UNIVERSITY OF LJUBLJANA
BIOTECHNICAL FACULTY

Živa MAJCEN ROŠKER

VISUAL DISTURBANCES IN SUBJECTS WITH CERVICOGENIC DISORDERS

DOCTORAL DISSERTATION

Ljubljana, 2022

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VIDNO ZAZNAVANJE PRI POSAMEZNIKIH S PATOLOGIJAMI VRATNE HRBTENICE

DOKTORSKA DISERTACIJA

Ljubljana, 2022

Based on the Statute of the University of Ljubljana and the decision of the Biotechnical Faculty senate, as well as the decision of the Commision for Doctoral Studies of the University of the University of Ljubljana adopted on May 13, 2022, it has been confirmed that the candidate meets the requirements for pursuing a PhD in the interdisciplinary doctoral programme in Biosciences, Scientific Field Bioengineering in Health Sciences. Asist. Prof. Dr. Eythor Kristjansson is appointed as a supervisor and Asist. Prof. Dr. Miha Vodičar as co-advisor.

Commission for assessment and defence / komisija za zagovor:

President /	assoc. prof. Katja TOMAŽIN
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TI VISUAL DISTURBANCES IN SUBJECTS WITH CERVICOGENIC DISORDERS
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AB The aim of the thesis was to study; metric characteristics of smooth pursuit neck torsion test (SPNT) in idiopathic neck pain patients (INP) and healthy individuals, relationship between oculomotor functions and subjective visual complaints and presence of cognitive involvement during SPNT test, relationship between sensorimotor functions in INP and healthy and sensorimotor functions between healthy and different patient groups (mild traumatic brain injury (mTBI), whiplash associated disorders (WAD) and INP). Infrared video-oculography was used to measure eye movements, phasic and tonic alertness. Butterfly and relocation test measured cervicocephalic kinaesthesia and force plate postural balance during quiet stance. Major results; SPNT test should be performed at 30°/s velocity and 40° amplitude under 45° of neck torsion, intensity of visual symptoms was related to SPNT, tonic and phasic alertness were altered in neck pain patients, cervicocephalic kinaesthesia was related to postural balance and oculomotor control and differences in sensorimotor control were found between healthy and all patient groups but not between patient groups except for postural balance. Early detection and diagnosis of functional characteristic in patients with neck pain could help towards faster recovery and less reoccurrence.

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AI Namen naloge je bil preučiti; merske lastnosti horizontalnega sledilnega pogleda med torzijo vratu (SPTV) pri ljudeh z bolečino v vratu in brez, preveriti povezanost med okulomotoriko in simptomi vidnega zaznavanja ter pomen kognitivnih funkcij med SPTV testom, povezanost med senzorično-motoričnimi sposobnostmi pri bolnikih in zdravimi posameznikih ter razlike v senzorično-motoričnih sposobnostih med bolniki z blažjo travmatsko poškodbo možganov (BPM), idiopatsko bolečino v vratu in nihajno poškodbo vratu (NPV) ter zdravimi posamezniki. Za SPTV in meritve fazične in tonične pozornosti smo uporabili infrardečo video-okulografijo. Metuljni in repozicijski test sta bila uporabljena za vrednotenje cervikocefalične kinestezije, ravnotežje smo merili s ploščo za merjenje reakcijskih sil na podlago. Ključni rezultati: pri SPTV testu je potrebno uporabiti hitrosti 30°/s, amplitude 40°, v 45° torziji vratu, natančnost sledenja tarče je povezana z intenzivnostjo vidnih simptomov, viden je upad tonične in fazične pozornosti pri bolnikih z bolečinami v vratu, vratna kinestezija je povezana z ravnotežjem in okulomotoričnimi funkcijami ter prisotne so razlike v naštetih senzorično-motoričnih funkcijah med zdravimi preiskovanci in skupinami bolnikov (BPM, idiopatska bolečina v vratu in NPV). Zgodnje prepoznavanje in diagnosticiranje funkcionalnih sprememb pri bolnikih bi lahko omogočilo hitrejše okrevanje in zmanjšanje števila remisij.

