. (90cm low speed)			**Dugailly et al. (90cm high speed)**			**Dugailly et al. (180cm low speed)**			**Dugailly et al. (180cm high speed)**		
Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus
A	A	A	A	A	A	A	A	A	A	A	A
D	D	D	D	D	D	D	D	D	D	D	D
A	A	A	A	A	A	A	A	A	A	A	A
A	A	A	A	A	A	A	A	A	A	A	A
A	A	A	A	A	A	A	A	A	A	A	A

I (sample size, did not report ICC model)	I	I (sample size, did not report ICC model)	I (sample size, did not report ICC model)	I	I (sample size, did not report ICC model)	I (sample size, did not report ICC model)	I	I (sample size, did not report ICC model)	I (sample size, did not report ICC model)	I	I (sample size, did not report ICC model)
V	V	V	V	V	V	V	V	V	V	V	V
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
I	I	I	I	I	I	I	I	I	I	I	I

Measurement error

Score: V= very good; A = adequate; D = doubtful; I = inadequate; N= not applicable
1- Were patients stable in the time between the repeated measurements on the construct to be measured?
2- Was the time interval between the repeated measurements appropriate?
3- Were the measurement conditions similar for the repeated measurements – except for the condition being evaluated as a source of variation?
4- Did the professional(s) administer the measurement without knowledge of scores or values of other repeated measurement(s) in the same patients?

5- Did the professional(s) assign scores or determine values without knowledge of the scores or values of other repeated measurement(s) in the same patients?
6- Were there any other important flaws in the design or statistical methods of the study?
7- For continuous scores: was the Standard Error of Measurement (SEM), Smallest Detectable Change (SDC), Limits of Agreement (LoA) or Coefficient of Variation (CV) calculated?
8- For dichotomous/nominal/ordinal scores: Was the percentage specific (e.g. positive and negative) agreement calculated?
Total (lowest score)

Alahmari et al. (Intra NHP)			**Alahmari et al. (inter NHP)**			**Alahmari et al. (Intra THP)**			**Alahmari et al. (inter THP)**		
Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus
A	A	A	A	A	A	A	A	A	A	A	A
D	D	D	D	D	D	D	D	D	D	D	D
A	A	A	A	A	A	A	A	A	A	A	A
A	A	A	A	A	A	A	A	A	A	A	A
A	A	A	A	A	A	A	A	A	A	A	A
I (No. of trials	I	I (No. of trials	I (No. of trials	I	I (No. of trials	I (No. of trials	I	I (No. of trials	I (No. of trials	I	I (No. of trials
V	V	V	V	V	V	V	V	V	V	V	V

NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
I	I	I	I	I	I	I	I	I	I	I	I

Artz et al. (JPE) within day sitting			**Artz et al. (JPE) between day sitting**			**Artz et al. (JPE) within day standing**			**Artz et al. (JPE) between day standing**		
Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus
A	A	A	A	A	A	A	A	A	A	A	A
D	D	D	D	D	D	D	D	D	D	D	D
A	A	A	A	A	A	A	A	A	A	A	A
A	A	A	A	A	A	A	A	A	A	A	A
A	A	A	A	A	A	A	A	A	A	A	A
I (No. of trials)	I	I (No. of trials)	I (No. of trials)	I	I (No. of trials)	I (No. of trials)	I	I (No. of trials)	I (No. of trials)	I	I (No. of trials)
V	V	V	V	V	V	V	V	V	V	V	V
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
I	I	I	I	I	I	I	I	I	I	I	I

Burke et al. (intra CROM)			Burke et al. (Intra AL)			Burke et al. (Inter CROM)			Burke et al. (Inter AL)		
Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus
A	A	A	A	A	A	A	A	A	A	A	A
D	D	D	D	D	D	D	D	D	D	D	D
A	A	A	A	A	A	A	A	A	A	A	A
A	A	A	A	A	A	A	A	A	A	A	A
A	A	A	A	A	A	A	A	A	A	A	A
I (age not provided and No of trials)	I	I (age not provided and No of trials)	I (age not provided and No of trials)	I	I (age not provided and No of trials)	I (age not provided and No of trials)	I	I (age not provided and No of trials)	I (age not provided and No of trials)	I	I (age not provided and No of trials)
V	V	V	V	V	V	V	V	V	V	V	V
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
I	I	I	I	I	I	I	I	I	I	I	I

Goncalves and Silva (within day HRNT)			Goncalves and Silva (within day TT)			Goncalves and Silva (within day HR30T)			Goncalves and Silva (within day F8T)		
Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus
A	A	A	A	A	A	A	A	A	A	A	A

D	D	D	D	D	D	D	D	D	D	D	D
A	A	A	A	A	A	A	A	A	A	A	A
A	A	A	A	A	A	A	A	A	A	A	A
A	A	A	A	A	A	A	A	A	A	A	A
V	V	V	V	V	V	V	V	V	V	V	V
V	V	V	V	V	V	V	V	V	V	V	V
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
D	D	D	D	D	D	D	D	D	D	D	D

Goncalves and Silva (between day HRNT)			**Goncalves and Silva (between day TT)**			**Goncalves and Silva (between day HR30T)**			**Goncalves and Silva (between day F8T)**		
Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus
A	A	A	A	A	A	A	A	A	A	A	A
D	D	D	D	D	D	D	D	D	D	D	D
A	A	A	A	A	A	A	A	A	A	A	A
A	A	A	A	A	A	A	A	A	A	A	A

A	A	A	A	A	A	A	A	A	A	A	A
V	V	V	V	V	V	V	V	V	V	V	V
V	V	V	V	V	V	V	V	V	V	V	V
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
D	D	D	D	D	D	D	D	D	D	D	D

Kristjansson et al. 2001 (NHP)			**Kristjansson et al. 2001 (THP)**			**Kristjansson et al. 2001 (preset trunk rotation)**			**Kristjansson et al. 2001 (Fo8 relocation test)**		
Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus
A	A	A	A	A	A	A	A	A	A	A	A
D	D	D	D	D	D	D	D	D	D	D	D
A	A	A	A	A	A	A	A	A	A	A	A
A	A	A	A	A	A	A	A	A	A	A	A
A	A	A	A	A	A	A	A	A	A	A	A
I (sample size and No. of trials)	I	I (sample size and No. of trials)	I (sample size and No. of trials)	I	I (sample size and No. of trials)	I (sample size and No. of trials)	I	I (sample size and No. of trials)	I (sample size and No. of trials)	I	I (sample size and No. of trials)
V	V	V	V	V	V	V	V	V	V	V	V

NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
I	I	I	I	I	I	I	I	I	I	I	I

Lee et al. (NHP)			Lee et al. (THP)			Pinsault et al.			Strimpakos et al. (intrarater sitting)		
Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus
A	A	A	A	A	A	A	A	A	A	A	A
D	D	D	D	D	D	D	D	D	D	D	D
A	A	A	A	A	A	A	A	A	A	A	A
A	A	A	A	A	A	A	A	A	A	A	A
A	A	A	A	A	A	A	A	A	A	A	A
I (No. of trials, no randomisation)	I	I (No. of trials, no randomisation)	I (No. of trials, no randomisation)	I	I (No. of trials, no randomisation)	V	V	V	I (No. of trials, no randomisation)	I	I (No. of trials, no randomisation)
V	V	V	V	V	V	V	V	V	V	V	V
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
I	I	I	I	I	I	D	D	D	I	I	I

Strimpakos et al. (interrater)			Wibault et al.			Roren (Intrarater within day Revel visual technique)			Roren (Intrarater within day US technique)		
Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus
A	A	A	A	A	A	A	A	A	A	A	A
D	D	D	D	D	D	D	D	D	D	D	D
A	A	A	A	A	A	A	A	A	A	A	A
A	A	A	A	A	A	A	A	A	A	A	A
A	A	A	A	A	A	A	A	A	A	A	A
I (No. of trials, no randomisation)	I	I (No. of trials, no randomisation)	I (No. of trials)	I	I (No. of trials)	I (No. of trials, speed of testing)	I (No. of trials, speed of testing)	I (No. of trials, speed of testing)	I (No. of trials, speed of testing)	I (No. of trials, speed of testing)	I (No. of trials, speed of testing)
V	V	V	V	V	V	V	V	V	V	V	V
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
I	I	I	I	I	I	I	I	I	I	I	I

Nikkhoo (within day intra US MOCAP)			Nikkhoo (between day intra US MOCAP)			Nikkhoo (within day intra IMU)			Nikkhoo (between day intra IMU)		
Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus

A	A	A	A	A	A	A	A	A	A	A	A
D	D	D	D	D	D	D	D	D	D	D	D
A	A	A	A	A	A	A	A	A	A	A	A
A	A	A	A	A	A	A	A	A	A	A	A
A	A	A	A	A	A	A	A	A	A	A	A
A	A	A	A	A	A	A	A	A	A	A	A
V	V	V	V	V	V	V	V	V	V	V	V
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
D	D	D	D	D	D	D	D	D	D	D	D

Strimpakos et al. (intrarater standing)			**Dugailly et al. (90cm low speed)**			**Dugailly et al. (90cm high speed)**			**Dugailly et al. (180cm low speed)**			**Dugailly et al. (180cm high speed)**		
Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus	Rater 1	Rater 2	Consensus
A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
A	A	A	A	A	A	A	A	A	A	A	A	A	A	A

A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
I (No. of trials, no randomisation)	I	I (No. of trials, no randomisation)	I (sample size)	I	I (sample size)	I (sample size)	I	I (sample size)	I (sample size)	I	I (sample size)	I (sample size)	I	I (sample size)
V	V	V	V	V	V	V	V	V	V	V	V	V	V	V
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
I	I	I	I	I	I	I	I	I	I	I	I	I	I	I

Appendix 1. 5. Study 1 Modified GRADE tables

NP (AE) (NHP) (Table 5 in manuscript)

Reference	Intrarater reliability			Interrater reliability			Measurement error			Convergent validity			Discriminative validity			Criterion validity		
	n	Meth. Qual.	Rating	n	Meth. Qual.	Rating	n	Meth. Qual.	Rating	n	Meth. Qual.	Rating	n	Meth. Qual.	Rating	n	Meth. Qual.	Rating
Alahmari et al. (intra NHP)	69	I	(+) (ICC: 0.74-0.78)				69	I	(?)	#SPILL!								
Alahmari et al. (inter NHP)				69	I	(+) (ICC: 0.74-0.79)	69	I	(?)									
Burke et al. (intra CROM)	50	I	(-) (ICC: 0.25-0.38)				50	I	(?)									
Burke et al. (intra AL)	50	I	(-) (ICC: 0.48-0.55)				50	I	(?)									
Burke et al. (inter CROM)				50	I	(+) (ICC: 0.71-0.77)	50	I	(?)									
Burke et al. (inter AL)				50	I	(+) (ICC: 0.58-0.75)	50	I	(?)									
Chen and Treleavan (JPE Conventional)													50	I	(?)	51	A	(+) (r=0.87)
Chen and Treleavan (JPE Torion)													50	I	(?)	51	A	(-) (r=0.67)
Chen and Treleavan (JPE Enbloc)													50	I	(?)			
Chen and Treleavan (JPE Conventional vs NDI)										51	A	(-)						
Chen and Treleavan (JPE Torion vs NDI)										51	A	(-)						
Chen and Treleavan (JPE Enbloc vs NDI)										51	A	(-)						

Chen and Treleavan (JPE Conventional vs VAS)										51	A	(+) (r=0.51)						
Chen and Treleavan (JPE Torion vs VAS)										51	A	(-)						
Chen and Treleavan (JPE Enbloc vs VAS)										51	A	(-)						
Goncalves and Silva (intra within day HRNT)	33	D	(+) (ICC: 0.9-0.93)				33	D	(?)									
Goncalves and Silva (intra within day TT)	33	D	(+) (ICC: 0.88-0.9)				33	D	(?)									
Goncalves and Silva (intra within day F8T)	33	D	(+) (ICC: 0.89-0.93)				33	D	(?)									
Goncalves and Silva (intra between day HRNT)	33	D	(+) (ICC: 0.61-0.85)				33	D	(?)									
Goncalves and Silva (intra between day TT)	33	D	(+) (ICC: 0.58-0.71)				33	D	(?)									
Goncalves and Silva (intra between day F8T)	33	D	(+) (ICC: 0.66-0.85)				33	D	(?)									
Goncalves and Silva (HRNT vs disability)										66	A	(-) (r<0.3)						
Goncalves and Silva (HRNT vs pain catastrophising)										66	A	(-) (r<0.3)						
Goncalves and Silva (HRNT vs fear of movement										66	A	(-) (r<0.3)						
Goncalves and Silva (TT vs disability)										66	A	(-) (r<0.3)						

Goncalves and Silva (TT vs disability)										66	A	(-) (r<0.3)						
Goncalves and Silva (TT vs disability)										66	A	(-) (r<0.3)						
Goncalves and Silva (HR30T vs disability)										66	A	(-) (r<0.3)						
Goncalves and Silva (HR30T vs disability)										66	A	(-) (r<0.3)						
Goncalves and Silva (HR30T vs disability)										66	A	(-) (r<0.3)						
Goncalves and Silva (F8T vs disability)										66	A	(-) (r<0.3)						
Goncalves and Silva (F8T vs disability)										66	A	(-) (r<0.3)						
Goncalves and Silva (F8T vs disability)										66	A	(-) (r<0.3)						
Goncalves and Silva (HRNT vs TT)										66	A	(+) (r=0.35-0.61)						
Goncalves and Silva (HRNT vs HR30T)										66	A	(+) (r=0.35-0.61)						
Goncalves and Silva (HRNT vs F8T)										66	A	(+) (r=0.35-0.61)						
Goncalves and Silva (TT vs HRNT)										66	A	(+) (r=0.35-0.61)						
Goncalves and Silva (TT vs HR30T)										66	A	(+) (r=0.35-0.61)						
Goncalves and Silva (TT vs F8T)										66	A	(+) (r=0.35-0.61)						
Goncalves and Silva (HR30T vs HRNT)										66	A	(+) (r=0.35-0.61)						

Goncalves and Silva (HR30T vs TT)										66	A	(+) (r=0.35-0.61)						
Goncalves and Silva (HR30T vs F8T)										66	A	(+) (r=0.35-0.61)						
Goncalves and Silva (F8T vs HRNT)										66	A	(+) (r=0.35-0.61)						
Goncalves and Silva (F8T vs TT)										66	A	(+) (r=0.35-0.61)						
Goncalves and Silva (F8T vs HR30T)										66	A	(+) (r=0.35-0.61)						
Goncalves and Silva (HRNT)													66	I	(?)			
Goncalves and Silva (TT)													66	I	(?)			
Goncalves and Silva (HR30T)													66	I	(?)			
Goncalves and Silva (F8T)													66	I	(?)			
Roren et al. (intra Revel visual technique)	82	I	(-) (ICC: 0.68)				82	I	(?)									
Roren et al. (intra US technique)	82	I	(-) (ICC: 0.62)				82	I	(?)									
Roren (US technique)																		
Roren et al. (validity)													82	I	(+) Kappa 0.65	82	I	(+) (r=0.94-0.95)
Wibault et al.	36	I	(+) (ICC: 0.79-0.85)				36	I	(?)									
Cid et al.	13	I	(+) (ICC: 0.77-0.86)															
Pooled or summary results	580	I	(+) (ICC: 0.58-0.93)	169	I	(+) (0.58-0.79)	736	I	(?)	1890	A	(-) (r<0.5)	496	I	(?)	184	A	(+) (r=0.87-0.95)

GRADE (with reason)	Very low (-2 risk of bias, -2 inconsistency)	Low (-2 risk of bias)	Not graded	Low (-2 inconsistency)	Very Low (-2 risk of bias,-2 inconsistency)	low (-2 inconsistency)

NP (AE) (THP) (Table 5 in manuscript)

Reference	Intrarater reliability			Interrater reliability			Measurement error		
	n	Meth. Qual.	Rating	n	Meth. Qual.	Rating	n	Meth. Qual.	Rating
Alahmari et al. (intra THP)	69	I	(+) (ICC: 0.7-0.83)				69	I	(?)
Alahmari et al. (inter THP)				69	I	(+) (ICC: 0.62-0.84)	69	I	(?)
Goncalves and Silva (intra within day HR30T)	33	D	(+) (ICC: 0.73-0.79)				33	D	(?)
Goncalves and Silva (intra between day HR30T)	33	D	(+) (ICC: 0.67-0.7)				33	D	(?)
Pooled or summary results	135	D	(+) (ICC: 0.67-0.83)	69	I	(+) (0.58-0.84)	204	I	(?)
GRADE (with reason)	Low (-2 risk of bias)			very low (-3 risk of bias, -1 imprecision)			Not graded		

Healthy (AE) (NHP) (Table 5 in manuscript)

Reference	Intrarater reliability	Interrater reliability	Measurement error	Criterion validity	Intrasession reliability	Intersession reliability

	n	Meth. Qual.	Rating	n	Meth. Qual.	Rating	n	Meth. Qual.	Rating	n	Meth. Qual.	Rating	n	Meth. Qual.	Rating	n	Meth. Qual.	Rating
Kristjansson et al. 2001 (NHP)	19	I	(-) (ICC: 0.35-0.44)				19	I	(?)									
Kristjansson et al. 2001 (preset trunk rotation)	19	I	(+) (ICC: 0.52-0.74)				19	I	(?)									
Kristjansson et al. 2001 (F8 relocation test)	19	I	(-) (ICC: 0.67)				19	I	(?)									
Pinsault et al.	44	D	(+) (ICC: 0.52-0.81)				44	D	(?)									
Strimpakos et al. (intra sitting)	35	I	(-) (ICC: -0.01-0.35)				35	I	(?)									
Strimpakos et al. (intra standing)	35	I	(-) (0.17-0.5)															
Strimpakos et al. (inter)				35	I	(-) (ICC: -0.2-0.64)	35	I	(?)									
Goncalves and Silva (intra within day HRNT)	33	D	(+) (ICC: 0.79-0.89)				33	D	(?)									
Goncalves and Silva (intra within day TT)	33	D	(+) (ICC: 0.75-0.78)				33	D	(?)									
Goncalves and Silva (intra within day F8T)	33	D	(+) (ICC: 0.83-0.93)				33	D	(?)									
Goncalves and Silva (intra between day HRNT)	33	D	(+) (ICC: 0.75-0.85)				33	D	(?)									
Goncalves and Silva (intra between day TT)	33	D	(-) (ICC: 0.57-0.59)				33	D	(?)									
Goncalves and Silva (intra between day F8T)	33	D	(+) (ICC: 0.8-0.83)				33	D	(?)									
Wibault et al.										36	D	(?)						
Nikkhoo et al (within day intra US MOCAP)	35	D	(+) (ICC: 0.83-0.93)				35	I	(?)									

Nikkhoo et al (between day intra US MOCAP)	35	D	(+) (ICC: 0.69-0.85)				35	I	(?)									
Nikkhoo et al (within day intra IMU)	35	D	(+) (ICC: 0.66-0.91)				35	I	(?)									
Nikkhoo et al (between day intra IMU)	35	D	(+) (ICC: 0.63-0.76)				35	I	(?)									
Nikkhoo et al										35	A	(+)						
Cid et al.	28	D	(-) (ICC: -0.16-0.5)															
Kramer et al. (Intra)													57	D	(-) (ICC: 0.63)			
Kramer et al. (inter)																57	D	(-) (ICC: 0.48)
Pooled or summary results	537	D	(+) (0.52-0.93)	35	I	(-) (ICC: -0.2-0.64)	509	I	(?)	71		(±)	57	D	(-) (ICC: 0.63)	57	D	(-) (ICC: 0.48)
GRADE	Very low (-2 risk of bias, -2 inconsistency)			Very low (-2 risk of bias, -1 imprecision)			Not graded			Not graded due to inconsistency			Very low (-3 risk of bias, -1 imprecision)			Very low (-3 risk of bias, -1 imprecision)		

Healthy (AE) (THP) (Table 5 in manuscript)

Reference	Intrarater reliability			Measurement error		
	n	Meth. Qual.	Rating	n	Meth. Qual.	Rating
Artz (intra within day sitting)	21	I	(-) (ICC: -0.81-0.66)	21	I	(?)
Artz (intra within day standing)	21	I	(-) (ICC: -0.11-0.68)	21	I	(?)