TABLE OF CONTENTS

TABLE OF CONTENT OF SCIENTIFIC WORKS

PUBLISHED SCIENTIFIC WORKS

ADDITIONAL SCIENTIFIC WORKS

LIST OF ANNEXES

ABBREVIATIONS AND SYMBOLS

Gain	Accuracy of smooth pursuit eye movement
GBD	Global burden disease
mTBI	Mild traumatic brain injury
SPNT	Smooth pursuit neck torsion
$SPNT_{diff}$	Smooth pursuit neck torsion difference

1 INTRODUCTION

Musculoskeletal disorders are one of the most debilitating conditions that have over the years put increased burden on healthcare system and are categorised as significant health decline that often leads to increased risk of developing other chronic health conditions (Briggs et al., 2018). Rapid advances in conservative treatment modalities, understanding of pain mechanisms, movement alterations, sensorimotor control, importance of behavioural science in treating musculoskeletal disorders amongst others led clinicians to understand that in the contemporary practice, musculoskeletal disorders require complex and multimodal approaches. Discord between approaches to spinal and extremity disorders have been stressed out previously (Jull, 2016), with evidence emerging that over the last decade the primary focus in the patient centred outcome in spinal disorders have been in many cases a numerical scale for pain and questionnaires about disability with a lack of understanding about other involved neuromuscular mechanisms that led patients with spinal disorders to experience chronicity and episodes of recurrences.

Chronicity and recurrence are suggested to be the main causes of disability and are increasingly putting financial demands on the healthcare system. The 1990–2017 Global burden disease (GBD) report recognised that pain in the neck was in the top 10 of 354 conditions, represented of years lived with a disability (Safiri et al., 2020). Analysis conducted by Safiri et al. (2020) found that the point prevalence of neck pain increased right up until the age of 70–74 years while the prevalence peaked between 45 and 54 years for both females and males. Most disturbingly, the point prevalence, the annual incidence of neck pain and the years lived with a disability had essentially not changed in the last 28 years.

Spinal disorders have been suggested to rise despite the increased amount of research over the past 20 years directed towards recognising the most appropriate approaches towards treating these disorders. According to GBD 2015 (GBD 2015 Disease and Injury Incidence and Prevalence Collaborators, 2016) low back pain lasting for more than 3 months increased in global prevalence by 17,3% from 2005 to 2015, while neck pain in individuals experiencing pain of longer than 3 months increased by 21,1% over the 10-year period, while from 1990 to 2017 an increase in neck pain of 75,7% globally was reported (Wu et al., 2021).

Anecdotal evidence reports that in order to achieve desirable treatment outcome, rehabilitation should be targeted with caution, with common advice by clinicians when treating patients with neck pain disorders: “To hurry slowly”. Based on the point prevalence, high reoccurrence rate and chronicity, some could say that such approach might not bring the desirable outcome. Have we perhaps been hurrying too slowly?

Since it is known that treatments for patients with neck pain disorders and rehabilitation don't always achieve desirable outcome with high reoccurrence rate reported (Cohen, 2015) it is also suggested that those studies that report improvements lack rigorous scientific approaches that would allow firmer conclusions on the effectiveness of different interventions (Hahne et al., 2010).

As number of patients with neck pain disorders are growing it could be also speculated that current diagnostic methods are not likely able to provide us with the information needed to eliminate pain in the neck and other accompanied symptoms. Perhaps, one of the reasons might be the lack of understanding of mechanisms across clinicians and other healthcare specialists as suggested complains in patients with neck pain disorders are not likely solely related to pain in the neck but are accompanied or prevailing by other symptoms. Some might even propose that this might lead many to experience secondary problems to neck pain such as radiculopathy (Thoomes et al., 2018) due to disc herniation or osteophytes compressing on the nerve root, headaches (Bogduk and Govind, 2009) that result from cervical spine impairments, cognitive disfunction (Borenstein et al., 2010), dizziness (De Vestel et al., 2022) as a consequence of sensory mismatch, tinnitus (Koning, 2021) that might be caused by cervical spine impairments and less commonly investigated, but not less commonly reported in neck pain patients; visual disturbances (Treleaven and Takasaki, 2014).