Artz (intra between day sitting)	19	I	(+) (ICC: -0.48-0.77)	19	I	(?)
Artz (intra between day standing)	19	I	(-) (ICC: 0.09-0.58))	19	I	(?)
Kristjansson et al. 2001 (THP)	19	I	(+) (ICC: 0.69-0.74)	19	I	(?)
Goncalves and Silva (intra within day HR30T)	33	D	(+) (ICC: 0.78-0.83)	33	D	(?)
Goncalves and Silva (intra between day HR30T)	33	D	(+) (ICC: 0.55-0.76)	33	D	(?)
Pooled or summary results	165	I	(+) (-0.48-0.83)	165	I	(?)
GRADE	Very low (-2 risk of bias, -2 inconsistency)			Not graded		

Healthy (CE) (NHP) (Table 6 in manuscript)

Reference	Intrarater reliability			Measurement error			Convergent validity			Criterion validity		
	n	Meth. Qual.	Rating	n	Meth. Qual.	Rating	n	Meth. Qual.	Rating	n	Meth. Qual.	Rating
Lee et al. (NHP)	20	I	(+) (ICC: 0.38-0.84)	20	I	(?)						
Dugailly et al. (90cm low speed)	5	I	(-) ICC: 0.22-0.47	5	I	(?)				17	D	(?)
Dugailly et al. (90cm high speed)	5	I	(+) ICC: 0.58-0.79	5	I	(?)						

Dugailly et al. (180cm low speed)	5	I	(+) 0.52-0.75	5	I	(?)						
Dugailly et al. (180cm high speed)	5	I	(+) 0.8-0.86	5	I	(?)						
Dugailly (JPE vs disability)							71	A	(-) (r=0.32)			
Dugailly (JPE vs pain intensity)							71	A	(-) (r=0.03)			
Dugailly (JPE vs pain duration)							71	A	(-) (r=0.14)			
Pooled or summary results	40	I	(+) ICC: 0.38-0.86	40	I	(?)	213	A	(-)	17	D	(?)
GRADE (with reason)	Very low (-2 risk of bias, -2 imprecision, -2 inconsistency)			Not GRADED			Hight (multiple studies with adequate rating)			Very low (-3 risk of bias, -2 imprecision)		

Healthy (CE) (THP) (Table 6 in manuscript)

Reference	Intrarater reliability			Measurement error		
	n	Meth. Qual.	Rating	n	Meth. Qual.	Rating
Lee et al. (THP)	20	I	(+) (ICC: -0.47-0.83)	20	I	(?)
Pooled or summary results	20	I	(+) ICC: -0.47-0.83)	20	I	(?)
GRADE (with reason)	Very low (-3 risk of bias, -2 imprecision)			Not GRADED		

Appendix 1. 6. Study 1 search example in Medline Database

	# ▲	Searches	Results	Type	Actions	Annotations
☐	1	(Neck pain or neck dysfunction or cervical pain or cervical dysfunction).mp. [mp=title, book title, abstract, original title, name of substance word, subject heading word, floating sub-heading word, keyword heading word, organism supplementary concept word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]	16521	Advanced	Display Results | More ▾	
☐	2	(Propriocept* or movement sense or kinesthes* or repositioning or repositioning error or position sense or motion perception or active position sense or passive position sense).mp. [mp=title, book title, abstract, original title, name of substance word, subject heading word, floating sub-heading word, keyword heading word, organism supplementary concept word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]	56296	Advanced	Display Results | More ▾	
☐	3	(reliability or validity or responsiveness or reproducibility of results or reproducib* or reliab* or valid* or stability or interrater or interrater or intrarater or intrarater or intra-rater or intratester or intra-tester or interobserver or inter-observer or intraobserver or intra-observer or intertechnician or inter-technician or intratechnician or intra-technician or interexaminer or inter-examiner or intraexaminer or intra-examiner or intraclass correlation or standard error of measurement or sensitiv* or responsive* or minimal detectable concentration or interpretab* or small detectable change or ceiling effect or floor effect).mp. [mp=title, book title, abstract, original title, name of substance word, subject heading word, floating sub-heading word, keyword heading word, organism supplementary concept word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]	4106716	Advanced	Display Results | More ▾	
☐	4	1 and 2 and 3	87	Advanced	Display Results | More ▾	

Appendix 2. 1. Study 2 ethical approval

Application for Ethical Review ERN_21-0618

SC Susan Cottam (Research Support Services)
To Deborah Falla (Sport, Exercise and Rehabilitation Sciences)
Cc Ahmad Aldahas (PhD Physiotherapy FT)

Reply | Reply All | Forward

Thu 12/08/2021 14:30

Flag for follow up.

Action Items | Get more add-ins

Dear Professor Falla

Re: "Measurement properties of tests of sensorimotor control in adults with and without neck pain"
Application for Ethical Review ERN_21-0618

Thank you for your application for ethical review for the above project, which was reviewed by the Science, Technology, Engineering and Mathematics Ethical Review Committee.

On behalf of the Committee, I confirm that this study now has full ethical approval.

Appendix 2. 2. Study 2 publication

PLOS ONE

RESEARCH ARTICLE

Measurement properties of cervical joint position error in people with and without chronic neck pain

Ahmad AlDahas[1,2], **Valter Devecchi**[1], **Janet A. Deane**[1], **Deborah Falla**[1*]

1 Centre of Precision Rehabilitation for Spinal Pain (CPR Spine), School of Sport, Exercise and Rehabilitation Sciences, College of Life and Environmental Sciences, University of Birmingham, Birmingham, United Kingdom, 2 Department of Physical Therapy, Al-Sabah Medical Hospital, Ministry of Public Health, Kuwait

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Abstract

Background

People with chronic neck pain (CNP) often present with impaired neck proprioception. The most widely used clinical test for assessing neck proprioception is cervical joint position sense which measures joint position error (JPE). This clinical test is typically performed using a laser pointer to examine the accuracy of returning to a neutral head position (NHP) or target head position (THP) following active neck movements. The aim of this study was to determine the measurement properties of JPE using a laser pointer when tested in people with and without CNP under a variety of different testing conditions (i.e., different movement directions, sitting versus standing, NHP versus THP).

Methods

Forty-three participants (23 asymptomatic and 20 with CNP) underwent neck proprioception testing, returning to a NHP and THP in both sitting and standing positions (six trials for each test). A laser pointer was secured on the participant's forehead and inertial measurement unit (IMU) sensors were placed beneath the laser pointer and at the level of the spinous process of the seventh cervical vertebra. Both the absolute and the constant JPE were assessed.

Findings

For the asymptomatic participants, good reliability (ICC: 0.79) was found only for right rotation of the THP task in sitting. In standing, good reliability (ICC: 0.77) was only found in flexion for the THP task. In standing, good reliability (ICC: 0.77) was only found for right rotation of the THP for the absolute JPE and left rotation (ICC: 0.85) for the constant error of the NHP task. In those with CNP, when tested in sitting, good reliability was found for flexion (ICC: 0.8) for the absolute JPE and good reliability (ICC range: 0.8–0.84) was found for flexion, extension, and right rotation for the constant JPE. In standing, good reliability (ICC range: 0.81–0.88) was found for flexion, and rotation for the absolute JPE. The constant

OPEN ACCESS

Citation: AlDahas A, Devecchi V, Deane JA, Falla D (2023) Measurement properties of cervical joint position error in people with and without chronic neck pain. PLoS ONE 18(10): e0292798. https://doi.org/10.1371/journal.pone.0292798

Editor: Ravi Shankar Yerragonda Reddy, King Khalid University, SAUDI ARABIA

Received: June 7, 2023

Accepted: September 28, 2023

Published: October 12, 2023

Data Availability Statement: All relevant data are within the paper and its Supporting Information files.

Funding: The authors received no specific funding for this work.

Competing interests: The authors have declared that no competing interests exist.

Appendix 2. 3. Study 2 Bland and Altman supplementary files

Reliability

Bland Altman plots of JPE in sitting position (asymptomatic participants)

Bland Altman plots for the limits of agreement for the absolute JPE measured in sitting show that most of the scores lie between the 95% confidence interval with mean differences 0.001-0.63 for NHP (Figure 1) and -0.05-0.57 for THP (Figure 2).

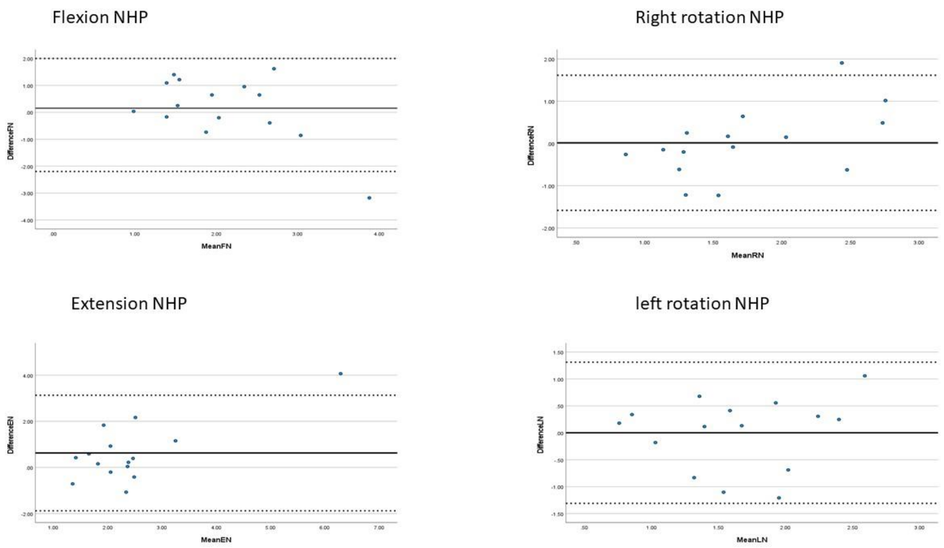

Figure 1, Bland Altman plots for intra-rater reliability of absolute error for flexion direction, extension, and right and left rotation for neutral head position (NHP) task in sitting. Limits of agreement are presented as the dotted lines with the mean difference illustrated by the black line.

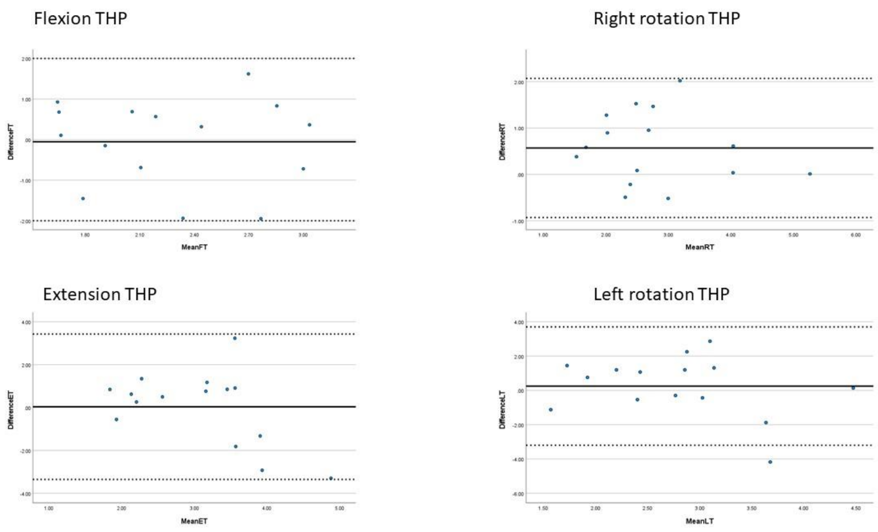

Figure 2, Bland Altman plots for intra-rater reliability of absolute error for flexion direction, extension, and right and left rotation for target head position (THP) task in sitting. Limits of agreement are presented as the dotted lines with the mean difference illustrated by the black line.

Bland Altman plots for the limits of agreement for the constant JPE measured in sitting show that most of the scores lie between the 95% confidence interval with mean differences -0.2-1.41 for NHP (Figure 3) and -0.47-0.38 for THP (Figure 4).

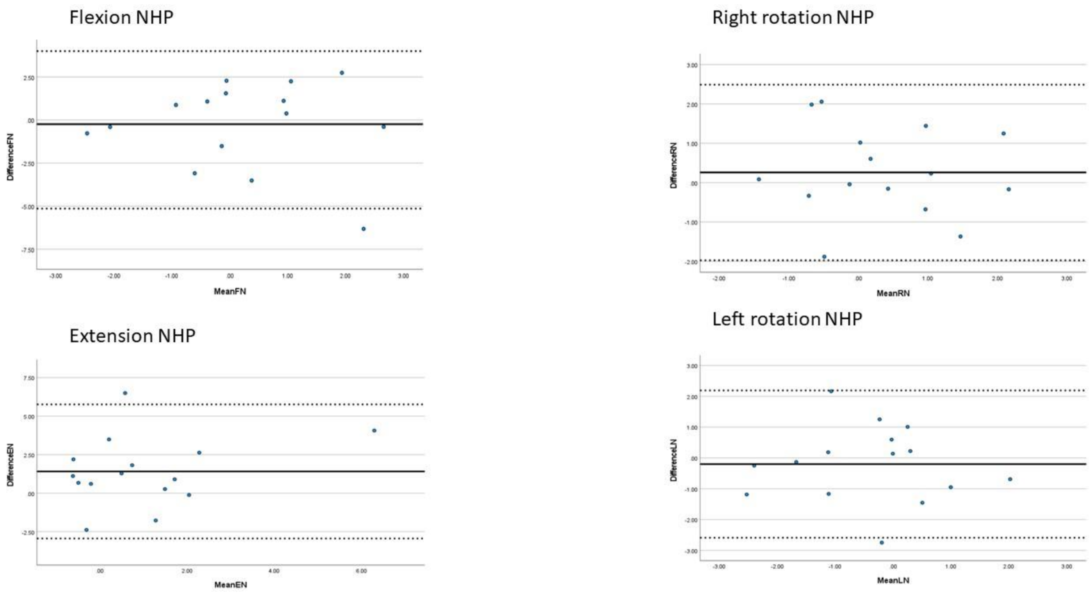

Figure 3, Bland Altman plots for intra-rater reliability of constant error for flexion direction, extension, and right and left rotation for neutral head position (NHP) task in sitting. Limits of agreement are presented as the dotted lines with the mean difference illustrated by the black line.

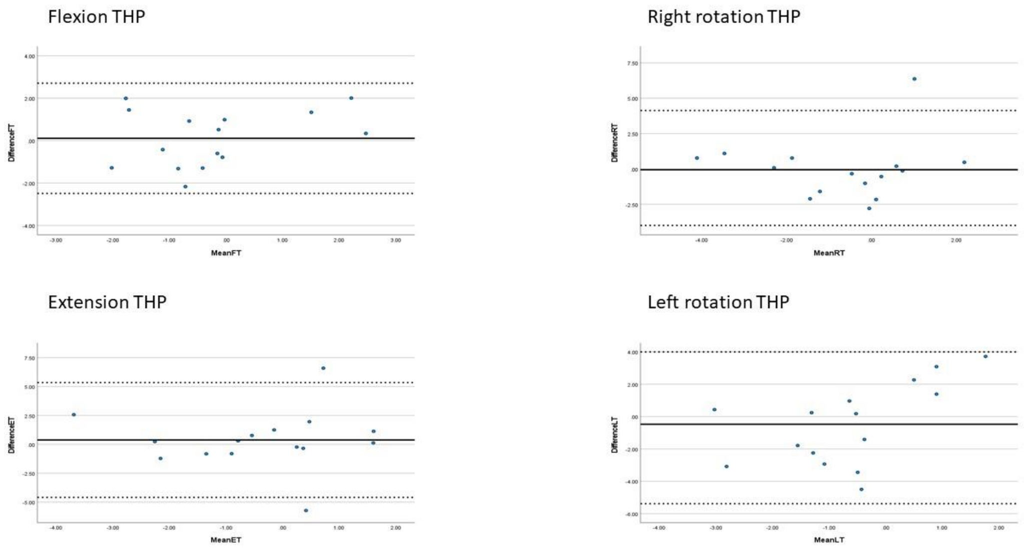

Figure 4, Bland Altman plots for intra-rater reliability of constant error for flexion direction, extension, and right and left rotation for target head position (THP) task in sitting. Limits of agreement are presented as the dotted lines with the mean difference illustrated by the black line.

Bland Altman plots of JPE in standing position (asymptomatic participants)

Bland Altman plots for the limits of agreement for absolute JPE measured in standing show that most of the scores lie between the 95% confidence interval with mean differences -0.3-0.11 for NHP (Figure 5) and 0.05-0.28 for THP (Figure 6).

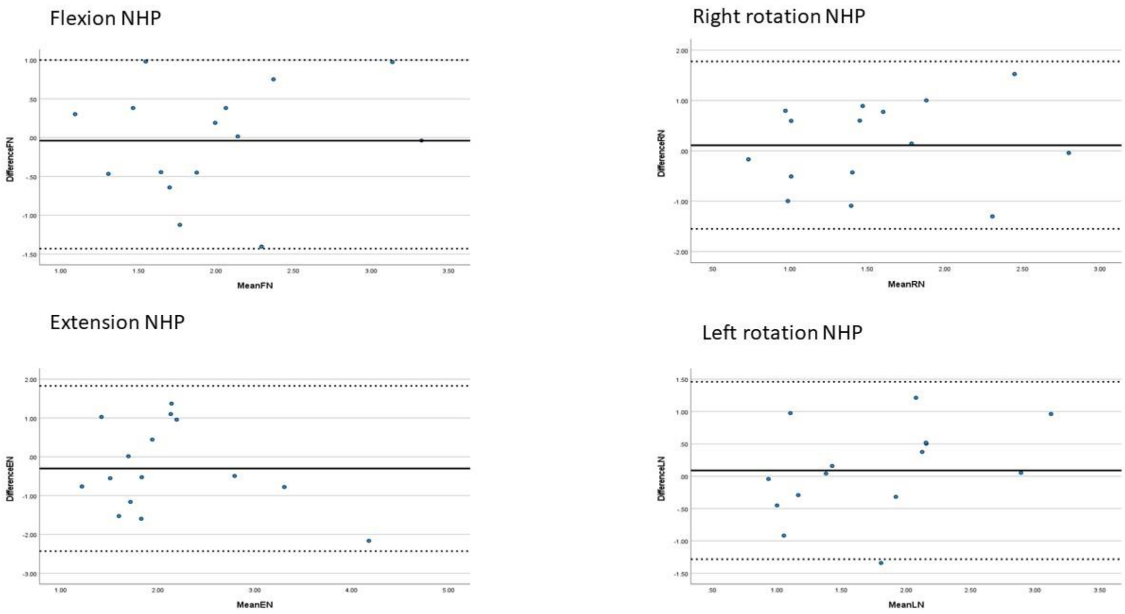

Figure 5, Bland Altman plots for intra-rater reliability of absolute error for flexion direction, extension, and right and left rotation for neutral head position (NHP) task in standing. Limits of agreement are presented as the dotted lines with the mean difference illustrated by the black line.