Visual disturbances have been suggested to be present in patients with neck pain disorders. Patients commonly report a myriad of vision related symptoms such as needing to concentrate to read, sore eyes, words moving on page, eye strain, heavy eyes, difficulty judging distance, blurred vision, and red eyes (Treleaven and Takasaki, 2014) but it is not clear to what extend they corelate to objectively measured oculomotor functions that are altered in patients with neck pain disorders (Kristjansson and Treleaven, 2009). Smooth pursuit eye movements are an important component of the oculomotor system (Kristjansson and Treleaven, 2009). When evaluating smooth pursuit eye movements, participants are instructed to follow horizontally moving target with their eyes, by keeping their head still. In patients with neck pain disorders, proposed mechanisms for disturbances in the accuracy of eye movements is suggested to be a sensory mismatch between cervical spine proprioception, vestibular and visual systems (Cheever et al., 2016a). More in-depth description of neural mechanisms explaining connections between visual disturbances and above-described symptoms have been provided by Cheever et al. (2016b) and Peterson (2004). They suggest that upper cervical afferent information ascends to different parts of the central nervous system and is involved in complex sensory and motor processing. The major areas of upper cervical afferents processing are the sensory and motor nuclei of the brainstem, cerebellum, thalamus and primary somatosensory cortex. The upper cervical sensory information is integrated in the cerebellum with vestibular and visual information. This information is used for processing anticipatory ocular and postural adjustments in the primary somatosensory cortex. Cervical afferents and other sensory information interactions that are taking place in the superior colliculus provide efferent output for the cervico-ocular and vestibulo-ocular reflexes (stabilizing the gaze during head and neck-body movements). It has been shown that abnormal upper cervical spine sensory function has an important effect on alteration of cervico-ocular reflexes and vestibulo-ocular reflexes (de Vries et al., 2016).

Disturbed afferent information derived from various structures of the cervical spine could lead to less accurate eye movement control and consequently inappropriate image stabilization of the moving target on or near the fovea (Majcen Rosker et al., 2021; Tjell et al., 2002). This has been proposed to show greater alterations when the trunk is rotated underneath a stationary head to the left and to the right, called smooth pursuit neck torsion test (SPNT) (Tjell and Rosenhall, 1998). Alterations in oculomotor control during neck torsion are proposed to derive from abnormal cervico-colic and cervico-ocular reflexes. The test is considered positive when the accuracy of smooth pursuit eye movements (gain) is worse in the torsioned positions as compared to the neutral position, causing an increased difference in gain ($SPNT_{diff}$).

Despite SPNT test being commonly investigated, some controversy exists between the studies. These were proposed to be a result of methodological inconsistencies (Centeno and Freeman, 2008) that could potentially affect SPNT test results, as some studies managed to find differences between healthy individuals and patients with neck pain disorders (Janssen et al., 2015; Tjell and Rosenhall, 1998; Treleaven et al., 2005a; Treleaven et al., 2011) during neck torsion manoeuvre. On the contrary, some studies were unable to make such conclusion with no observed differences between patients with neck pain disorders and asymptomatic controls (Kongsted et al., 2007; Prushansky et al., 2004). Of these, most commonly proposed discrepancies include, different degrees of analysed neck torsion manoeuvres such as some studies applied 30° of neck torsion (Prushansky et al., 2004), while others applied 45° of neck torsion (Treleaven et al., 2005a), but found different results. According to Prushansky et al. (2004) an important functional impairment in neck pain disorders patients is decreased range of motion of the cervical spine. Some patients are therefore not able to perform SPNT test under 45° of neck torsion angle but could perform it under 30° of neck torsion. This is in accordance with rationales that other authors have proposed where those who could not reach 45° of neck torsion during SPNT test were advised to perform the test under 30° of neck torsion (Treleaven et al., 2005a) and were included for further analysis altogether. Although the two angles during the SPNT test are commonly used in research interchangeably, no systematical comparisons were done to determine the level of agreement between these two angles.

Another inconsistency reported across studies was number of cycles used when analysing SPNT test. These varied between different studies (Gimse et al., 1996; Janssen et al., 2015;

Prushansky et al., 2004; Tjell and Rosenhall, 1998; Treleaven et al., 2005a). Although majority of articles used 10 cyclic sinusoidal target movements of which averages from 6th to 9th cycle (Tjell and Rosenhall, 1998; Treleaven et al., 2005a) were used for further analysis, some averaged all performed cycles (Janssen et al., 2015), but no justification was provided across the studies for such decisions. These inconsistencies could importantly influence intra-trial reliability.

According to Bexander and Hodges (2019) eye movement amplitude and velocity can influence cervical spine muscle activity. Furthermore, this can lead to altered proprioceptive feedback that would influence accuracy of eye movement control. In addition, Land (2006) suggested an increase in saccadic intrusions during eye movements with increased smooth pursuit velocities. These imply that accuracy of SPNT test could be influenced by target movement amplitude and velocity and therefore interplay between saccadic and smooth pursuit eye movements. Due to the above-mentioned discrepancies and methodological inconsistencies found across different studies it would be of importance to understand how amplitude and velocity of target movements affect SPNT test outcome measure, reliability and sensitivity.

Despite commonly investigated predictable SPNT tasks in neck pain patients, unpredictable conditions have been seldom investigated but are indicative of preserved oculomotor functions during neck torsion (Janssen et al., 2015). Although not previously studied, some speculations about compensatory cognitive mechanisms such as increased phasic alertness during unpredictable tasks were suggested, therefore eye movement accuracy and pupillometric responses during predictable and unpredictable SPNT test in neck pain patients and asymptomatic controls should be investigated.

As neck pain patients commonly suffer from reoccurrence and chronicity, disturbances in the sensorimotor control system have been proposed as important contributors for these malfunctions (Alalawi et al., 2022; Devecchi et al., 2021; Treleaven, 2008). Sensorimotor disturbances affect multiple subsystems of which altered postural balance (Treleaven, 2008), eye movement control (Janssen et al., 2015) and kinaesthesia (Kristjansson and Treleaven, 2009; Malmström et al., 2017) are commonly identified in patients with neck pain disorders. Sensory mismatch between cervical spine proprioception, vestibular and visual system is proposed as one of the reasons for these disturbances in neck pain patients. Based on these suggestions altered cervical proprioception could influence eye movement control and postural balance therefore the relationship between neck kinaesthesia, postural balance and eye movement control should be studied in neck pain patients and healthy controls.

Sensorimotor control is not only altered in idiopathic neck pain patients, but have been proposed to be altered in patients with whiplash associated disorders (de Vries et al., 2016; Gimse et al., 1996; Janssen et al., 2015; Kristjansson and Treleaven, 2009) and concussion patients (Degani et al., 2017; Wetzel et al., 2018). Although etiology of whiplash associated disorders is still poorly understood, some evidence exists that upper cervical spine sustains tensile forces (Dowdell et al., 2018) which mainly stresses ligaments and suboccipital muscles. Upper cervical spine ligaments, as well as suboccipital muscles have been found to have substantially high number of proprioceptors (Kulkarni et al., 2001). When injured, sensory mismatch is suggested to take place.

Some researchers suggest that signs and symptoms related to concussion and oculomotor function could be due to forces sustained by the upper cervical spine due to hit (Cheever et al., 2016a). Therefore, concussion subjects could in fact sustain upper cervical spine injuries (whiplash associated disorder) along with or absence of mild traumatic brain injuries. Limitations in imaging diagnostics cannot confirm or reject upper cervical spine injury (Uhrenholt et al., 2022) or mild traumatic brain injury (Broglio et al., 2015). Therefore, additional functional diagnostics could provide better understanding of possible cervical deficits and its correlation to oculomotor deficits. Some researchers suggest that signs and symptoms related to concussion and oculomotor function could be due to forces sustained by the upper cervical spine due to hit (Cheever et al., 2016a). Therefore, concussion subjects could in fact sustain upper cervical spine injuries along with or absence of mild traumatic brain injuries.