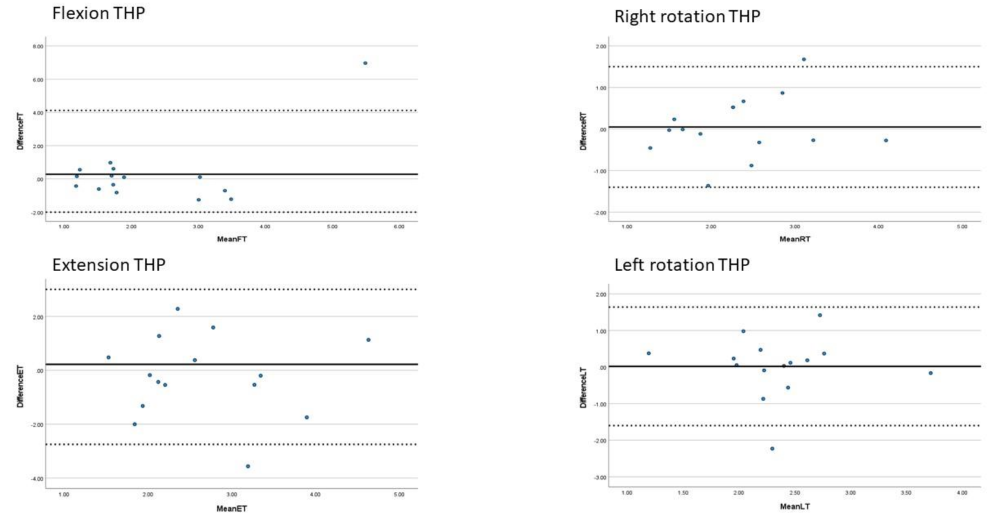

Figure 6, Bland Altman plots for intra-rater reliability of absolute error for flexion direction, extension, and right and left rotation for target head position (THP) task in standing. Limits of agreement are presented as the dotted lines with the mean difference illustrated by the black line.

Bland Altman plots for the limits of agreement for constant JPE measured in standing show that most of the scores lie between the 95% confidence interval with mean differences 0.04-0.23 for NHP (Figure 7) and -0.53-1.06 for THP (Figure 8).

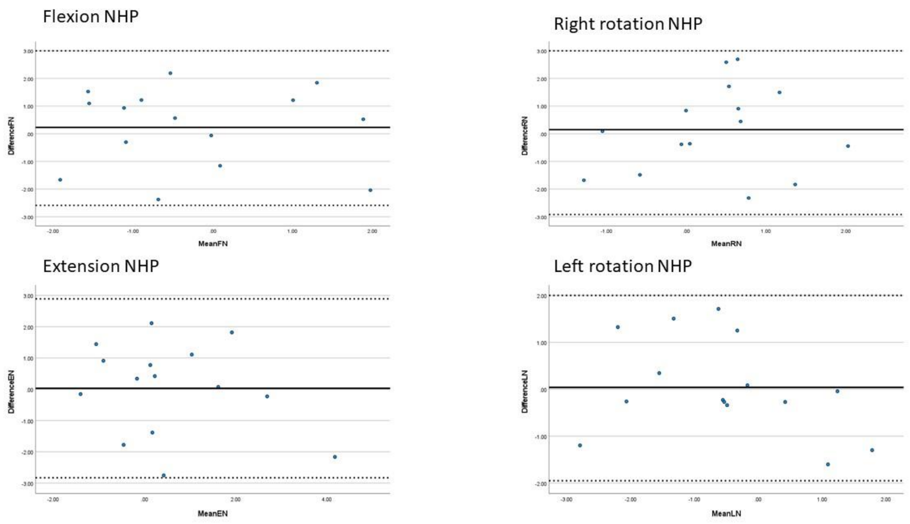

Figure 7, Bland Altman plots for intra-rater reliability of constant error for flexion direction, extension, and right and left rotation for neutral head position (NHP) task in standing. Limits of agreement are presented as the dotted lines with the mean difference illustrated by the black line.

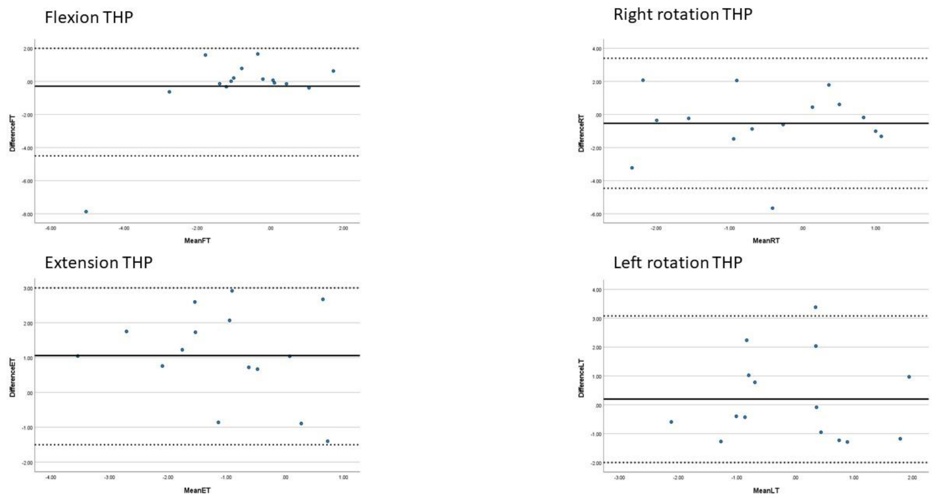

Figure 8, Bland Altman plots for intra-rater reliability of constant error for flexion direction, extension, and right and left rotation for target head position (THP) task in standing. Limits of agreement are presented as the dotted lines with the mean difference illustrated by the black line.

Bland Altman plots for JPE in sitting (CNP participants)

Bland Altman plots for the limits of agreement for absolute JPE measured in sitting show that most of the scores lie between the 95% confidence interval with mean differences -0.27-0.48 for NHP (figure 9).

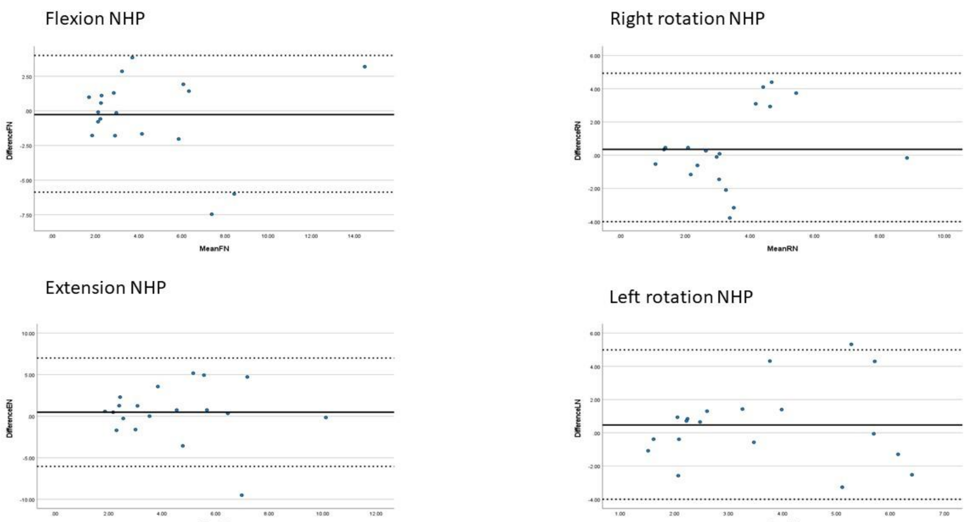

Figure 9, Bland Altman plots for intra-rater reliability of absolute error for flexion direction, extension, and right and left rotation for neutral head position (NHP) task in sitting. Limits of agreement are presented as the dotted lines with the mean difference illustrated by the black line.

Bland Altman plots for the limits of agreement for constant JPE measured in sitting show that most of the scores lie between the 95% confidence interval with mean differences -2.79-1.11 for NHP (Figure 10).

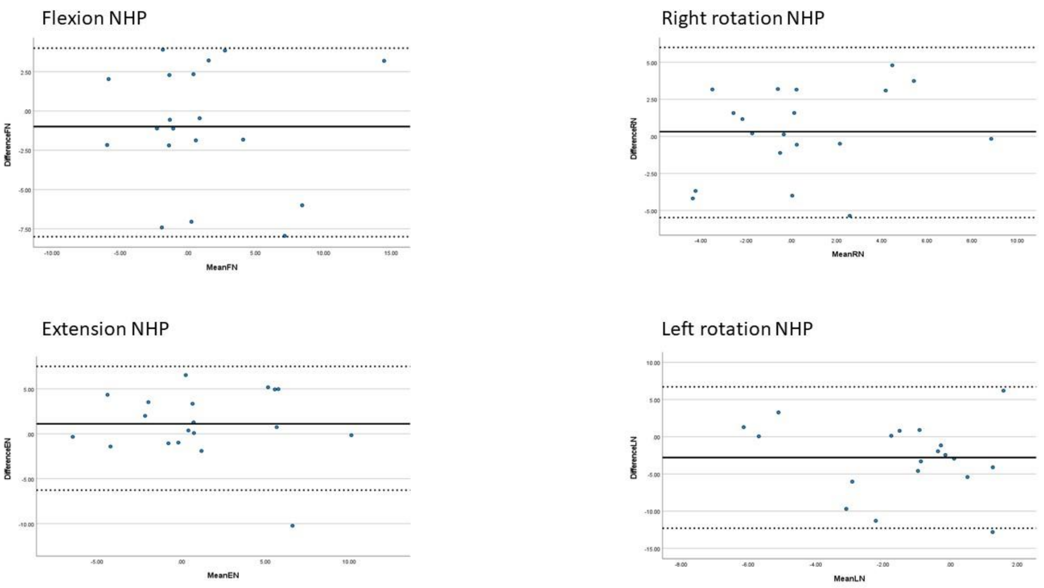

Figure 10, Bland Altman plots for intra-rater reliability of constant error for flexion direction, extension, and right and left rotation for neutral head position (NHP) task in sitting. Limits of agreement are presented as the dotted lines with the mean difference illustrated by the black line.

Bland Altman plots for JPE in standing (CNP participants)

Bland Altman plots for the limits of agreement for absolute JPE measured in standing show that most of the scores lie between the 95% confidence interval with mean differences -0.81-0.75 for NHP (Figure 11).

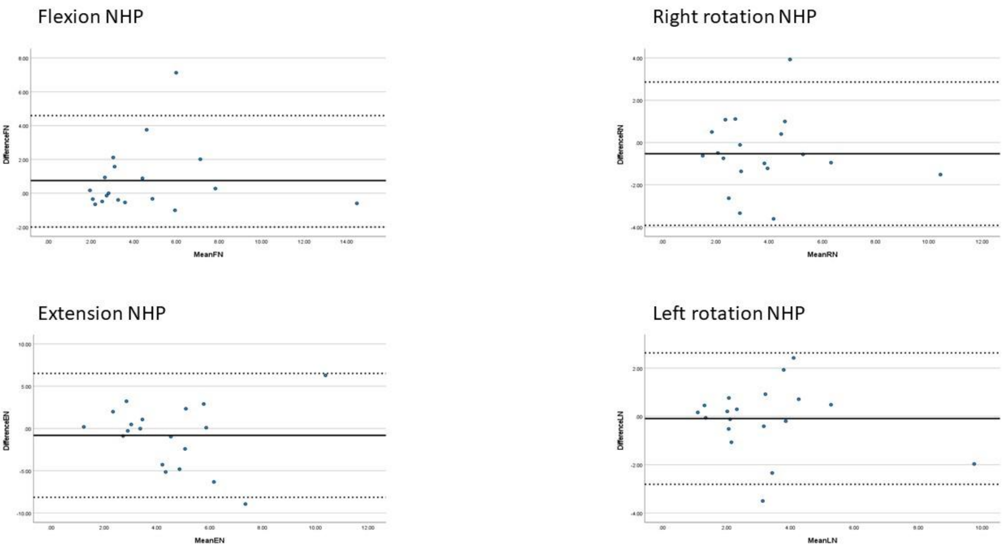

Figure 11, Bland Altman plots for intra-rater reliability of absolute error for flexion direction, extension, and right and left rotation for neutral head position (NHP) task in standing. Limits of agreement are presented as the dotted lines with the mean difference illustrated by the black line.

Bland Altman plots for the limits of agreement for constant JPE measured in standing show that most of the scores lie between the 95% confidence interval with mean differences -1.53-0.99 for NHP (Figure 12).

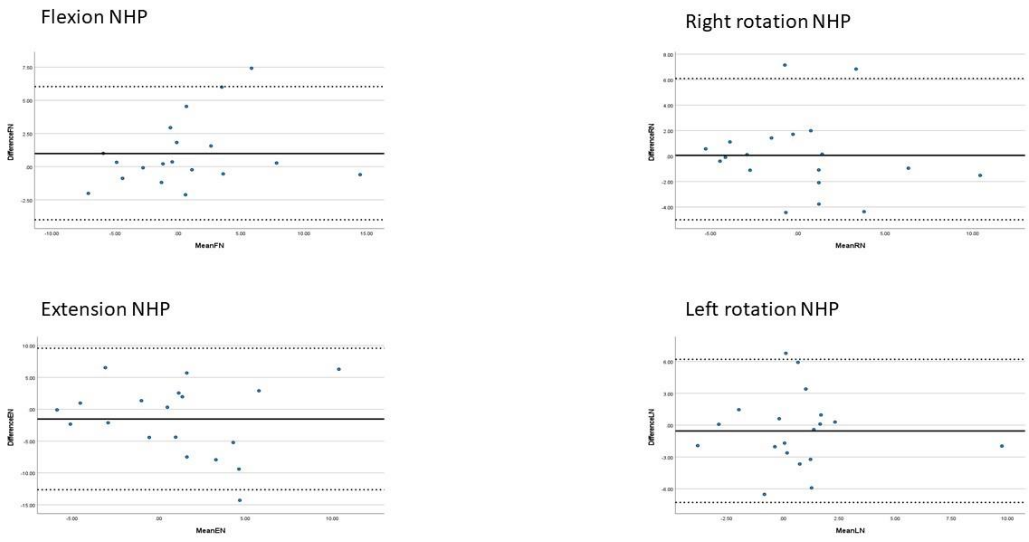

Figure 12, Bland Altman plots for intra-rater reliability of constant error for flexion direction, extension, and right and left rotation for neutral head position (NHP) task in standing. Limits of agreement are presented as the dotted lines with the mean difference illustrated by the black line.

Validity

Bland Atman plots in sitting

Bland Altman plots for the limits of agreement for absolute JPE measured in sitting show that most of the scores lie between the 95% confidence interval with mean differences -1.1 to 0.29 for the NHP (Figure 13) and 0.1-1.49 for the THP (Figure 14).

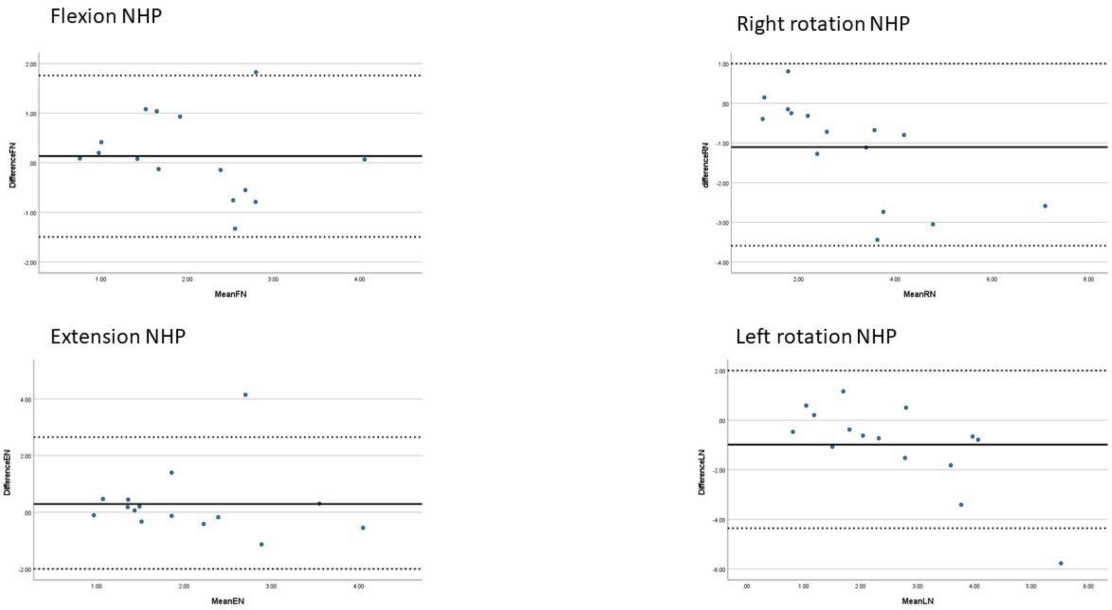

Figure 13, Bland Altman plots for criterion-related validity of absolute error for flexion direction, extension, and right and left rotation for neutral head position (NHP) task in sitting. Limits of agreement are presented as the dotted lines with the mean difference illustrated by the black line.

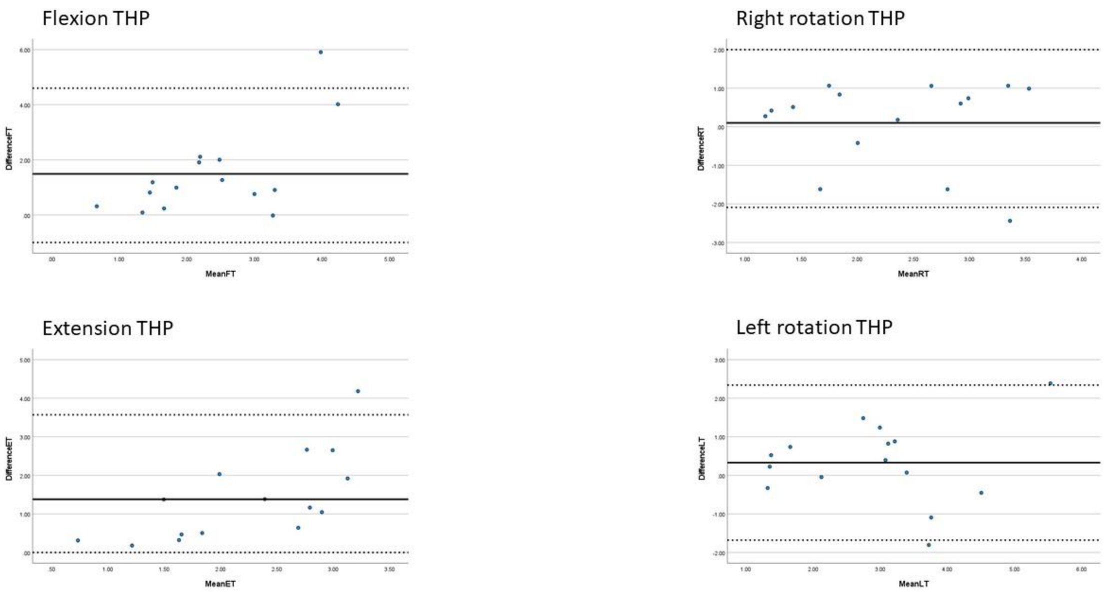

Figure 14, Bland Altman plots for criterion-related validity of absolute error for flexion direction, extension, and right and left rotation for target head position (THP) task in sitting. Limits of agreement are presented as the dotted lines with the mean difference illustrated by the black line.

Bland Altman plots for the limits of agreement for constant JPE measured in sitting show that most of the scores lie between the 95% confidence interval with mean differences -1.92-0.24 for the NHP (Figure 15) and -1.35-0.34 for the THP (Figure 16).

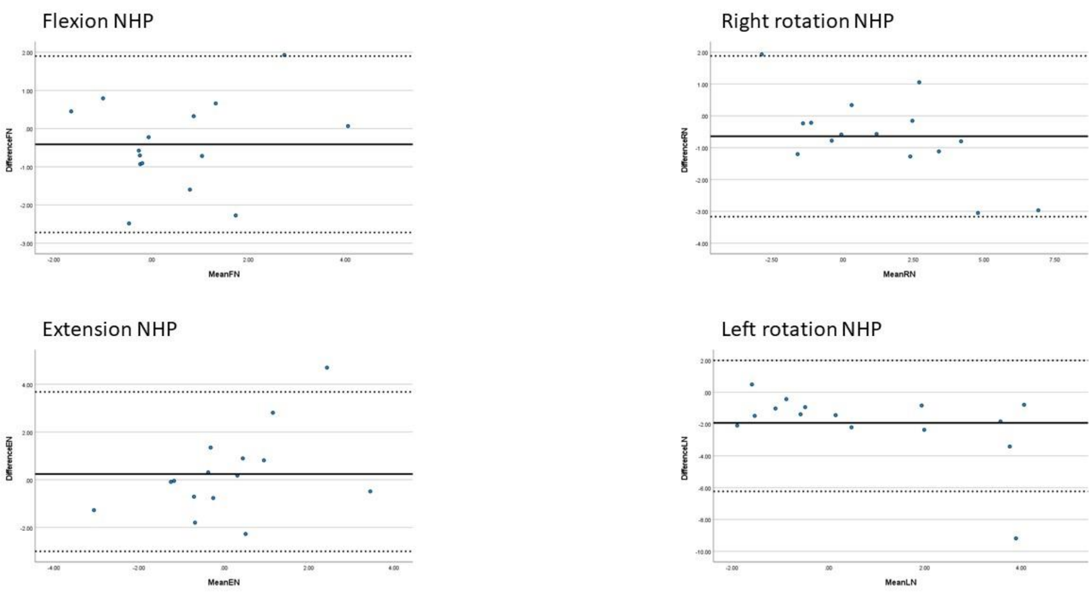

Figure 15, Bland Altman plots for criterion related validity of constant error for flexion direction, extension, and right and left rotation for neutral head position (NHP) task in sitting. Limits of agreement are presented as the dotted lines with the mean difference illustrated by the black line.