Although researchers have studied individual pathologies, no attempts have been made to systematically compare them in cervicocephalic kinaesthetic sensibility, postural balance, and smooth pursuit eye movements. Knowledge of these interconnections could help understanding potential cervicogenic involvement in concussion injuries which would help improving effectiveness of rehabilitation protocols.

And should we ask ourselves; how long before we are able to answer a commonly asked question: can a stitch in time saves nine? (Jull, 2021). Would better diagnostics contribute towards better understanding of underlying deficits? Due to the paucity of scientifically rigorous studies our goal was to investigate metric characteristics of smooth pursuit neck torsion test and its relations to visual symptoms. In addition, attentional deficits in neck pain patients and their involvement in SPNT test should be studied. Furthermore, relationship between cervicocephalic kinaesthesia and eye movement control or postural balance (both during neck torsion manoeuvre) should be studied. As concussion patients have been suggested to present with similar cervicogenic deficits as traumatic and nontraumatic neck pain patients, differences in sensorimotor control (postural balance, eye movement control and cervicocephalic kinaesthesia) should be compared between different pathologies and healthy controls.

1.1 RESEARCH QUESTIONS AND HYPOTHESES

In the PhD thesis, following research questions were addressed, each in its separate study:

1. How reliable are different SPNT tasks in idiopathic neck pain patients and healthy individuals when measured at two visits?
2. How reliable are different SPNT tasks in idiopathic neck pain patients and healthy individuals when considering different cycles?
3. What is the agreement between the two most commonly used neck torsion angles in SPNT test in idiopathic neck pain patients and healthy individuals?
4. What is the sensitivity of SPNT test for identifying idiopathic neck pain patients and which target movement profiles measured at two neck torsion angles present with highest classification accuracy?
5. How well can we classify intensity and frequency of visual symptoms using gain or $SPNT_{diff}$ in idiopathic neck pain patients?
6. Are pupillometric parameters of tonic and phasic alertness during predictable and unpredictable SPNT tasks altered in idiopathic neck pain patients and healthy individuals?
7. What is the relationship between two tests of cervicocephalic kinaesthetic sensibility and postural balance or eye movement control in idiopathic neck pain patients and healthy individuals?
8. What are the differences in two cerviocephalic kinaesthetic tests, postural balance and smooth pursuit eye movements between idiopathic neck pain patients, patients with whiplash associated disorders, mild traumatic brain injury patients and healthy individuals?

Based on the first research question aiming at studying inter-visit reliability of SPNT test in idiopathic neck pain patients and healthy individuals, following hypothesis have been made:

- H1.1.: Inter-visit reliability of gain and $SPNT_{diff}$ is higher in healthy individuals as compared to patients with neck pain disorders.
- H1.2.: Inter-visit reliability of gain and $SPNT_{diff}$ is higher at slower velocities of target movements regardless of the observed group.
- H1.3.: Inter-visit reliability of gain and $SPNT_{diff}$ differs between different target movements amplitudes regardless of the observed group.
- H1.4.: Inter-visit reliability of gain differs between the neutral and neck torsion positions.

Based on the second research question aiming at studying intra-trial reliability of SPNT test in idiopathic neck pain patients and healthy individuals, following hypothesis have been made:

- H2.1.: Intra-trial reliability of gain and $SPNT_{diff}$ is higher in healthy individuals as compared to patients with neck pain disorders.
- H2.2.: Intra-trial reliability of gain and $SPNT_{diff}$ is higher at slower velocities of target movement regardless of the observed group.
- H2.3.: Intra-trial reliability of gain and $SPNT_{diff}$ differs between different target movement amplitudes regardless of the observed group.
- H2.4.: Statistically significant differences in gain and $SPNT_{diff}$ between the average gain from 2nd to 5th and average gain from 6th to 9th cycle of SPNT test are present in idiopathic neck pain patients but not in healthy controls.

Based on the third research question aiming at studying agreement between the two most commonly used neck torsion angles in SPNT test for neck pain patients and healthy individuals, following hypothesis have been made:

- H3.1.: Gain and $SPNT_{diff}$ measured at 30° and 45° will present with high agreement.
- H3.2.: Gain and $SPNT_{diff}$ measured at 30° and 45° will present with high agreement regardless of the target movement velocity and amplitude.
-

Based on the fourth research question aiming at studying sensitivity of SPNT test for identifying idiopathic neck pain patients and searching for most accurate classifiers (target movement profiles), following hypothesis have been made:

- H4.1.: Gain and $SPNT_{diff}$ measured at lower velocities and higher target movement amplitudes present with higher classification accuracy for neck pain patients as opposed to higher velocities and lower target movement amplitudes.
- H4.2.: Gain and $SPNT_{diff}$ present with higher classification accuracy for neck pain patients when more than one movement profile is used as classifiers.
- H4.3.: Gain and $SPNT_{diff}$ do not differ in their ability to classify neck pain patients.

Based on the fifth research question aiming at studying classification accuracy for identifying intensity and frequency of visual symptoms using gain or $SPNT_{diff}$ in idiopathic neck pain patients, following hypothesis have been made:

- H5.1.: Gain and $SPNT_{diff}$ will be more accurate in classifying intensity of visual symptoms than their frequency in neck pain patients.

Based on the sixth research question aiming at studying alterations in pupillometric parameters of tonic (average pupil diameter) and phasic alertness (index of cognitive activity – ICA) during predictable and unpredictable SPNT tasks in idiopathic neck pain patients and healthy individuals, following hypothesis have been made:

- H6.1.: Patients with idiopathic neck pain have lower tonic and phasic alertness than healthy individuals in predictable and unpredictable target movement profiles during SPNT test.

- H6.2.: Tonic and phasic alertness during predictable smooth pursuit eye movements is statistically significantly lower than during unpredictable smooth pursuit eye movement in neck pain patients but not in healthy individuals.
- H6.3.: In neck pain patients' tonic and phasic alertness differ statistically significantly between neutral and neck torsion positions in unpredictable target movements, which is not present in healthy individuals.

Based on the seventh research question aiming at studying the relationship between two tests of cervicocephalic kinaesthetic sensibility and postural balance or eye movement control in idiopathic neck pain patients and healthy individuals, following hypothesis have been made:
- H7.1.: Cervicocephalic kinaesthetic tests (sense of movement and sense of position) present with relations to postural balance and smooth pursuit eye movement in neck pain patients and healthy controls.
- H7.2.: Cervicocephalic kinaesthetic tests (sense of movement and sense of position) present with stronger relations to postural balance and smooth pursuit eye movement in neck pain patients than in healthy controls.

Based on the eight-research question aiming at studying differences in two cerviocephalic kinaesthetic tests, postural balance and smooth pursuit eye movements between idiopathic neck pain patients, patients with whiplash associated disorders, mild traumatic brain injury patients (MBI) and healthy individuals, following hypothesis have been made:
- H8.1.: Patients with MBI present with similar deficits in cervicocephalic kinaesthetic tests as patients with traumatic and nontraumatic cervical pathologies.
- H8.2.: Patients with MBI present with similar deficits in SPNT tests as patients with traumatic and nontraumatic cervical pathologies.
- H8.3.: Patients with MBI present with similar deficits in postural balance in neutral and neck torsion positions as patients with traumatic and nontraumatic cervical pathologies.
- H8.4.: All patient groups (MBI, whiplash associated disorders and idiopathic neck pain) differ significantly from healthy individuals in all functional tests (postural balance, cervicocephalic kinaesthetic tests and smooth pursuit eye movements).