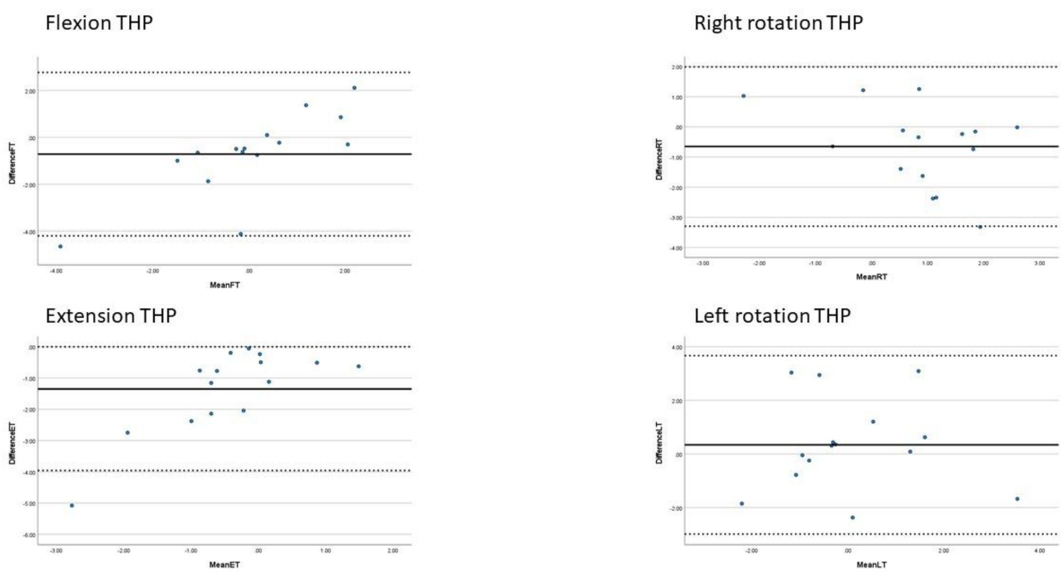

Figure 16, Bland Altman plots for criterion related validity of constant error for flexion direction, extension, and right and left rotation for target head position (THP) task in sitting. Limits of agreement are presented as the dotted lines with the mean difference illustrated by the black line.

Bland Altman plots in standing

Bland Altman plots for the limits of agreement for absolute JPE measured in standing show that most of the scores lie between the 95% confidence interval with mean differences -0.77 to 2.48 for the NHP (Figure 17) and -0.37 to 1.29 for the THP (Figure 18) apart from right rotation in NHP (Figure 17) where the scores are not evenly distributed above and below the mean difference indicating a bias.

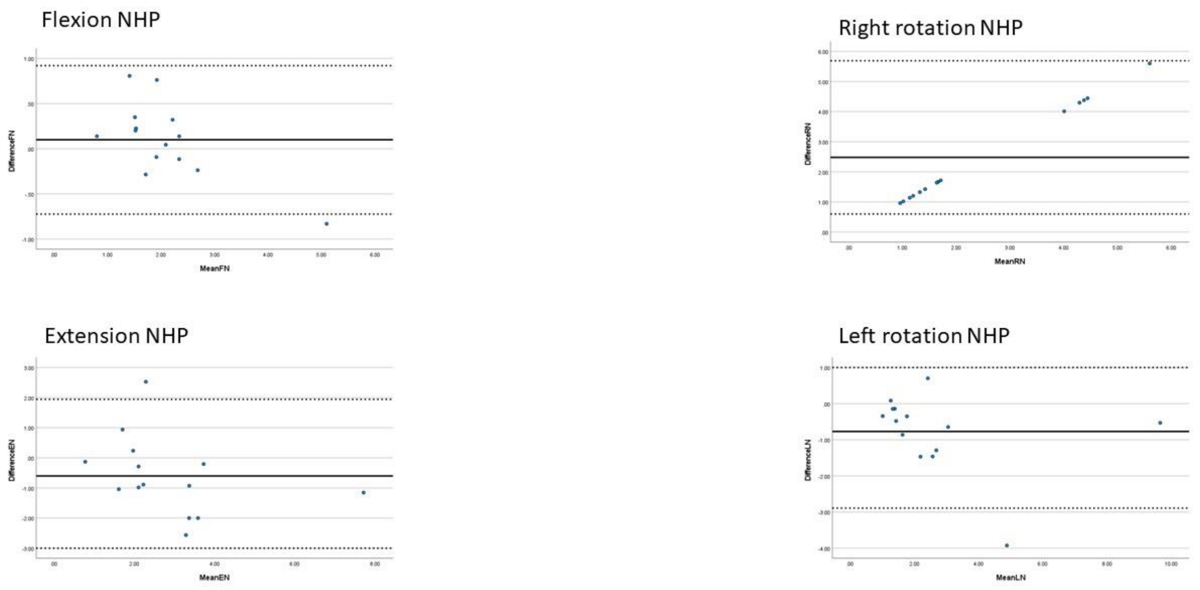

Figure 17, Bland Altman plots for criterion-related validity of absolute error for flexion direction, extension, and right and left rotation for neutral head position (NHP) task in standing. Limits of agreement are presented as the dotted lines with the mean difference illustrated by the black line.

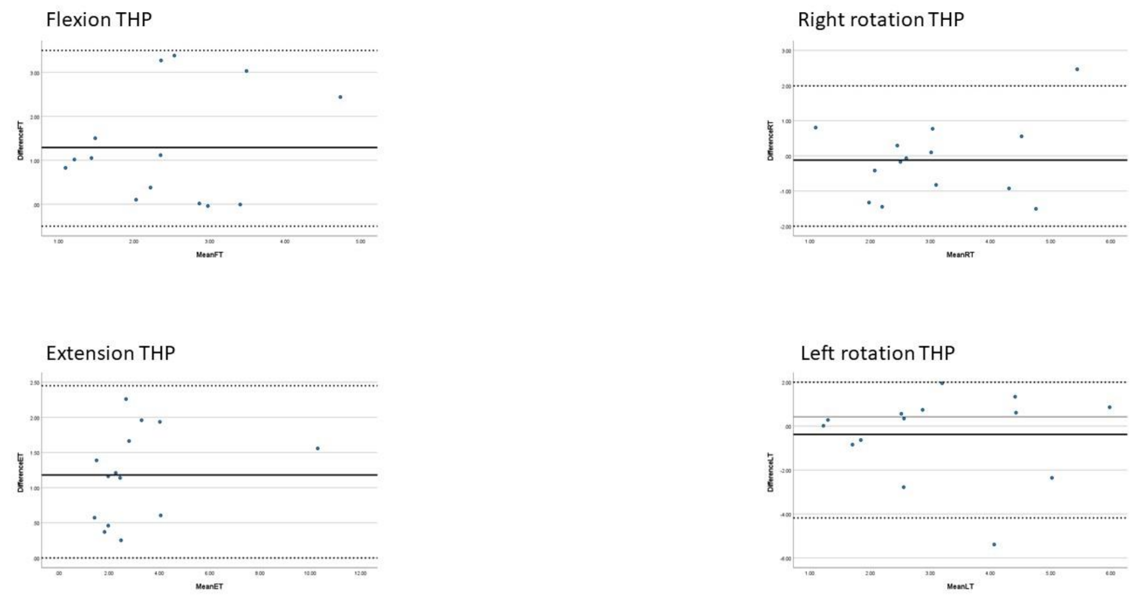

Figure 18, Bland Altman plots for criterion-related validity of absolute error for flexion direction, extension, and right and left rotation for target head position (THP) task in standing. Limits of agreement are presented as the dotted lines with the mean difference illustrated by the black line.

Bland Altman plots for the limits of agreement for constant JPE measured in standing show that most of the scores lie between the 95% confidence interval with mean differences -0.99 to 0.11 for the NHP (Figure 19) and -1.71 to -0.2 for the THP (Figure 20).

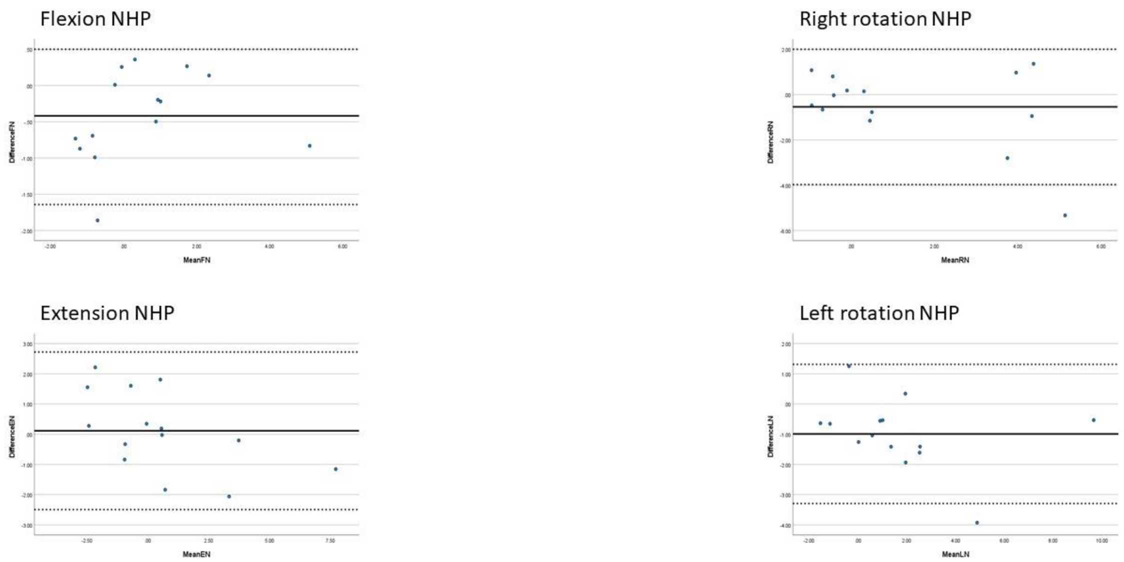

Figure 19, Bland Altman plots for criterion-related validity of constant error for flexion direction, extension, and right and left rotation for neutral head position (NHP) task in standing. Limits of agreement are presented as the dotted lines with the mean difference illustrated by the black line.

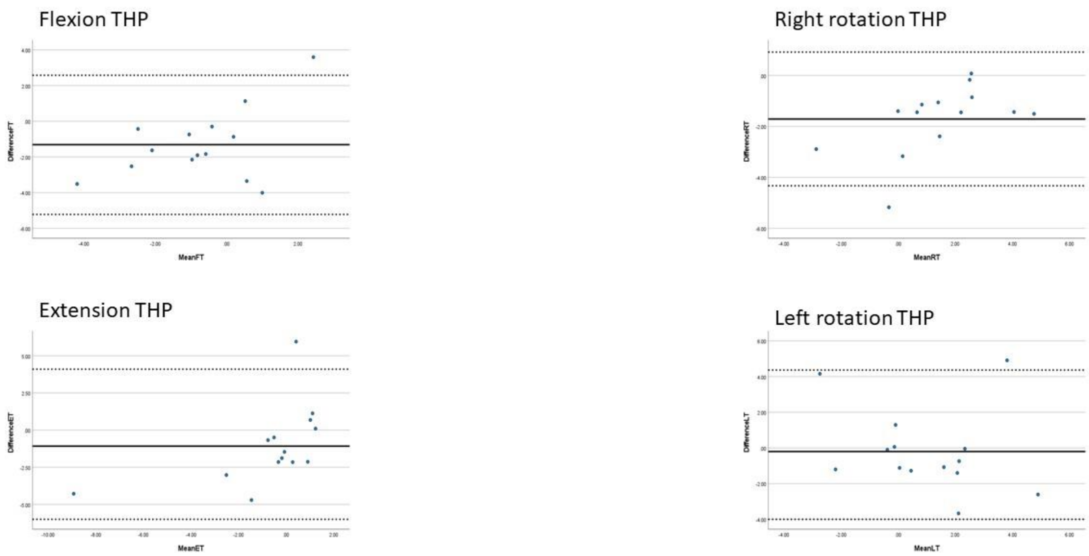

Figure 20, Bland Altman plots for criterion-related validity of constant error for flexion direction, extension, and right and left rotation for target head position (THP) task in standing. Limits of agreement are presented as the dotted lines with the mean difference illustrated by the black line.

Appendix 2. 4. Study 2 demographic data, healthy, total data

No.	Gender	Age	Height	Weight	TSK
1	M	33	168	75	30
2	M	29	181	120	38
3	M	34	171	77	21
4	M	30	171	76	25
5	M	25	175	80	51
6	M	27	180	86	20
7	F	36	158.8	58	38
8	F	19	170	62	43
9	F	28	168	66	37
10	M	34	175	88	41
11	F	42	160	50	39
12	F	22	176	71	34
13	F	19	157	56	26
14	F	21	171	68	24
15	F	19	177	73	35
16	F	21	167	58	35
17	F	20	162.5	43	29
18	F	18	177.8	65	26
19	F	20	167	53	33
20	F	21	165	68	35
21	F	21	169	66	35
22	F	20	161	52	36
23	M	32	185	66	21
		25.69565	170.1348	68.56522	32.69565
	M 8, F 15	6.851906	7.471498	15.98814	7.801135

Appendix 2. 5. Study 2 demographic data, validity (sitting) data

No.	Gender	Age	Height	Weight	TSK
1	M	33	168	75	30
2	M	29	181	120	38
3	M	34	171	77	21
4	M	30	171	76	25
5	M	25	175	80	51
6	M	27	180	86	20
7	F	36	158.8	58	38
8	F	19	170	62	43
9	F	28	168	66	37
10	M	34	175	88	41
11	F	42	160	50	39
12	F	22	176	71	34
13	F	19	157	56	26
14	F	21	171	68	24
15	F	19	177	73	35
		27.86667	170.5867	73.73333	33.46667
	M 8, F 15	7.069721	7.349817	16.72238	8.895157

Appendix 2. 6. Study 2 demographic data, validity, standing data

No.	Gender	Age	Height	Weight	TSK
1	M	33	168	75	30
2	M	29	181	120	38
3	M	34	171	77	21
4	M	30	171	76	25
5	M	25	175	80	51
6	M	27	180	86	20
7	F	36	158.8	58	38
8	F	19	170	62	43
9	F	28	168	66	37
10	M	34	175	88	41
11	F	42	160	50	39
12	F	22	176	71	34
13	F	21	171	68	24
14	F	19	177	73	35
		28.5	171.5571	75	34
	M 8, F 15	6.880854	6.554472	16.59008	8.978607

Appendix 2. 7. Study 2 reliability, healthy, demographic data

No.	Gender	Age	Height	Weight	TSK
1	M	33	168	75	30
2	M	29	181	120	38
3	M	34	171	77	21
4	M	27	180	86	20
5	F	19	170	62	43
6	F	28	168	66	37
7	F	42	160	50	39
8	F	22	176	71	34
9	F	19	177	73	35
10	F	21	167	58	35
11	F	20	162.5	43	29
12	F	18	177.8	65	26
13	F	21	165	68	35
14	F	20	161	52	36
15	M	32	185	66	21
Mean		25.66667	171.2867	68.8	31.93333
SD		6.915361	7.515572	17.39808	6.89412

Appendix 2. 8. Study 2 reliability, healthy, sitting data

Absolute error

No.	flexN1	ExtN1	RtN1	LtN1		FlexT1	ExtT1	RtT1	LtT1
1	2.29061	3.824638	1.060912	1.792561	0	1.792561	2.470674	4.194183	4.542291
2	2.851821	8.323117	3.391339	1.347263	0	2.597749	3.232716	5.26904	2.809483
3	2.820068	1.951546	2.163478	1.697156	0	1.993937	3.761255	3.158674	3.792948
4	2.608338	1.80316	2.978816	0.986663	0	3.50763	5.174338	2.735385	1.59114
5	1.930349	2.280017	1.601742	0.848764	0	1.76076	4.014731	1.972741	4.531747
6	3.518201	1.898554	3.264445	2.396536	0	2.640102	2.809483	4.341905	4.004173
7	2.269423	2.661277	0.944234	1.453303	0	1.834959	3.539341	3.243292	3.454774
8	2.460084	2.491855	0.689638	1.675954	0	1.060912	2.661277	1.718358	2.131692
9	1.935648	0.99727	1.432096	1.739559	0	1.718358	2.444197	2.062817	2.798899
10	2.179371	1.622946	1.182884	1.023788	0	2.470674	3.243292	3.486489	2.618926
11	1.64945	3.592188	0.923019	2.523625	0	3.269733	2.332982	2.280017	2.301203
12	1.50632	2.841237	2.036325	2.205858	0	2.401832	3.87745	4.051684	2.698332
13	1.304845	1.946247	0.732073	0.901804	0	2.110501	1.64945	2.645396	2.449493
14	2.152883	2.385944	1.691856	3.12165	0	3.216851	2.94707	2.53951	2.962943
15	1.002574	2.513035	2.105203	0.93893	0	1.368472	2.258829	2.470674	1.007877

No.	flexN2	ExtN2	RtN2	LtN2		FlexT2	ExtT2	RtT2	LtT2
1	5.468871	2.671865	1.209398	1.379076	0	3.740125	5.395265	2.174074	4.405196
2	2.205858	4.257499	1.485113	2.555394	0	2.280017	6.528779	5.258519	3.243292
3	1.866757	2.152883	2.788313	1.018484	0	1.31545	2.587161	2.205858	2.481265
4	3.465346	2.872989	2.491855	2.089308	0	1.887955	1.940948	3.253869	5.763115
5	2.131692	2.693039	1.686555	0.66842	0	2.449493	3.105781	1.389681	1.665353
6	1.898554	1.739559	2.248235	2.089308	0	3.359619	2.311796	3.72956	1.75016
7	1.622946	2.269423	1.559333	1.336659	0	1.983339	2.777728	1.718358	2.258829
8	2.851821	2.269423	1.909152	2.36476	0	2.513035	4.479023	1.336659	2.671865

9	0.84346	1.707757	1.182884	1.607043	0	1.612344	1.81906	2.555394	1.601742
10	0.779811	1.198792	1.384379	0.684334	0	1.903853	4.56865	2.02043	2.915322
11	1.400285	1.426794	2.152883	2.27472	0	2.438902	2.073414	2.49715	1.54343
12	2.242938	1.007877	1.394983	1.64945	0	1.713058	3.026431	4.014731	4.573921
13	1.47451	1.357868	0.991967	1.734259	0	1.182884	2.205858	1.368472	1.002574
14	0.93893	2.343575	1.522224	2.062817	0	2.851821	1.601742	2.454788	1.893254
15	0.965449	1.585839	1.956845	1.119247	0	3.306746	1.416191	1.575237	2.131692