2 SCIENTIFIC WORKS

2.1 PUBLISHED SCIENTIFIC WORKS

2.1.1 Inter-visit reliability of smooth pursuit neck torsion test in patients with chronic neck pain and healthy individuals

Majcen Rosker Z., Vodicar M., Kristjansson E. 2021. Inter-visit reliability of smooth pursuit neck torsion test in patients with chronic neck pain and healthy individuals. Diagnostics, 11, 5: 752, doi: 10.3390/diagnostics11050752: 9 p.

Abstract

Visual disturbances are commonly reported in patients with neck pain. Smooth pursuit neck torsion (SPNT) test performed in neutral position and with trunk rotated under the stationary head has been used to discriminate between those with cervical component and those with-out. However, no studies investigated the reliability of the SPNT-test in patients with chronic neck pain and healthy controls. The aim of this study was to assess inter-visit reliability of the SPNT-test while applying different amplitudes and velocities of target movement. Thirty-two controls and thirty-one patients were enrolled in the study. The SPNT-test was performed in neu-tral position and through 45° torsion positions. The test was performed at 20°/s, 30°/s and 40°/s velocities and at 30°, 40° and 50° amplitudes of cyclic sinusoidal target movements. Interclass correlation coefficient and smallest detectable change were calculated for parameters of gain and SPNT-differences. In patients, moderate to good reliability was observed for gain at 40° and 50° amplitudes and for 20°/s and 30°/s velocities, while moderate to excellent reliability for gain was observed in controls. Both groups presented with moderate to good reliability for SPNT-difference. Our findings imply that amplitudes of 40° and 50° and velocities of 20°/s and 30°/s are the most reliable and should be applied in future studies assessing oculomotor functions during the SPNT test.

diagnostics

MDPI

Article

Inter-Visit Reliability of Smooth Pursuit Neck Torsion Test in Patients with Chronic Neck Pain and Healthy Individuals

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Abstract: Visual disturbances are commonly reported in patients with neck pain. Smooth pursuit neck torsion (SPNT) test performed in neutral position and with trunk rotated under the stationary head has been used to discriminate between those with cervical component and those without. However, no studies investigated the reliability of the SPNT-test in patients with chronic neck pain and healthy controls. The aim of this study was to assess inter-visit reliability of the SPNT-test while applying different amplitudes and velocities of target movement. Thirty-two controls and thirty-one patients were enrolled in the study. The SPNT-test was performed in neutral position and through 45° torsion positions. The test was performed at 20°/s, 30°/s and 40°/s velocities and at 30°, 40° and 50° amplitudes of cyclic sinusoidal target movements. Interclass correlation coefficient and smallest detectable change were calculated for parameters of gain and SPNT-differences. In patients, moderate to good reliability was observed for gain at 40° and 50° amplitudes and for 20°/s and 30°/s velocities, while moderate to excellent reliability for gain was observed in controls. Both groups presented with moderate to good reliability for SPNT-difference. Our findings imply that amplitudes of 40° and 50° and velocities of 20°/s and 30°/s are the most reliable and should be applied in future studies assessing oculomotor functions during the SPNT test.

Keywords: smooth pursuit neck torsion test; neck pain; reliability; oculomotor functions

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1. Introduction

According to research and anecdotal evidence, patients with chronic neck pain frequently complain about different characteristics of visual disturbances such as blurred vision, words jumping on the page and difficulty focusing and concentrating on reading [1]. These could be due to malfunctions of the oculomotor system that enable them to efficiently direct and keep their gaze on a slowly moving target [2].

An important component of the oculomotor system is smooth pursuit eye movements [3]. The task is often used to assess eye movement control with participants instructed to follow a horizontally moving target. In patients with neck pain, a proposed mechanism for disturbances in smoothly following the target is likely to be a mismatch between cervical proprioceptive input and its interconnection to the vestibular and the visual systems [4]. Disturbed afferent input from the cervical spine can lead to less accurate image stabilization of the moving target on or near the fovea, especially when the neck is in the torsioned position [5].