Constant error

No.	flexN1	ExtN1	RtN1	LtN1		FlexT1	ExtT1	RtT1	LtT1
1	-0.84876	3.824638	-0.14854	0.75329	#DIV/0!	-0.77451	1.453303	4.194183	-4.35245
2	-2.85182	8.323117	2.714212	0.01061	#DIV/0!	2.174074	-2.40713	-3.72956	-2.80948
3	-2.26942	1.951546	0.318307	-1.69716	#DIV/0!	-1.06091	2.174074	-0.63659	1.633548
4	1.485113	-0.06366	0.625985	0.392576	#DIV/0!	-2.66128	1.665353	-0.04244	1.59114
5	-1.37908	1.622946	-1.38968	0.063662	#DIV/0!	0.127324	4.014731	0.657812	-1.08212
6	3.306746	1.64415	2.078712	-1.56994	#DIV/0!	2.640102	-2.76714	2.417719	3.623893
7	1.082125	0.392576	0.498673	-0.22282	#DIV/0!	-0.45623	-2.14229	-0.97606	2.438902
8	2.460084	1.983339	0.477454	1.675954	#DIV/0!	-0.19099	-2.44949	0.679029	-0.15915
9	0.705551	0.488063	-1.4321	-1.73956	#DIV/0!	0.466844	0.132629	-1.49042	-1.18819
10	2.179371	1.135157	0.535806	0.408491	#DIV/0!	-1.80316	-1.76076	-1.4533	-2.40713
11	-0.49337	3.592188	0.785115	-2.52363	#DIV/0!	-0.99197	-0.63659	-2.25883	-2.21645
12	0.148544	0.095493	-0.88059	-1.02909	#DIV/0!	-1.33136	-0.15915	-2.92061	-2.5501
13	1.166975	-1.50102	0.350137	0.519892	#DIV/0!	-1.50632	0.472149	-2.50774	-2.44949
14	-2.15288	2.163478	1.691856	-3.12165	#DIV/0!	3.216851	-1.30484	-0.66312	-2.67716
15	-0.8965	-0.15915	1.161672	0.270561	#DIV/0!	-0.45623	0.190985	-2.01513	-0.43502

No.	flexN2	ExtN2	RtN2	LtN2		FlexT2	ExtT2	RtT2	LtT2

1	5.468871	-2.67186	-0.1061	-0.25465	#DIV/0!	-2.76714	-0.50928	-2.17407	-1.27303
2	-2.07871	4.257499	1.463907	-2.15288	#DIV/0!	0.838156	-4.97432	-4.50011	-3.24329
3	-1.86676	-1.53813	-1.66535	-0.5305	#DIV/0!	0.233426	1.039698	-0.29709	-0.63659
4	0.371356	-1.17758	1.304845	-0.85937	#DIV/0!	-1.37908	1.538128	0.498673	0.201595
5	2.131692	1.357868	-1.47451	-0.07427	#DIV/0!	-0.39258	-2.57657	0.795724	0.328917
6	0.562329	-0.16976	2.248235	1.177581	#DIV/0!	2.301203	-1.54873	1.951546	-0.09549
7	-1.19879	2.163478	-1.55933	1.230609	#DIV/0!	0.328917	-2.37535	1.188187	-0.6472
8	2.851821	2.099905	-0.12732	2.36476	#DIV/0!	-1.11394	3.27502	0.488063	-1.12455
9	-0.84346	-1.70776	0.45093	-1.60704	#DIV/0!	-0.51989	0.366051	-2.25883	-1.4321
10	-0.06897	-0.14854	-0.48276	0.18568	#DIV/0!	0.366051	-0.93893	1.341961	-0.15915
11	-1.36847	0.960145	2.152883	-2.27472	#DIV/0!	-2.4389	-0.93893	-2.33828	1.225306
12	-0.92832	-0.50928	-0.54642	-1.2147	#DIV/0!	-0.90711	-0.92832	-4.01473	0.381966
13	0.785115	0.880588	0.503978	1.469209	#DIV/0!	-0.18568	-0.77451	-0.39258	-0.66312
14	0.93893	1.262425	0.249341	-1.93565	#DIV/0!	1.209398	-0.49867	0.355441	1.81906
15	0.615375	-0.83285	0.928323	-0.32361	#DIV/0!	0.148544	0.535806	-0.4191	-0.61538

Appendix 2. 9. Study 2r reliability, healthy, standing data

Absolute error

No.	flexN1	ExtN1	RtN1	LtN1		FlexT1	ExtT1	RtT1	LtT1
1	3.623893	3.095202	2.777728	2.915322	0	3.042302	2.999979	3.285596	3.43363
2	2.745971	2.163478	3.211562	1.76076	0	2.174074	1.27303	3.084622	2.703626
3	1.241214	1.930349	1.75016	0.912411	0	1.262425	1.930349	1.675954	1.379076
4	1.59114	1.135157	1.654751	1.50632	0	1.940948	3.57105	2.523625	1.781961
5	1.071518	2.671865	0.647203	1.59114	0	1.368472	3.021141	1.654751	2.068116
6	3.306746	2.915322	0.848764	0.774507	0	2.375352	1.410889	1.283635	3.63446
7	2.089308	1.029091	0.75329	1.135157	0	1.209398	3.243292	2.523625	2.94707
8	1.379076	0.832852	1.368472	2.311796	0	1.50632	0.838156	2.719505	2.52892
9	1.421492	1.569936	1.988638	2.407128	0	1.797861	5.195386	1.81376	2.179371
10	2.147585	2.544804	1.856158	3.602756	0	3.079332	3.491774	3.946097	2.158181
11	2.253532	1.702457	2.380648	2.682452	0	2.878281	2.745971	2.412423	1.182884
12	2.036325	0.832852	0.488063	1.400285	0	1.554032	1.903853	1.485113	2.004534
13	1.64945	2.682452	1.304845	0.594157	0	0.960145	1.76606	3.951377	2.51833
14	1.204095	2.82536	1.914452	1.018484	0	2.036325	2.767143	1.045002	2.42831
15	1.654751	1.230609	1.188187	2.412423	0	8.976441	1.930349	2.041624	2.417719

No.	flexN2	ExtN2	RtN2	LtN2		FlexT2	ExtT2	RtT2	LtT2
1	2.65069	5.258519	2.820068	2.862405	0	3.75069	3.539341	2.417719	2.015131
2	1.993937	1.718358	1.686555	2.078712	0	1.198792	2.597749	3.354332	2.51833
3	0.93893	0.901804	1.151066	0.954841	0	1.108641	2.47597	1.4427	1.002574
4	2.994688	2.295907	2.957652	1.347263	0	1.840259	1.983339	1.999235	2.65069
5	1.538128	1.713058	0.81694	0.615375	0	2.189966	4.76891	1.665353	1.834959
6	3.343758	3.692579	1.940948	1.225306	0	3.63446	4.974319	2.645396	3.798229
7	1.898554	2.62422	1.262425	2.47597	0	1.81906	3.444203	1.999235	2.576572
8	2.02043	1.596441	0.572939	1.935648	0	0.954841	2.841237	2.052221	1.548731

9	1.866757	2.094606	1.214701	1.903853	0	1.612344	4.06752	1.930349	2.269423
10	2.131692	3.037012	1.713058	2.640102	0	2.968234	1.214701	2.269423	2.719505
11	1.872057	1.686555	1.379076	1.469209	0	4.099189	2.370056	2.735385	3.412485
12	1.055608	2.359464	1.485113	1.357868	0	1.903853	2.338279	1.511621	1.951546
13	2.099905	1.580538	0.710856	1.511621	0	1.389681	1.288938	4.225842	2.401832
14	2.327686	1.453303	1.023788	1.310147	0	1.426794	1.495717	1.501018	1.956845
15	1.27303	1.781961	1.617645	1.893254	0	2.009833	2.110501	2.920614	2.385944

Constant error

No.	flexN1	ExtN1	RtN1	LtN1		FlexT1	ExtT1	RtT1	LtT1
1	2.227047	3.095202	1.80316	-1.53813	#DIV/0!	-1.07152	-0.24404	-3.24329	-1.90915
2	-2.74597	-0.44562	1.792561	-0.57294	#DIV/0!	-0.39258	0.084883	-2.17407	-0.28648
3	-1.24121	1.209398	-1.00788	0.297087	#DIV/0!	-0.9018	-1.71836	-1.67595	-1.2094
4	0.954841	0.435015	0.445625	-0.12732	#DIV/0!	-1.36847	1.983339	1.25182	0.318307
5	-0.05305	1.59114	-0.13793	-0.65781	#DIV/0!	0.859372	-1.83496	0.742681	1.368472
6	-0.19099	2.576572	-0.38197	-0.66842	#DIV/0!	0.106103	-0.66842	0.413796	0.244036
7	-0.6472	-0.51989	0.413796	1.135157	#DIV/0!	0.063662	0.55172	0.806332	2.036325
8	0.562329	0.005305	-1.32605	-2.19526	#DIV/0!	-0.13793	-0.13793	-1.68125	-1.07682
9	-0.28648	-1.34726	1.988638	-1.37908	#DIV/0!	0.366051	-3.02114	0.127324	-0.03714
10	2.147585	-0.95484	1.389681	-3.39134	#DIV/0!	-3.07933	0.599462	-3.9461	1.204095
11	-1.87206	-1.47981	-2.12639	0.286477	#DIV/0!	-0.98136	-1.14576	-1.12985	-0.30239
12	1.612344	0.514587	-0.25465	1.220003	#DIV/0!	-1.45861	0.026526	-0.57294	0.286477
13	-1.00257	1.654751	0.901804	0.233426	#DIV/0!	0.482759	-0.25995	-1.14576	0.132629
14	-0.80103	2.82536	1.914452	-0.66842	#DIV/0!	2.036325	-0.16976	0.355441	2.42831
15	-0.48806	-0.33953	1.103338	0.291782	#DIV/0!	-8.97644	-1.56994	0.493368	-2.41772

No.	flexN2	ExtN2	RtN2	LtN2		FlexT2	ExtT2	RtT2	LtT2

1	0.381966	5.258519	2.248235	-2.86241	#DIV/0!	-1.08212	-2.84124	2.417719	-0.63659
2	-1.08212	-1.35787	-0.79572	-2.07871	#DIV/0!	-1.17758	-1.98334	-1.81906	-1.31015
3	-0.93893	-0.9018	-1.09803	-0.95484	#DIV/0!	-1.10864	-2.47597	-1.4427	-0.81164
4	2.994688	0.015915	2.280017	-0.21221	#DIV/0!	-1.045	-0.68964	-0.53581	0.403186
5	0.01061	0.482759	0.222816	-0.31831	#DIV/0!	1.246517	-3.5869	0.923019	-0.66842
6	-0.75859	2.804191	1.940948	-0.44032	#DIV/0!	0.031831	-2.39654	1.734259	1.532827
7	-1.58054	0.864676	-0.42441	2.433606	#DIV/0!	0.153849	-2.36476	0.19629	-1.34726
8	-1.62825	-0.33422	0.159155	-1.93565	#DIV/0!	-0.27587	-0.80633	-0.2069	-0.6472
9	-1.50632	0.42971	-0.70555	-1.72366	#DIV/0!	0.509282	-4.06752	-1.93035	0.912411
10	1.622946	1.797861	-0.32361	-2.19526	#DIV/0!	-2.44949	-0.44032	-0.72146	2.380648
11	0.503978	-1.32605	-0.44562	0.557025	#DIV/0!	-2.57657	-2.37006	-0.25465	-1.08212
12	0.397881	-0.25995	0.127324	1.262425	#DIV/0!	-1.32075	1.426794	0.037136	-1.95155
13	-2.0999	1.580538	0.456235	-1.47981	#DIV/0!	-1.17758	-0.98136	-3.22214	1.36317
14	-2.32769	1.007877	0.419101	-0.39788	#DIV/0!	1.405587	0.721464	-0.09019	1.458605
15	0.66842	-1.78196	0.19629	1.893254	#DIV/0!	-1.10864	-0.71086	1.501018	-1.82436

Appendix 2. 10. Study 2 Sitting versus standing data

Sitting

Healthy participants (absolute error)

No.	Flexion	Extension	Rt rotation	Lt rotation
1	2.29061	3.824638	1.060912	1.792561
2	1.887955	3.771819	5.805125	2.629514
3	2.820068	1.951546	2.163478	1.697156
4	1.007877	0.976056	0.891196	1.81376
5	2.089308	3.412485	9.369385	5.247998
6	2.608338	1.80316	2.978816	0.986663
7	1.453303	1.707757	2.216453	1.304845
8	1.930349	2.280017	1.601742	0.848764
9	3.518201	1.898554	3.264445	2.396536
10	2.862405	1.463907	2.936487	1.389681
11	2.269423	2.661277	0.944234	1.453303
12	2.460084	2.491855	0.689638	1.675954
13	1.877356	1.448002	2.968234	2.280017
14	3.111071	2.317093	1.850858	1.066215
15	1.935648	0.99727	1.432096	1.739559
16	2.179371	1.622946	1.182884	1.023788
17	1.64945	3.592188	0.923019	2.523625
18	1.50632	2.841237	2.036325	2.205858
19	2.189966	2.099905	5.563482	1.559333
20	1.304845	1.946247	0.732073	0.901804
21	2.13699	1.357868	2.200561	2.338279

Healthy participants (constant error)

No.	Flexion	Extension	Rt rotation	Lt rotation
1	-0.84876	3.824638	-0.14854	0.75329
2	-2.85182	8.323117	2.714212	0.01061
3	-2.26942	1.951546	0.318307	-1.69716
4	-0.45623	-0.14854	-0.16976	1.686555
5	0.435015	-3.41249	9.369385	5.247998
6	1.485113	-0.06366	0.625985	0.392576
7	-1.32605	-0.54111	-1.51692	0.413796
8	-1.37908	1.622946	-1.38968	0.063662
9	3.306746	1.64415	2.078712	-1.56994
10	-2.03633	1.039698	0.244036	-1.19879
11	1.082125	0.392576	0.498673	-0.22282
12	2.460084	1.983339	0.477454	1.675954
13	-1.87736	-0.29178	-2.96823	-2.28002
14	2.401832	1.893254	-0.66312	-0.4191
15	0.705551	0.488063	-1.4321	-1.73956
16	2.179371	1.135157	0.535806	0.408491
17	-0.49337	3.592188	0.785115	-2.52363
18	0.148544	0.095493	-0.88059	-1.02909
19	2.041624	2.099905	5.563482	-1.15637
20	1.166975	-1.50102	0.350137	0.519892
21	-1.38438	-0.13793	2.200561	2.13699

22	2.152883	2.385944	1.691856	3.12165
23	1.002574	2.513035	2.105203	0.93893
Average	2.097582	2.233252	2.461239	1.866774
SD	0.630955	0.827803	2.023344	0.969123

22	-2.15288	2.163478	1.691856	-3.12165
23	-0.8965	-0.15915	1.161672	0.270561
avg	-0.02431	1.130168	0.845498	-0.14686
SD	1.786932	2.239115	2.535683	1.814266

Standing

Healthy participants (absolute error)

No.	Flexion	Extension	Rt rotation	Lt rotation
1	1.654751	2.142288	1.230609	4.468477
2	3.623893	3.095202	2.777728	2.915322
3	2.745971	2.163478	3.211562	1.76076
4	1.241214	1.930349	1.75016	0.912411
5	5.721098	3.888012	4.489569	5.983598
6	1.59114	1.135157	1.654751	1.50632
7	0.848764	1.379076	0.66842	3.063463
8	1.071518	2.671865	0.647203	1.59114
9	3.306746	2.915322	0.848764	0.774507
10	3.063463	3.602756	4.753104	6.528779
11	2.089308	1.029091	0.75329	1.135157
12	2.724799	2.883573	2.42831	0.880588
13	1.850858	1.681255	2.009833	2.126394
14	1.379076	0.832852	1.368472	2.311796
15	1.421492	1.569936	1.988638	2.407128
16	2.147585	2.544804	1.856158	3.602756
17	2.253532	1.702457	2.380648	2.682452
18	0.477454	3.454774	3.523486	1.564635
19	2.036325	0.832852	0.488063	1.400285

Healthy participants (constant error)

No.	Flexion	Extension	Rt rotation	Lt rotation
1	-1.0397	-0.42441	-0.59416	-4.46848
2	2.227047	3.095202	1.80316	-1.53813
3	-2.74597	-0.44562	1.792561	-0.57294
4	-1.24121	1.209398	-1.00788	0.297087
5	-5.7211	3.888012	4.489569	5.983598
6	0.954841	0.435015	0.445625	-0.12732
7	-0.70025	0.445625	0.053052	-2.15288
8	-0.05305	1.59114	-0.13793	-0.65781
9	-0.19099	2.576572	-0.38197	-0.66842
10	2.597749	3.49706	3.740125	4.637173
11	-0.6472	-0.51989	0.413796	1.135157
12	2.36476	0.954841	2.385944	0.435015
13	1.119247	0.132629	0.663116	-1.57524
14	0.562329	0.005305	-1.32605	-2.19526
15	-0.28648	-1.34726	1.988638	-1.37908
16	2.147585	-0.95484	1.389681	-3.39134
17	-1.87206	-1.47981	-2.12639	0.286477
18	-0.32892	3.454774	3.01585	-1.18288
19	1.612344	0.514587	-0.25465	1.220003

20	1.64945	2.682452	1.304845	0.594157
21	1.204095	2.82536	1.914452	1.018484
22	1.654751	1.230609	1.188187	2.412423
avg	2.079877	2.190615	1.965284	2.34732
SD	1.141107	0.925385	1.186929	1.602284

20	-1.00257	1.654751	0.901804	0.233426
21	-0.80103	2.82536	1.914452	-0.66842
22	-0.48806	-0.33953	1.103338	0.291782
avg	-0.16058	0.944041	0.92144	-0.27539
SD	1.900458	1.660063	1.647378	2.285109

Appendix 2. 11. Study 2 validity, sitting data

Absolute error

Laser

No.	flexN1	ExtN1	RtN1	LtN1		FlexT1	ExtT1	RtT1	LtT1
1	2.311796	0.912411	2.841237	1.283635	0	0.827548	1.304845	1.4427	3.528771
2	1.887955	3.771819	5.805125	2.629514	0	3.264445	3.01056	2.280017	4.278602
3	2.396536	1.347263	2.227047	1.951546	0	3.137518	4.099189	1.993937	3.655595
4	1.071518	1.4427	1.728959	2.057519	0	1.781961	0.891196	0.859372	2.099905
5	1.209398	3.697862	3.782384	3.666162	0	6.245846	4.088633	3.87745	3.613325
6	4.088633	1.792561	1.75016	2.015131	0	3.158674	3.423058	3.190408	3.27502
7	0.795724	1.580538	1.707757	0.965449	0	2.089308	3.084622	2.449493	1.633548
8	1.601742	2.301203	1.060912	0.572939	0	3.253869	2.089308	3.359619	3.486489
9	2.057519	4.774179	3.232716	3.63446	0	3.486489	4.320805	2.258829	6.727689
10	2.152883	2.015131	3.253869	2.671865	0	1.389681	1.887955	3.222139	1.463907
11	2.163478	1.59114	1.368472	1.336659	0	6.936892	2.184669	4.02529	2.025728
12	3.708428	2.555394	2.385944	1.728959	0	2.343575	5.311121	1.792561	3.211562
13	1.458605	1.463907	1.909152	1.612344	0	3.380766	1.792561	1.681255	1.156369
14	2.396536	2.317093	2.036325	3.047592	0	3.755972	3.375479	2.142288	2.820068
15	2.380648	1.304845	2.189966	2.27472	0	1.861458	3.006327	1.31545	3.428344
Mean	2.112093	2.191203	2.485335	2.096566	0	3.1276	2.924689	2.39272	3.093662
SD	0.8604	1.056599	1.145142	0.880073	0	1.597391	1.189695	0.918877	1.327718

Noraxon

No.	flexN2	ExtN2	RtN2	LtN2		FlexT2	ExtT2	RtT2	LtT2

1	2.45706	1.018384	3.956251	1.080697	0	0.512535	1.124445	1.023052	2.705265
2	3.217108	4.322429	8.393405	8.40139	0	3.285657	2.369912	1.21478	4.731531
3	2.9472	1.67483	2.94595	2.682117	0	1.22922	1.433844	3.613944	2.775473
4	0.872519	1.262409	1.978856	5.468426	0	1.548016	0.5785	2.477396	2.144313
5	0.793456	3.394031	4.581382	4.454058	0	2.228581	2.168414	2.813392	2.373414
6	4.02139	1.918995	3.02524	3.540116	0	1.891758	2.376271	2.129446	2.879204
7	0.709202	1.135441	1.857496	2.039073	0	0.902801	1.701302	2.270274	1.110237
8	1.729107	2.477354	1.457904	1.044798	0	1.142844	1.584864	2.620667	2.004238
9	0.976504	0.628139	3.909148	4.292526	0	1.483324	1.670108	1.422609	4.343255
10	2.909092	2.430626	6.304066	4.489936	0	1.301649	1.420269	2.619895	1.238453
11	1.124053	1.383784	1.221026	0.750122	0	1.02972	0.809648	3.03658	1.288289
12	1.882161	1.156556	5.12312	2.35044	0	1.351823	1.129293	2.213293	4.303752
13	1.379644	1.399653	5.351063	1.993356	0	2.62247	1.471209	1.170285	1.48488
14	3.184712	3.452399	2.35189	2.543743	0	2.849839	2.211015	4.580804	4.623958
15	1.448885	0.83448	1.384511	1.113478	0	1.048982	0.975042	1.041601	3.357294
Mean	1.976806	1.899301	3.58942	3.082952	0	1.628615	1.534942	2.283201	2.75757
SD	1.028888	1.057261	1.999926	2.004275	0	0.762795	0.543239	0.981239	1.226204

Constant error

Laser

No.	flexN1	ExtN1	RtN1	LtN1		FlexT1	ExtT1	RtT1	LtT1
1	-0.59416	0.403186	2.841237	-1.09273	#DIV/0!	-0.50928	-0.09549	-1.01848	-0.18038
2	0	3.200985	5.426812	-0.70025	#DIV/0!	1.909152	-0.50928	-0.18038	2.693039
3	-1.42149	1.347263	0.488063	-1.61234	#DIV/0!	1.877356	-3.31732	0.275866	1.919751
4	-0.68964	0.891196	-1.51692	2.057519	#DIV/0!	-1.78196	-0.21221	-0.09549	-1.08212
5	1.039698	-3.69786	3.782384	3.666162	#DIV/0!	-6.24585	0.615375	2.587161	1.347263

6	4.088633	-0.62598	1.75016	0.806332	#DIV/0!	-2.22705	1.177581	1.77136	-0.92302
7	-0.58355	-1.58054	-1.22	-0.62598	#DIV/0!	-0.32892	-1.24121	0.095493	-0.08488
8	-0.54111	-1.19879	-0.33953	-0.57294	#DIV/0!	3.253869	-1.77136	1.495717	-0.07427
9	-1.69716	4.774179	3.232716	-1.34726	#DIV/0!	2.343575	-2.18467	1.47451	-3.12694
10	0.604766	-1.29424	3.253869	2.65069	#DIV/0!	0.519892	-1.25182	-0.02122	-1.46391
11	-0.63659	0.360746	-0.77451	-0.95484	#DIV/0!	-1.38968	-0.40319	1.4427	1.135157
12	3.708428	2.555394	2.385944	1.516923	#DIV/0!	-0.2016	-5.31112	0.456235	3.021141
13	-0.16446	-0.63659	-1.88796	-1.27303	#DIV/0!	-1.98334	-0.16976	0.663116	-0.96545
14	0.689638	-0.21751	0.912411	-2.94178	#DIV/0!	0.42971	-1.00257	-1.77136	0.350137
15	1.660052	-1.06091	-2.18997	-2.27472	#DIV/0!	-0.44032	-1.27939	0.498673	0.885892
Mean	0.364204	0.214701	1.076314	-0.17988	#DIV/0!	-0.3183	-1.13043	0.511593	0.230094
SD	1.632034	2.049945	2.283011	1.832051	#DIV/0!	2.247921	1.548655	1.083108	1.595895

Noraxon

No.	flexN2	ExtN2	RtN2	LtN2		FlexT2	ExtT2	RtT2	LtT2
1	-1.38808	0.227626	3.956251	-0.6597	0	-0.0145	0.140016	-0.37185	-0.48715
2	1.597184	3.68846	8.393405	8.485215	0	2.210308	-0.31597	1.21478	4.369915
3	-1.87428	0.53289	0.147377	-0.59161	0	0.506841	-0.57002	3.595381	1.296281
4	0.240361	-0.00373	-1.28332	5.468426	0	0.090497	0.282993	2.27951	1.291645
5	0.712323	-2.42431	4.581382	4.454058	0	-1.59184	1.124944	2.603013	1.25868
6	4.02139	1.645596	3.02524	3.168093	0	1.891758	1.802029	1.9266	-0.6774
7	0.118287	0.2173	-1.00479	1.580035	0	0.148005	0.799961	1.723563	-0.52032
8	0.033231	-1.15174	0.245134	0.868528	0	1.142844	0.368571	1.731916	-0.43006
9	0.785371	0.076237	2.174257	-1.83535	0	1.483324	0.192565	0.219692	-1.27371
10	2.878181	-1.20559	6.304066	4.489936	0	0.746466	-0.49131	2.323778	-0.68187
11	0.269343	-0.98842	0.003584	-0.01639	0	-0.73551	0.716224	2.182791	-0.07058
12	1.779677	-0.25262	2.539224	2.35044	0	0.550072	-0.23256	-0.75862	-0.07098
13	0.059436	0.130558	-3.82219	0.112744	0	-0.98775	-0.11531	1.007987	-0.917
14	1.405222	-0.52629	1.483327	-0.84983	0	0.330556	-0.22892	-2.79711	-2.68745
15	0.999477	-0.35057	-0.98894	-0.7912	0	0.181797	-0.12309	0.616523	-2.05975
Mean	0.775808	-0.02564	1.716934	1.748892	0	0.396857	0.223342	1.16653	-0.11065

SD	1.43369	1.336828	3.092641	2.832531	0	0.998266	0.631991	1.544688	1.62071

Appendix 2. 12. Study 2 validity, standing data

Absolute error

Laser

No.	flexN1	ExtN1	RtN1	LtN1		FlexT1	ExtT1	RtT1	LtT1
1	2.407128	2.904739	4.447385	1.31545	0	3.401913	2.608338	2.682452	1.166975
2	2.110501	3.623893	3.391339	2.767143	0	2.957652	4.278602	6.67536	4.732029
3	2.565983	2.587161	1.75016	2.724799	0	2.407128	4.363003	3.423058	5.079608
4	1.686555	1.962144	1.866757	1.188187	0	1.50632	1.718358	1.31545	2.798899
5	4.679334	2.36476	3.401913	9.390042	0	5.952111	11.07509	3.845764	6.413548
6	2.280017	0.710856	1.209398	2.915322	0	2.872989	2.205858	2.565983	1.527525
7	0.86998	1.781961	1.029091	1.304845	0	1.962144	2.205858	1.866757	1.283635
8	1.64415	1.612344	1.463907	1.453303	0	4.225842	4.99538	4.004173	3.243292
9	1.81376	2.004534	0.75329	1.198792	0	5.005909	2.555394	1.495717	4.173075
10	2.301203	3.549911	5.058553	2.036325	0	3.993614	3.814075	4.795252	1.368472
11	1.866757	1.092731	1.241214	0.838156	0	1.718358	3.63446	2.417719	2.735385
12	1.569936	7.135463	4.078076	1.834959	0	2.237641	2.015131	3.063463	3.845764
13									
14	2.375352	2.089308	1.193489	1.25182	0	2.078712	3.01585	1.47451	1.230609
15	1.622946	2.174074	1.299542	1.59114	0	2.910031	2.878281	2.597749	1.437398
16									
17									

Noraxon

No.	flexN2	ExtN2	RtN2	LtN2		FlexT2	ExtT2	RtT2	LtT2
1	2.268969	3.831202	3.573594	1.455883	0	3.409923	2.35738	3.50899	3.946131
2	2.065757	3.829974	5.200346	2.065595	0	2.9985	2.319502	4.211987	4.119541

3	2.803382	4.585849	1.681015	3.370905	0	2.029014	3.757487	2.652489	3.741445
4	1.337022	2.247915	1.464457	1.669102	0	0.679589	1.146194	2.643629	2.235776
5	5.509853	4.363344	7.797828	9.92171	0	3.512644	9.517412	4.772556	5.553504
6	2.394909	0.841142	2.072373	6.84154	0	2.857088	0.817526	2.632199	2.160346
7	0.731591	2.669571	1.623931	1.220879	0	0.911465	1.7463	2.283287	2.125681
8	1.417929	2.595686	1.38829	2.921024	0	0.842923	3.059495	5.510455	2.501216
9	1.006812	4.568378	1.168392	2.05998	0	1.973248	1.393649	0.689945	2.220324
10	1.539106	1.022749	3.698842	3.327317	0	0.721855	1.554076	4.240749	6.757102
11	1.958558	2.134166	0.796778	1.182606	0	0.701831	1.971802	2.588185	2.388999
12	1.854675	8.289413	4.813244	3.296904	0	0.735538	1.644976	2.964911	6.201289
13									
14	2.054222	1.851529	1.211795	1.395928	0	1.97617	1.876783	2.922458	1.212927
15	1.421511	1.235713	0.97786	1.941262	0	1.793688	1.668751	2.304222	1.154941
16									
17									

Constant error

Laser

No.	flexN1	ExtN1	RtN1	LtN1		FlexT1	ExtT1	RtT1	LtT1
1	2.407128	-2.29061	4.447385	0.063662	#DIV/0!	-2.70363	1.357868	2.152883	0.275866
2	0.901804	3.623893	2.354167	2.110501	#DIV/0!	-1.00788	-1.12455	-4.3208	1.368472
3	-0.23343	-1.06091	-0.11671	-1.85616	#DIV/0!	-0.24404	3.391339	-1.4321	2.311796
4	-1.68656	0.116713	-0.42441	0.742681	#DIV/0!	-1.50632	-1.40028	0.254646	-2.7989
5	4.679334	2.301203	2.470674	9.390042	#DIV/0!	-5.95211	-11.0751	3.338471	6.266815
6	-1.28364	0.562329	-0.40319	2.915322	#DIV/0!	-1.11394	-0.80633	0.86998	1.060912
7	0.488063	-0.21221	0.116713	-0.60477	#DIV/0!	-1.77136	-1.10334	-0.06366	-0.43502

8	-1.64415	-1.10334	0	0.986663	#DIV/0!	4.225842	-4.02529	4.004173	1.76076
9	-1.19879	-1.70776	-0.03183	0.647203	#DIV/0!	-3.93026	1.283635	-0.71086	0.55172
10	0.838156	1.410889	5.058553	1.718358	#DIV/0!	-2.04692	-3.81407	-2.91532	-0.66842
11	-1.63355	0.095493	-1.00788	0.625985	#DIV/0!	1.082125	-0.15915	2.417719	-0.19099
12	0.636594	7.135463	3.866888	1.834959	#DIV/0!	-0.56233	-0.80633	2.597749	3.592188
13									
14	1.866757	0.647203	0.387271	0.254646	#DIV/0!	-1.42149	1.670653	1.47451	-0.1061
15	0.074272	-1.37908	-1.17228	-1.47451	#DIV/0!	-2.91003	-0.75859	0.254646	-0.51459
16									
17									

Noraxon

No.	flexN2	ExtN2	RtN2	LtN2		FlexT2	ExtT2	RtT2	LtT2
1	2.268969	-2.56794	3.475056	1.102885	0	-2.2741	0.673941	3.009184	3.946131
2	1.120494	3.829974	5.153816	1.766755	0	2.9985	0.761055	-1.42911	2.76967
3	-0.24377	-3.27561	1.032635	-1.22165	0	0.623435	-2.56154	1.737924	2.35666
4	-0.95502	-0.23045	-0.39297	1.277132	0	0.328218	0.745673	2.643629	-1.59698
5	5.509853	4.363344	7.797828	9.92171	0	-2.44047	-6.79815	4.772556	1.356052
6	-0.2935	0.586738	-1.48027	6.84154	0	2.236874	0.660175	1.928137	2.136251
7	0.129244	1.623899	0.890998	0.651813	0	0.128285	-0.42925	1.38027	-0.33248
8	0.215293	-0.77452	-0.18207	2.921024	0	0.630762	-1.00501	5.510455	2.501216
9	-0.50633	-3.26313	-0.83457	2.05998	0	-1.40946	1.181804	0.689945	-0.7414
10	1.034511	-0.39717	3.698842	3.327317	0	0.100775	0.890001	2.257498	-4.8265
11	-0.76243	-1.50884	-0.3467	1.182606	0	-0.04956	1.971802	2.588185	1.086339
12	1.132969	8.289413	4.813244	3.244839	0	-0.2672	1.348397	2.522124	6.201289
13									
14	1.600715	0.457437	0.240818	-0.99709	0	-0.68595	0.543612	2.922458	-0.16499
15	-0.18189	-0.54102	-0.69847	-0.82112	0	-1.28121	-0.26465	1.398222	0.602723
16									
17									

Appendix 3. 1. Study 3 ethical approval

Application for Ethical Review ERN_22-0269

SC Susan Cottam (Research Support Services)
To Deborah Falla (Sport, Exercise and Rehabilitation Sciences)
Cc Ahmad Aldahas (PhD Physiotherapy FT)
Flag for follow up.
Action Items

Reply | Reply All | Forward | ...
Tue 02/08/2022 12:31

Get more add-ins

Dear Professor Falla

Re: "Responsiveness of tests of sensorimotor control in adults with neck pain"
Application for Ethical Review ERN_22-0269

Thank you for your application for ethical review for the above project, which was reviewed by the Science, Technology, Engineering and Mathematics Ethical Review Committee.

On behalf of the Committee, I confirm that this study now has full ethical approval.

Appendix 3. 2. Study 3 publication

Notification of Formal Acceptance for PONE-D-24-09461R1 - [EMID:53a2bbbaa779d91c]

PO em.pone.0.8b0bbe.cb5ebf86@editorialmanager.com on behalf of PLOS ONE <em@editorialmanage
To Ahmad Aldahas (PhD Physiotherapy FT)
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You are being carbon copied ("cc:'d") on an e-mail "To" "Deborah Falla" d.falla@bham.ac.uk
CC: aaa895@student.bham.ac.uk, vxd823@student.bham.ac.uk, j.deane@bham.ac.uk

PONE-D-24-09461R1
PLOS ONE

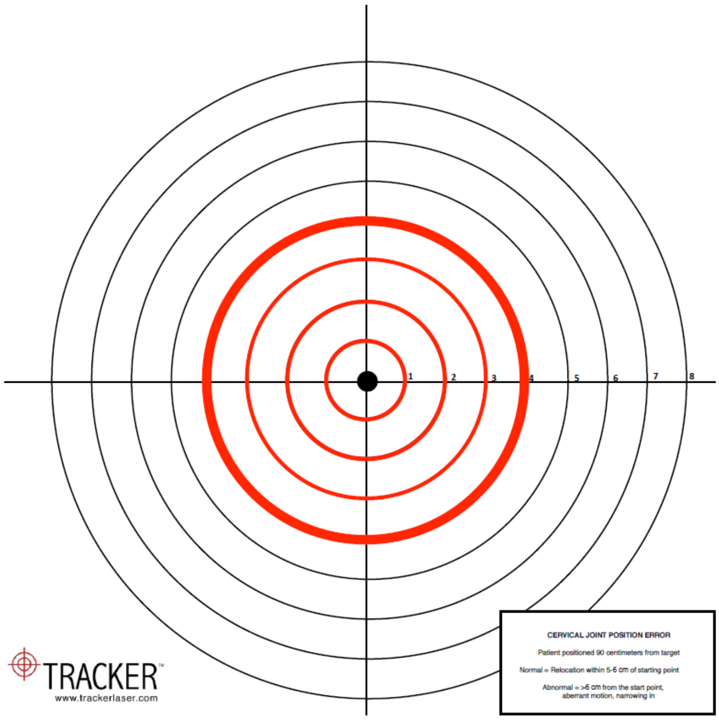
Dear Dr. Falla,

I'm pleased to inform you that your manuscript has been deemed suitable for publication in PLOS ONE. Congratulations! Your manuscript is now being handed over to our production team.

Appendix 3. 3. Study 3 four weeks proprioception training

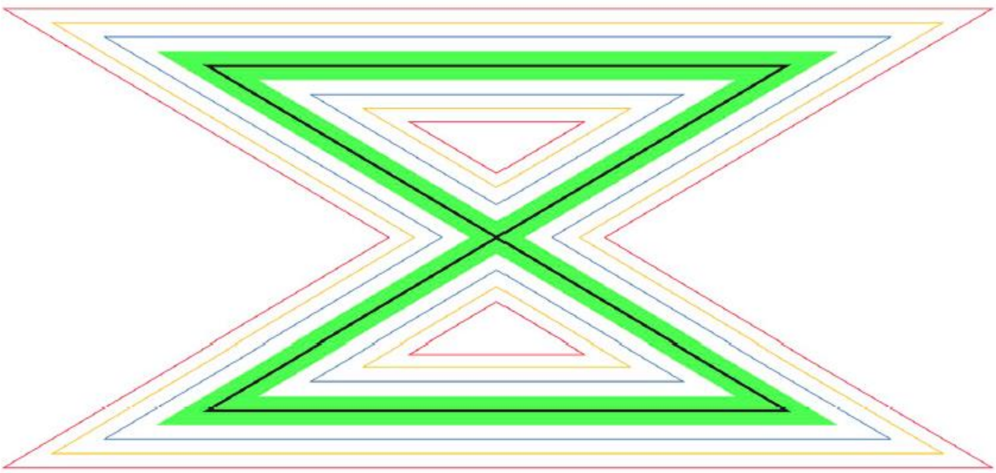
The following exercises were to be carried out for a period of 4 weeks. Each exercise needs to be done twice a day, 3 times a week. Each exercise is to be done in a sitting and standing position. Each direction of movement is to repeated 10 times. The repositioning task will initially be performed 3 times with the eyes open and then 10 times with the eyes closed for each movement direction. The movement sense tasks will be performed 10 times to the left and 10 times to the right with the eyes opened.

Exercise 1: Neck repositioning task



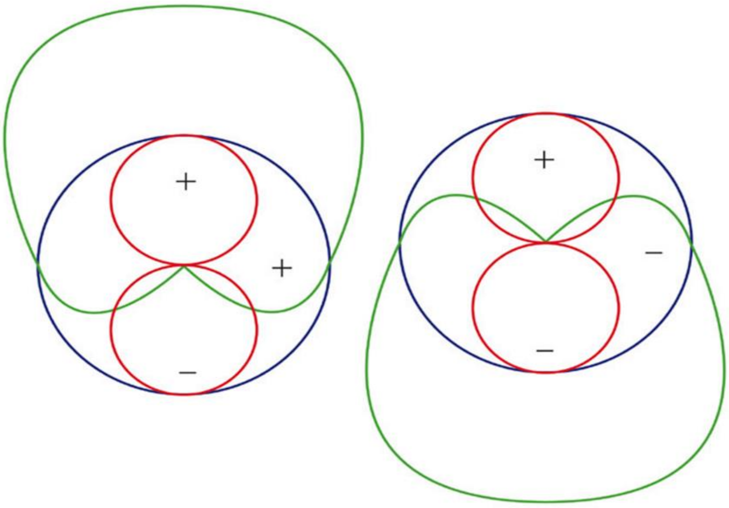
Participants will be asked to perform repetitions in flexion, extension, right and left rotation with their eyes closed. Participants will start from the bull's eye, move to full range then return to the starting position at a comfortable pace. They will then open their eyes between repetitions and reposition themselves back to the start position. At week 2, participants will additionally perform the target head position (THP) task. They will be asked to reposition their head at mid-range in each direction.

Exercise 2: Movement sense task (ZZ pattern)



Participants will be asked to move the laser pointer in the ZZ pattern to the right and to the left to trace the pattern as accurately as possible then return to the starting point.

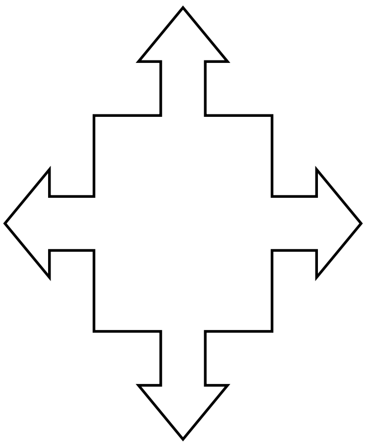
Exercise 3: Movement sense task (circles with different sizes)



Participants will be asked to move the laser pointer to trace the lines in both clockwise and anticlockwise directions.

Week 1: Blue circle; Week 2: Green circle (right and left figures); Week 3: Red circles; Week 4 Red circles

Exercise 4: Movement sense task



Participants will be asked to move the laser pointer to trace the lines in both clockwise and anticlockwise directions.

Appendix 3. 4. Study 3 demographic data

	Demographic data			
No.	Age	Height	Weight	Gender
1	25	169	53	F
2	25	160	69	M
3	29	168	56	F
4	28	176	92	F
5	25	161	50.8	F
6	28	179	70	M
7	45	174	85	F
8	20	174	60	F
9	33	173	88	M
10	30	175	98	M
11	35	162	66	F
12	36	176	92	M
13	31	189	91.1	M
14	19	170	63	F
15	27	193	89	M
16	22	175	73	M
18	23	175	87.9	F
19	21	151	47	F
20	25	172	70	F
Mean	27.73684	172.2105	73.72632	9 M, 11 F
SD	6.205618	9.406487	15.76378	

Appendix 3. 5. Study 3 questionnaires data

Session 1

No.	NDI	NRS	TSK	DHI
1	20	6	45	24
2	32	4	46	32
3	34	4	48	34
4	28	2	31	18
5	31	4	38	24
6	28	5	40	20
7	38	5	36	28
8	28	6	40	28
9	26	3	33	10
10	22	3	36	18
11	26	5	34	20
12	30	7	42	38
13	20	3	42	18
14	50	7	32	18
15	18	3	33	8

16	20	5	30	6
18	18	3	32	12
19	46	6	32	32
20	22	4	32	6
	28.26316	4.473684	36.94737	20.73684
	8.716845	1.427859	5.443235	9.385555

Session 2

No.	NDI	NRS	TSK	DHI
1	16	6	44	30
2	26	4	38	16
3	32	6	49	26
4	8	1	30	16
5	18	3	39	16
6	30	5	37	32
7	26	5	38	30
8	26	4	39	30
9	18	3	24	18
10	22	2	31	18
11	14	3	30	20
12	16	7	46	36
13	20	4	37	24
14	22	6	29	20
15	18	2	33	8
16	4	1	24	0
18	4	0.5	32	6
19	12	1	34	16
20	8	1	26	4
Mean	17.89474	3.394737	34.73684	19.26316
SD	8.012456	1.990629	6.85828	9.759433

Absolute JPE (sitting)

	S1					S2			
	Flex	ext	rt rot	lt rot		Flex	ext	rt rot	lt rot
1	5.25851919	2.745970988	1.983339	2.41771912	1	1.654751	2.39124	0.838156	1.501018
2	3.972495941	6.460694158	6.654425	6.06229946	2	1.675954	2.814776	1.161672	1.946247
3	8.478874324	3.761254697	2.867697	0.6949425	3	1.622946	1.77136	2.857113	2.22175
4	3.592187667	2.624220028	1.50632	3.35961878	4	2.009833	1.421492	2.205858	1.956845
5	2.719505461	6.188173739	3.169252	2.19526336	5	4.705682	3.851045	2.317093	6.193417
6	3.845763806	7.881137242	7.208578	1.65475118	6	2.046922	1.527525	8.644877	2.666571
7	3.1480961	2.745970988	1.379076	2.58186625	7	0.84346	1.638849	1.14046	2.994688
8	3.03172163	8.193223854	1.135157	3.25386854	8	2.740678	1.013181	2.857113	0.84346
9	4.479023077	2.407127585	2.560688	2.03102697	9	1.4427	2.073414	1.151066	2.142288
10	3.068752632	3.312033966	1.575237	1.18818655	10	1.633548	1.214701	1.31545	0.854068
11	1.416190521	12.12880931	2.560688	4.26277497	11	0.954841	1.80316	0.859372	2.174074
13	2.285313333	3.354331808	2.751264	4.14141137	13	2.380648	2.745971	1.511621	1.919751
14	2.491855159	3.312033966	1.045002	2.55009906	14	2.470674	2.42831	1.034395	0.604766
15	2.491855159	3.312033966	1.045002	2.55009906	15	3.914415	2.168776	2.094606	0.93893
16	4.009452203	3.734842222	1.75546	3.01585042	16	1.220003	1.071518	1.495717	1.27303
17	2.470674273	6.821853078	1.898554	3.7137111	17	1.707757	1.087428	1.188187	1.421492
19	1.628247119	5.126976552	1.80846	10.3631925	19	1.36317	2.380648	1.230609	3.27502
20	5.852378989	6.151466547	6.821853	1.82435989	20	1.410889	0.71616	1.352566	0.588853
21	3.655595302	8.104848181	1.554032	3.52877122	21	1.972741	1.675954	1.14046	0.705551
Mean	3.573500099	5.177210677	2.698952	3.23104275	Mean	1.98798	1.883974	1.915599	1.906412
SD	1.597001126	2.549376955	1.916163	2.06159719	SD	0.93439	0.751286	1.697618	1.279206

	Flexion	Extension	Right rotation	Left rotation
Effect size	1.258349526	2.008071021	2.75	0.79797061

Cohens d=M1-M2/SD pooled

	Difference		
Flexion	extension	rt rot	lt rot
3.603768	0.354731008	1.145182822	0.916701
2.296542	3.645918315	5.492753166	4.116053
6.8559281	1.989894238	0.01058387	-1.52681
1.582355	1.202727595	-0.69953839	1.402774
-1.986177	2.337128666	0.852159328	-3.99815
1.7988415	6.3536118	-1.43629891	-1.01182
2.3046358	1.107122162	0.238616677	-0.41282
0.2910437	7.180043003	-1.72195655	2.410408
3.0363232	0.333713723	1.40962243	-0.11126
1.4352046	2.097333254	0.259787241	0.334118
0.4613493	10.32564882	1.701316058	2.088701
-0.095335	0.60836082	1.239642813	2.22166
0.0211809	0.883723485	0.010606836	1.945333
-1.42256	1.143257973	-1.04960489	1.611169
2.7894487	2.663323876	0.259743431	1.74282
0.7629171	5.734424886	0.710367264	2.292219
0.265077	2.746328512	0.577851421	7.088172
4.4414904	5.435306602	5.469287369	1.235507
1.6828539	6.428894269	0.413572303	2.82322

Pooled SD			
Flexion	Extension	Right rotation	Left rotation
1.26	1.64	2.75	1.66

Mean difference			
Flexion	extension	right rotation	left rotation
1.58552	3.2932365	0.783352331	1.32463122

Constant JPE (sitting)

	S1					S2			
	Flex	ext	rt rot	lt rot		Flex	ext	rt rot	lt rot
1	5.258519	1.050304962	1.4745102	2.41771912	1	-1.40028	-2.00983	0.339527	1.479812
2	-3.90913	-6.46069416	-6.654425	-6.06229946	2	1.29424	-2.81478	1.161672	1.776661
3	-8.47887	3.761254697	2.66657093	-0.12201861	3	-0.24404	-1.77136	-1.60704	-2.22175
4	3.592188	2.200560725	0.85937224	3.35961878	4	-0.81164	1.379076	0.615375	0.885892
5	-1.50102	3.312033966	1.53812818	-0.4986729	5	-4.70568	3.851045	2.317093	6.193417
6	3.317321	7.881137242	7.2085778	-0.80633181	6	2.046922	-1.52753	8.644877	-1.36317
7	-0.06366	2.745970988	-1.2836351	-2.58186625	7	0.726769	-0.88589	0.132629	-2.78302
8	-1.25182	-8.19322385	-0.233426	-0.68963811	8	-2.61363	0.079577	-2.60304	0.323612
9	4.479023	0.88058801	2.5606883	1.86145763	9	1.018484	1.554032	-0.92832	0.021221

10	0.259951	-3.31203397	-0.8540683	0.76389846	10	1.209398	-0.48276	-1.09273	-0.54642
11	0.153849	-12.1288093	-2.5606883	-4.26277497	11	-0.95484	-1.16697	-0.36075	-2.17407
13	0.832852	3.259156585	-2.751264	4.14141137	13	-1.05561	0.859372	-0.66312	-1.91975
14	5.090135	2.110500529	-5.0480249	8.47368442	14	-2.46008	2.42831	0.864676	0.350137
15	-0.60477	2.444197217	0.33422159	1.94624656	15	-3.91442	1.80846	-2.09461	-0.75859
16	-2.4442	0.673724873	0.09018773	-1.6600519	16	-1.19879	-0.46684	-0.99727	0.403186
17	-2.47067	6.821853078	-0.8593722	3.7137111	17	-0.04244	0.822244	-0.40319	-1.12455
19	0.302392	-5.12697655	-0.1538494	-10.3631925	19	-0.6419	-2.38065	-1.06091	-3.27502
20	-5.85238	4.510658566	-6.8218531	-1.82435989	20	-0.68964	-0.11141	-0.1008	-0.12202
21	-3.16925	8.104848181	0.04774647	-3.52877122	21	-1.69716	0	-0.94954	-0.5252
Mean	-0.33998	0.765002726	-0.5495054	-0.30117001	Mean	-0.84918	-0.04399	0.063923	-0.28314
SD	3.583201	5.319678157	3.23563077	4.07109119	SD	1.708391	1.707719	2.319254	2.045065

	Flexion	Extension	Right rotation	Left rotation
Effect size	0.192456	0.230241031	-0.2208609	-0.00589647

Cohens d=M1-M2/SD pooled

Difference

flexion	extension	rt rot	lt rot
6.6588038	3.060138	1.134983629	0.93790728
-5.203375	-3.64592	-7.81609693	-7.83896

-8.234838	5.532615	4.273614306	2.09973119
4.4038236	0.821484	0.243996794	2.47372687
3.2046643	-0.53901	-0.77896482	-6.6920901
1.2703991	9.408663	-1.43629891	0.55683827
-0.790431	3.631863	-1.41626395	0.2011545
1.3618122	-8.2728	2.369617537	-1.0132497
3.4605387	-0.67344	3.489010896	1.84023697
-0.949447	-2.82928	0.238663171	1.31031387
1.1086907	-10.9618	-2.19994186	-2.0887014
1.8884605	2.399784	-2.08814797	6.06116229
7.5502184	-0.31781	-5.91270107	8.12354791
3.3096488	0.635737	2.428828047	2.7048408
-1.245405	1.140569	1.087457981	-2.0632378
-2.428233	5.999609	-0.45618638	4.8382616
0.9442897	-2.74633	0.907062282	-7.0881721
-5.162741	4.622067	-6.72105505	-1.7023413
-1.472096	8.104848	0.997284026	-3.0035746

Pooled SD			
Flexion	Extension	Right rotation	Left rotation
2.6457958	3.513699	2.777442177	3.05807802

Mean difference			
Flexion	extension	right rotation	left rotation
0.5091992	0.808998	-0.61342833	-0.0180319

Absolute JPE (standing)

	S1					S2			
	Flex	ext	rt rot	lt rot		Flex	ext	rt rot	lt rot

1	5.794623	3.428344199	3.0634626	2.42301482	1	2.957652	2.862405	1.029091	1.77136
2	7.698868	2.947069868	8.0528443	8.8003713	2	2.094606	1.914452	1.437398	2.481265
3	7.521656	2.248235276	3.6027562	1.33135669	3	1.156369	1.023788	1.161672	0.901804
4	2.857113	4.489568545	3.2432923	1.85615805	4	1.861458	2.433606	1.060912	0.960145
5	3.87745	3.1480961	6.1619548	1.36317008	5	4.341905	9.105794	5.095398	0.769203
6	8.696723	1.940947502	6.0203283	8.3542782	6	4.579193	2.714212	5.242737	1.204095
7	5.111188	3.412485356	2.0999045	1.63354799	7	0.99727	1.64945	1.188187	1.373774
8	4.47375	5.363713356	3.9038541	3.69786209	8	1.81906	2.3065	1.384379	2.237641
9	11.07509	2.370055936	2.9364875	2.20585805	9	2.640102	3.555196	3.089912	1.898554
10	2.661277	2.057519041	2.0416239	1.01318085	10	2.27472	1.432096	0.689638	1.485113
11	1.74486	7.386043151	2.7565569	5.96785512	11	1.81376	1.723658	1.129854	0.885892
13	3.391339	3.565765209	3.518201	2.55009906	13	1.781961	2.550099	1.697156	2.857113
14	1.511621	3.349044777	3.692579	2.13698993	14	1.214701	2.004534	1.416191	1.230609
15	1.511621	3.349044777	3.692579	2.13698993	15	3.211562	2.867697	0.827548	1.124551
16	2.470674	2.714212216	1.5593333	4.53174736	16	1.437398	1.80846	0.944234	1.188187
17	2.666571	2.783020754	1.4745102	2.35416748	17	2.004534	0.673725	1.781961	2.491855
19	1.850858	7.886342596	1.0184843	8.38543474	19	1.516923	2.407128	1.230609	2.332982
20	8.5152	7.948796607	4.6319022	4.38937439	20	1.007877	0.710856	0.801028	0.705551
21	2.62422	4.963788538	3.7084282	1.35786791	21	1.29424	0.700247	0.541111	0.647203
Mean	4.529195	3.965899674	3.5357412	3.49943811	Mean	2.105542	2.339153	1.671001	1.502468
SD	2.805331	1.857887231	1.7007049	2.49740728	SD	1.007984	1.778698	1.31212	0.672471

	Flexion	Extension	Right rotation	Left rotation
Effect size	1.271153	0.894656197	1.2378686	1.25996642

Cohens d=M1-M2/SD pooled

Difference

flexion	extension	rt rot	lt rot
2.836971	0.565939	2.034371355	0.6516544
5.604261	1.032618	6.6154463	6.3191065
6.365287	1.224447	2.441084342	0.4295532
0.995656	2.055962	2.182380593	0.8960131
-0.464454	-5.9577	1.066556634	0.5939674
4.11753	-0.77326	0.777591271	7.1501831
4.113918	1.763035	0.911717967	0.2597736
2.65469	3.057213	2.51947558	1.4602209
8.434988	-1.18514	-0.15342457	0.3073042
0.386557	0.625423	1.35198579	-0.4719326
-0.068901	5.662385	1.626703252	5.0819632
1.609379	1.015666	1.821044776	-0.3070142
0.29692	1.344511	2.276388439	0.906381
-1.699941	0.481348	2.865030806	1.0124394
1.033276	0.905752	0.615099499	3.3435608
0.662037	2.109296	-0.30745039	-0.1376877
0.333936	5.479215	-0.212124612	6.0524524
7.507322	7.237941	3.830874562	3.6838231
1.32998	4.263542	3.167317439	0.7106653

Pooled SD			
Flexion	Extension	Right rotation	Left rotation
1.906657	1.818293	1.506412271	1.5849389

Mean difference			
Flexion	extension	right rotation	left rotation
2.423653	1.626747	1.864740475	1.9969699

Constant JPE (standing)

	S1					S2			
	Flex	ext	rt rot	lt rot		Flex	ext	rt rot	lt rot
1	5.794623	0.694942504	3.06346265	1.850858	1	-2.95765	2.640102	-0.04244	-1.34726
2	-7.69887	1.379076462	-8.05284432	-8.80037	2	-2.09461	-0.40849	0.18568	-2.48126
3	-7.52166	-1.35786791	3.60275622	-0.54642	3	-0.58355	-0.7692	0.238731	-0.86998
4	1.320752	1.421492433	2.62951405	-0.92302	4	0.376661	1.373774	1.060912	-0.92832
5	-3.23272	2.491855159	6.16195484	-0.45093	5	-4.3419	9.105794	5.095398	0.503978
6	8.696723	-1.26242488	6.02032825	8.354278	6	4.579193	-2.71421	5.242737	0.960145
7	4.816323	-3.41248536	-2.09990452	-0.80633	7	-0.55172	1.426794	0.084883	-1.37377
8	-3.92498	-5.36371336	-3.90385412	-3.08462	8	-1.75546	0.790419	0.949538	-1.26242
9	11.07509	-2.21115534	-2.89415595	2.205858	9	0.435015	-3.52349	-3.08991	1.071518
10	2.407128	-0.99727025	-1.36317008	0.068967	10	-2.27472	1.432096	0.212206	-0.14854
11	-1.32075	-7.38604315	-2.75655687	-5.96786	11	-1.81376	-1.29954	-0.70555	0.090188
13	3.349045	1.055608335	-3.51820097	2.550099	13	-1.64415	2.550099	-1.69716	0.970752
14	-2.23764	-2.53950965	3.5551958	-0.26526	14	-0.42971	1.781961	1.416191	-0.23343
15	-1.10864	-1.8349594	-3.69257896	-0.72677	15	-3.21156	2.867697	-0.70025	0.86998
16	1.707757	-0.04244131	0.02122066	-1.14576	16	-1.26773	-0.16446	-0.15915	-0.67903
17	-0.24934	2.06281735	-1.4745102	-0.46684	17	-2.00453	-0.24934	-1.23061	-2.49186

19	0.928323	-7.8863426	-0.21220562	-8.38543	19	-1.00788	-2.40713	1.230609	-2.33298
20	-8.5152	7.948796607	-4.63190225	-4.38937	20	-1.00788	-0.71086	-0.05836	-0.6419
21	1.384379	4.426291188	2.88357257	0.933626	21	-1.0397	0.360746	0.031831	0.095493
Mean	0.29844	-0.67438596	-0.3506252	-1.05238	Mean	-1.18924	0.635935	0.424489	-0.53835
SD	5.130289	3.744612748	3.79840436	3.843753	SD	1.785116	2.670016	1.928711	1.128741

	Flexion	Extension	Right rotation	Left rotation
Effect size	0.430252	-0.4085415	-0.27068215	-0.20675

Cohens d=M1-M2/SD pooled

	Difference		
flexion	extension	rt rot	lt rot
8.752275	-1.94516	3.105903956	3.19812192
-5.60426	1.787567	-8.23852444	-6.3191065
-6.93811	-0.58867	3.364025189	0.32356475
0.944091	0.047718	1.568602359	0.00530378
1.109189	-6.61394	1.066556634	-0.95490735
4.11753	1.451787	0.777591271	7.39413327
5.368043	-4.83928	-2.18478709	0.56744255
-2.16952	-6.15413	-4.85339168	-1.82219739
10.64007	1.312331	0.195756102	1.1343397
4.681847	-2.42937	-1.5753757	0.21751139

0.493008	-6.0865	-2.05100562	-6.05804285
4.993194	-1.49449	-1.82104478	1.57934681
-1.80793	-4.32147	2.139005279	-0.03183038
2.102921	-4.70266	-2.99233208	-1.59674875
2.975485	0.122018	0.180375192	-0.46673354
1.755193	2.312159	-0.24390124	2.02501099
1.9362	-5.47922	-1.44281458	-6.05245244
-7.50732	8.659652	-4.57354546	-3.74747631
2.424077	4.065545	2.851741589	0.83813348

Pooled SD			
Flexion	Extension	Right rotation	Left rotation
3.457703	3.207314	2.863557691	2.48624701

Mean difference			
Flexion	extension	right rotation	left rotation
1.487684	-1.31032	-0.77511395	-0.51403089

Appendix 3. 7. Study 3 IMU data (Absolute JPE)

Sitting

	Day 1			
	Flexion	Extension	Right rotation	Left rotation
1	6.91304	6.263933	6.200825276	6.71558035
2	5.854556	3.474312	2.874022947	3.59693565
3	13.01793	4.735208	4.390859645	6.88403987
4	6.789153	3.415477	4.203670478	9.66032992
5	7.229313	10.1602	15.67617901	17.7717919
6	7.98824	5.19399	7.95642781	10.425823
7	9.281705	3.885261	2.975573089	2.97339274
8	1.797409	3.909091	4.820726844	3.41153546
9	12.34588	7.891456	4.013499444	5.09166537
10	6.201775	5.76788	1.263761434	5.3180525
11	2.698954	3.161879	2.135346038	3.73643666
13	5.547782	2.695798	1.342708222	3.39914808
14	4.109421	6.703121	2.717236499	2.52195719
15	2.39449	10.17799	5.230304734	4.3649197
16	3.091819	4.024752	3.671666372	5.16500229
17	2.581534	7.751166	4.111691983	3.83969233
19	5.609364	8.951815	0.826730357	5.12783196
20	6.662123	2.623582	3.036947255	4.81325146
21	1.9097	6.037209	3.555742203	6.04116413
Average	5.896009	5.622322	4.263364192	5.83466056
SD	3.161198	2.367056	3.17221971	3.47512848

	Day 2			
	Flexion	Extension	Right rotation	Left rotation
1	3.955174	4.125978	5.358237649	2.992606362
2	7.315025	2.700802	2.798260814	2.465675039
3	4.4088	3.076419	5.491314733	5.375474031
4	3.744336	3.694342	6.008909622	8.287386198
5	4.569735	3.720906	11.11530536	10.17096729
6	3.571817	2.769899	5.582537159	3.607680939
7	3.490071	3.446454	2.04351518	1.692619106
8	5.261868	3.303567	4.318560463	3.080679499
9	17.45417	2.172904	4.808851318	4.388811074
10	3.570375	4.517492	1.849050208	7.491778905
11	1.978216	3.599073	6.849256593	2.557557787
13	4.693026	2.335273	3.022751233	3.069407475
14	6.82221	6.295761	1.56967261	1.350893482
15	4.81802	9.98276	3.597425203	4.213535849
16	7.563723	3.949056	1.369387416	4.632518902
17	3.808714	4.492904	1.919550243	2.624868521
19	4.225208	3.583481	0.776136314	1.401321081
20	6.619532	1.741299	2.429050139	8.184228079
21	1.526634	3.716297	1.776660998	8.11190633
Average	5.231403	3.85393	3.825496487	4.510521892
SD	3.284264	1.744625	2.465626065	2.604731819

	Flexion	Extension	Right rot	Left rot
M1-M2	0.66	1.77	0.44	1.32
SD pooled	3.22	2.05	2.81	3.03
Cohen's d	0.204969	0.863415	0.15658363	0.43564356

Difference

flexion	extension	rt rot	lt rot
2.9578659	2.137955	0.842588	3.722973984
-1.460469	0.773511	0.075762	1.131260614
8.6091258	1.658789	-1.10046	1.508565839
3.0448165	-0.27886	-1.80524	1.372943717
2.6595781	6.439292	4.560874	7.600824594
4.4164225	2.424091	2.373891	6.818142056
5.7916342	0.438806	0.932058	1.28077363
-3.46446	0.605524	0.502166	0.330855965
-5.108291	5.718552	-0.79535	0.7028543
2.6313995	1.250387	-0.58529	-2.1737264
0.7207384	-0.43719	-4.71391	1.178878876
0.8547558	0.360526	-1.68004	0.329740608
-2.712789	0.40736	1.147564	1.171063704
-2.42353	0.195234	1.63288	0.151383847
-4.471904	0.075696	2.302279	0.532483385
-1.227179	3.258261	2.192142	1.214823811
1.3841552	5.368335	0.050594	3.726510883
0.0425916	0.882282	0.607897	-3.370976621
0.3830658	2.320913	1.779081	-2.070742195

Standing

	Day 1			
	Flexion	Extension	Right rotation	Left rotation
1	14.14358	4.62646433	9.066537369	7.95258059
2	8.57737	3.91362128	4.195511639	9.74860475
3	16.99886	10.0050357	6.773290126	8.98883259
4	5.714988	2.30824964	14.99887479	7.66914663
5	7.828097	9.72931246	13.3146595	4.56238206
6	6.208136	3.44504215	13.37538362	13.0837519
7	13.64152	9.31946421	3.767913702	4.17006181
8	7.833847	3.96540051	3.12214775	5.62802253
9	22.80408	15.4826421	7.010533547	9.80870843
10	6.260886	7.28799948	5.513484037	6.71603709
11	1.702542	8.58817525	1.183859949	1.52342987
13	3.955577	3.86483591	1.029348177	2.58364917
14	6.18175	9.36180811	2.403805632	5.84230474
15	4.713564	11.6779506	8.863132536	13.0925591
16	7.832014	3.50455317	3.891441651	8.89381944
17	2.247011	5.21383162	4.988283757	6.82504061
19	4.598665	6.39567247	2.966587102	12.1878458
20	4.856605	4.32212449	2.135851328	3.64212916
21	6.901365	7.51951706	8.546791074	8.18456097
Average	8.052656	6.87008951	6.165654594	7.42649827
SD	5.167761	3.36876392	4.111988322	3.25568007

	Day 2			
	Flexion	Extension	Right rotation	Left rotation
1	2.860619	2.9711403	5.639262188	7.37709083
2	7.614658	4.4251711	4.671183886	7.346227695
3	6.835445	2.4584068	5.273821842	4.372182842
4	5.408586	3.7666645	9.25400039	5.815579068
5	3.434146	4.689605	11.38696875	6.819069399
6	5.121658	2.7909759	6.715387837	5.939999356
7	6.861962	3.1861885	2.538393393	3.255828433
8	2.489841	6.0258538	4.238975235	2.674452111
9	13.12317	6.9817181	10.74467858	6.993819146
10	5.065753	11.3745	3.635251047	6.771010113
11	2.216989	3.4193293	10.35355798	4.269504131
13	7.143121	4.9825566	1.379779586	2.681671208
14	10.34476	8.3849361	4.444585736	4.570367445
15	3.820976	15.75591	2.759799857	9.384592654
16	4.970157	4.0706739	1.688136138	4.827881439
17	4.313266	2.7872411	2.079191159	3.797590656
19	9.987879	2.3157311	2.001506943	1.661968833
20	7.259164	5.2590741	3.999904152	6.506757827
21	2.036768	4.3840914	4.776674007	5.7466292
Average	5.837312	5.2647246	5.135845195	5.305906441
SD	2.914428	3.3089496	3.079732268	1.932472274

	Flexion	Extension	Right rot	Left rot
M1-M2	2.22	1.61	1.03	2.12
SD pooled	4.03	3.33	3.59	2.59

Cohen's d	0.550868	0.48348348	0.286908078	0.81853282

Difference

Flexion	Extension	Rt rot	Lt rot
11.28296	1.655324	3.42727518	0.575489759
0.962712	-0.51155	-0.4756722	2.402377055
10.16341	7.546629	1.49946828	4.616649752
0.306402	-1.45841	5.7448744	1.85356756
4.39395	5.039707	1.92769075	-2.256687344
1.086477	0.654066	6.65999579	7.143752557
6.779556	6.133276	1.22952031	0.914233375
5.344006	-2.06045	-1.1168275	2.953570419
9.68091	8.500924	-3.734145	2.814889283
1.195133	-4.0865	1.87823299	-0.054973026
-0.51445	5.168846	-9.169698	-2.746074261
-3.18754	-1.11772	-0.3504314	-0.098022034
-4.16301	0.976872	-2.0407801	1.27193729
0.892588	-4.07796	6.10333268	3.707966401
2.861857	-0.56612	2.20330551	4.065937998
-2.06626	2.426591	2.9090926	3.027449958
-5.38921	4.079941	0.96508016	10.52587696
-2.40256	-0.93695	-1.8640528	-2.864628668
4.864597	3.135426	3.77011707	2.437931769

Appendix 3. 8. Study 3 IMU data (Constant JPE)

Sitting

	Day 1			
	Flexion	Extension	Right rotation	Left rotation
1	6.91304	5.748163	6.200825276	6.71558035
2	5.672529	-1.15924	1.660947101	3.59693565
3	13.01793	4.735208	4.390859645	6.88403987
4	6.789153	-0.0198	3.399156114	9.66032992
5	-1.17325	10.1602	15.67617901	17.7717919
6	7.98824	5.19399	7.95642781	12.5109876
7	8.262879	1.240713	2.028643305	2.97339274
8	-1.26348	1.20545	3.523415449	3.41153546
9	12.34588	7.891456	4.013499444	5.09166537
10	6.201775	5.76788	-0.91566185	4.45415953
11	-1.62912	0.822524	-1.34605854	-3.7364367
13	5.547782	0.010863	0.188239254	3.39914808
14	4.093634	6.703121	2.268750234	2.52195719
15	1.05083	10.17799	5.230304734	3.47013332
16	2.680357	0.876923	-0.34738474	5.16500229
17	1.822089	7.751166	2.803224021	3.83969233
19	5.609364	-8.95182	0.385453064	-4.5401042
20	6.662123	-0.2769	-3.03694725	4.67300086
21	0.734231	6.037209	-0.01043623	6.04116413
Average	4.806631	3.363952	2.845759781	4.94231451
SD	4.108306	4.572531	4.054881114	4.79876347

	Day 2			
	Flexion	Extension	Right rotation	Left rotation
1	2.589062	-1.12733	5.358237649	2.99260636
2	7.315025	-2.55357	2.434758671	2.06869616
3	4.316932	0.023563	2.180745489	5.02503294
4	3.744336	-0.5687	4.689446229	8.07379413
5	1.106702	1.941474	11.11530536	10.1709673
6	2.902184	-2.03047	5.582537159	3.60768094
7	2.266576	3.446454	2.04351518	1.27623285
8	2.889158	0.691094	3.601309686	1.45298598
9	17.45417	-0.26433	4.161393132	4.12196899
10	3.570375	4.517492	-0.003766753	7.4917789
11	1.284542	3.577257	6.849256593	2.55755779
13	4.693026	0.030813	-0.536056018	3.06940747
14	6.82221	6.295761	1.397786372	1.35089348
15	-4.49862	9.98276	2.398488542	4.21353585
16	7.563723	3.949056	-0.568262272	4.6325189
17	3.808714	4.492904	0.013283489	2.62486852
19	4.225208	2.271693	0.538455811	0.02395527
20	6.619532	0.414197	2.161043861	8.18422808
21	0.275431	3.716297	-0.202387811	8.11190633
Average	4.155173	2.042443	2.80079423	4.26582191
SD	4.162932	3.048685	2.917717718	2.79023278

	Flexion	Extension	Right rot	Left rot
M1-M2	0.65	1.32	0.04	0.68
SD pooled	4.13	3.8	3.48	3.79
Cohen's d	0.157385	0.347368	0.011494253	0.17941953

Difference

Flexion	Extension	Rt rot	Lt rot
4.323978	6.875488	0.842588	3.722973984
-1.6425	1.394328	-0.77381	1.528239493
8.700994	4.711645	2.210114	1.859006926
3.044817	0.548898	-1.29029	1.586535781
-2.27995	8.218723	4.560874	7.600824594
5.086055	7.224461	2.373891	8.903306655
5.996303	-2.20574	-0.01487	1.697159889
-4.15263	0.514357	-0.07789	1.958549479
-5.10829	8.155783	-0.14789	0.969696385
2.631399	1.250387	-0.9119	-3.03761938
-2.91366	-2.75473	-8.19532	-6.29399445
0.854756	-0.01995	0.724295	0.329740608
-2.72858	0.40736	0.870964	1.171063704
5.549454	0.195234	2.831816	-0.74340253
-4.88337	-3.07213	0.220878	0.532483385
-1.98662	3.258261	2.789941	1.214823811
1.384155	-11.2235	-0.153	-4.56405948
0.042592	-0.6911	-5.19799	-3.51122722
0.458801	2.320913	0.191952	-2.0707422

Standing

	Day 1			
	Flexion	Extension	Right rotation	Left rotation
1	14.14358	4.626464	9.066537369	7.95258059
2	8.57737	3.913621	4.195511639	9.74860475
3	16.99886	10.00504	6.773290126	8.98883259
4	6.857986	0.735023	14.99887479	7.66914663
5	-3.12682	9.729312	13.3146595	4.56238206
6	9.312204	1.023832	13.37538362	13.0837519
7	13.64152	9.319464	3.759006802	4.17006181
8	5.056127	3.965401	3.12214775	4.36256823
9	22.80408	15.48264	7.010533547	9.80870843
10	6.260886	7.287999	5.513484037	6.71603709
11	1.489601	8.588175	0.411334611	0.14821902
13	3.727068	1.798391	-0.383387213	2.58364917
14	7.4181	9.361808	2.403805632	5.47293593
15	-4.41692	11.12818	8.863132536	13.0925591
16	7.832014	-0.62531	2.271079177	8.89381944
17	1.062466	5.213832	4.988283757	6.82504061
19	4.598665	-6.39567	1.860441338	-12.187846
20	3.794599	3.118031	-1.948372218	3.3805014
21	6.901365	7.519517	8.546791074	8.18456097
Average	6.996461	5.568197	5.69171252	5.97137441
SD	6.420416	4.934292	4.643798052	5.3844171

	Day 2			
	Flexion	Extension	Right rotation	Left rotation
1	1.307259	2.97114	5.135616529	7.37709083
2	7.614658	-2.56564	4.671183886	7.3462277
3	6.835445	0.983743	5.273821842	3.84404953
4	4.622017	-1.86928	9.25400039	5.81557907
5	3.266863	-2.88376	11.38696875	5.15455751
6	5.121658	2.005062	6.715387837	5.93999936
7	6.861962	3.186189	2.538393393	3.25582843
8	2.266573	5.493799	3.574773332	-0.9920832
9	13.12317	6.60913	10.74467858	6.99381915
10	5.065753	11.3745	3.635251047	6.69196221
11	2.212286	2.294247	10.35355798	4.26950413
13	7.143121	2.423052	0.249293455	1.74324514
14	10.34476	8.384936	3.505939177	4.57036745
15	-2.55623	15.75591	2.124047185	9.38459265
16	4.759328	4.070674	-1.05772796	4.82788144
17	4.313266	2.787241	1.330947174	3.79759066
19	9.987879	0.560251	2.001506943	0.96353689
20	7.259164	5.259074	1.383798388	6.50675783
21	0.720639	4.384091	4.776674007	5.7466292
Average	5.277346	3.74865	4.610426943	4.90721768
SD	3.622467	4.471126	3.525201692	2.41520884

	Flexion	Extension	Right rot	Left rot
M1-M2	1.72	1.82	1.08	1.07

SD pooled	5.02	4.7	4.08	3.89
Cohen's d	0.342629	0.387234	0.264705882	0.27506427

Difference

Flexion	Extension	Rt rot	Lt rot
12.83632	1.655324	3.930921	0.575489759
0.962712	6.479261	-0.47567	2.402377055
10.16341	9.021293	1.499468	5.14478306
2.235969	2.604303	5.744874	1.85356756
-6.39368	12.61308	1.927691	-0.592175449
4.190545	-0.98123	6.659996	7.143752557
6.779556	6.133276	1.220613	0.914233375
2.789554	-1.5284	-0.45263	5.354651381
9.68091	8.873512	-3.73415	2.814889283
1.195133	-4.0865	1.878233	0.024074874
-0.72268	6.293928	-9.94222	-4.121285114
-3.41605	-0.62466	-0.63268	0.84040403
-2.92666	0.976872	-1.10213	0.902568483
-1.86069	-4.62773	6.739085	3.707966401
3.072686	-4.69598	3.328807	4.065937998
-3.2508	2.426591	3.657337	3.027449958
-5.38921	-6.95592	-0.14107	-13.15138268
-3.46457	-2.14104	-3.33217	-3.126256428
6.180727	3.135426	3.770117	2.437931769

Appendix 3. 9. Study 3 external responsiveness data

Absolute JPE (sitting)

Movement	Pearsons correlation
Flexion	-0.07
Extension	0.19
Right rotation	0.008
Left rotation	0.35

Absolute JPE (standing)

Movement	Pearsons correlation
Flexion	0.08
Extension	0.2
Right rotation	0.42
Left rotation	0.43

Constant JPE (sitting)

Movement	Pearsons correlation

Flexion	-0.2
Extension	0.11
Right rotation	0.05
Left rotation	0.7

Constant JPE (standing)

Movement	Pearsons correlation
Flexion	-0.2
Extension	0.59
Right rotation	0.27
Left rotation	0.44

Appendix 3. 10. Study 3 sub-analysis (Absolute JPE) data

Sitting

Movement	**Flexion**			**Extension**			**Right rotation**			**Left rotation**	
Session	S1	S2		S1	S2		S1	S2		S1	S2
1	5.25	1.65	1	6.46	2.81	1	6.65	1.16	1	6.06	1.94
2	3.97	1.67	2	3.76	1.77	2	3.16	2.31	2	3.35	1.95
3	8.47	1.62	3	6.18	3.85	3	7.2	8.64	3	3.25	0.84
4	3.59	2	4	7.88	1.52	4	6.82	1.35	4	4.26	2.17
5	3.84	2.04	5	8.19	1.01	Mean	5.9575	3.365	5	4.14	1.91
6	3.14	0.84	6	3.31	1.21	SD	1.627366	3.076561	6	3.01	1.27
7	3.03	2.74	7	12.1	1.8				7	3.71	1.42
8	4.47	1.44	8	3.35	2.74				8	10.36	3.27
9	3.06	1.63	9	3.31	2.42				9	3.52	0.7
10	4	1.22	10	3.31	2.16				Mean	4.628889	1.71888889
11	5.85	1.41	11	3.73	1.07				SD	2.198497	0.73406697
12	3.65	1.97	12	6.82	1.08						
Mean	4.36	1.685833	13	5.12	2.38						
SD	1.486405	0.455896	14	6.15	0.71						
			15	8.1	1.67						
			Mean	5.9475	1.6475						
			SD	2.665684	0.629936						

Pooled SD			
Flexion	Extension	Right rotation	Left rotation

Mean difference			
Flexion	extension	right rotation	left rotation

0.97115	1.64781	2.351963	1.46628183		2.674167	4.3	2.5925	2.91

	Flexion	Extension	Right rotation	Left rotation
Effect size	2.753607	2.609525	1.1022707	1.984612

Standing

Movement	**Flexion**			**Extension**			**Right rotation**			**Left rotation**	
Session	S1	S2		S1	S2		S1	S2		S1	S2
1	5.794623	2.957652	1	3.428344	2.86240523	1	3.063463	1.029091	1	8.8	2.48
2	7.698868	2.094606	2	4.489569	2.4336061	2	8.052844	1.437398	2	8.35	1.2
3	7.521656	1.156369	3	3.148096	9.10579448	3	3.602756	1.161672	3	3.69	2.23
4	3.87745	4.341905	4	3.412485	1.64945042	4	3.243292	1.060912	4	5.96	0.88
5	8.696723	4.579193	5	5.363713	2.30649994	5	6.161955	5.095398	5	4.53	1.18
6	5.111188	0.99727	6	7.386043	1.72365838	6	6.020328	5.242737	6	8.38	2.33
7	4.47375	1.81906	7	3.565765	2.55009906	7	3.903854	1.384379	7	4.38	0.7
8	11.07509	2.640102	8	3.349045	2.00453403	8	3.518201	1.697156	Mean	6.29857143	1.571429
9	3.391339	1.781961	9	3.349045	2.86769714	9	3.692579	1.416191	SD	2.01869426	0.693159
10	8.5152	1.007877	10	7.886343	2.40712758	10	3.692579	0.827548			
Mean	6.615589	2.337599	11	7.948797	0.7108556	11	4.631902	0.801028			
SD	2.3503	1.229413	12	4.963789	0.70024688	12	3.708428	0.541111			
			Mean	4.857586	2.61016457	Mean	4.441015	1.807885			
			SD	1.798113	2.07810384	SD	1.454006	1.534326			

Pooled SD			
Flexion	Extension	Right rotation	Left rotation
1.789857	1.938108	1.494166	1.35592663

Mean difference			
Flexion	extension	right rotation	left rotation
4.277989	2.247422	2.63313	4.72714286

	Flexion	Extension	Right rotation	Left rotation
Effect size	2.39013	1.159595	1.76227414	3.486282