The SPNT test was first introduced in 1998 by Tjell and Rosenhall [6]. The test is performed in neutral and rotated positions (i.e., to the left and right sides, respectively) by rotating the trunk underneath the stationary head in order to recruit neck proprioception but not the vestibular mechanoreceptors. Consequently, the SPNT test is positive when the ability to track a horizontally moving target is decreased in rotated positions as compared to neutral position.

Since it was introduced the SPNT test has been frequently used to screen for deficiencies in eye movement control as a consequence of altered afferent input derived from cervical spine resulting in altered proprioceptive reflexes of the neck, the cervico-collic and cervico-ocular reflexes. Abnormal values of the test typically indicate error in proprioceptive information derived from the neck, transmitted by these reflexes. Over the years, many attempts have been made to elucidate deficits in oculomotor performance in patients with neck pain, but results remain inconclusive. Some researchers managed to find differences between patients and healthy individuals [7], while others were unable to make the same conclusion [8]. Possible reasons as to why inconsistencies exist could be the lack of methodological consensus in equipment used (i.e., electro-oculography vs. video-oculography), application of chin rest in some studies, different neck torsion positions used and automated or semi-automated analysis of eye movement data, all of which could possibly influence the results [7–10]. In addition, different target velocities and amplitudes were applied across studies, with velocities ranging from 20 [10] to 37°/s [9] and higher velocities used in healthy subjects [11]. Similarly, different amplitudes were applied while tracking a horizontally moving target [7,10], suggesting non-homogenous approaches while assessing oculomotor functions. Discrepancy in the literature due to methodological inconsistencies could possibly result in differences in sensitivity.

Surprisingly, to our knowledge there is no research assessing test-retest reliability of the SPNT test which is a crucial component when reporting diagnostic validity. Smooth pursuit eye movement test has been shown to range from moderate [11] to good reliability [12] in healthy individuals, but the test was only conducted in a neutral position. As the SPNT test is commonly applied in healthy subjects [13] and in patients with chronic neck pain [10], it would be of importance to assess inter-visit reliability while applying different target velocities and amplitudes in neutral and neck torsioned positions. Therefore, the aim of this research was to study inter-visit reliability of the SPTN test at different amplitudes, velocities and in neutral as well in torsion positions for healthy individuals and patients with chronic neck pain.

2. Materials and Methods

2.1. Participants

Sixty-four participants, of which thirty-two were patients with chronic neck pain (23 women and 9 men; average age 46.2 ± 4.8 years, range 27–53 years, average pain duration 13.6 ± 8.3 months) and thirty-two healthy individuals (19 women and 13 men; average age 37.8 ± 6.1 years, age range 23–49 years) participated in the study. Healthy participants were recruited among university staff, doctoral students and their friends. Patients with neck pain were referred by an orthopedic surgeon and were previously assessed for suitability via a telephonic interview. Each patient underwent an MRI, indicating some sort of lower cervical spine degenerative structural abnormality (disc protrusions or herniations at the levels from C5 to Th1, facet joints edema at the levels from C5 to Th1, low grade spondylolisthesis and cervical spinal stenosis). Inclusion criteria for both groups were age range between 18 and 55 years. Subjects with chronic idiopathic neck pain having had to experience pain in the neck from 6 months to 5 years, were required to have at least 50 degrees of cervical rotation to both sides, a minimum score of 36 on the Dizziness Handicap Inventory out of 100 and a minimum score of 5 out of 10 on pain visual analogue scale (VAS). The VAS scale was a 10 cm horizontal line with ends marked "no pain" (left) and the "worst pain imaginable" (right) [14,15]. All subjects had to be free from previous injury to the neck or head, shoulder or upper extremities pain, any neurological or vestibular disorders, present with no myelopathy and were required to take no medication or alcohol for the last 30 h prior to participating in the study. Participants were not included in the study in a case of corrected vision (e.g., use of glasses or contact lenses). All participants were required to read and sign a consent form. The study was approved by the national medical ethics committee (number: 0120–47/2020/6) and was performed in accordance to declaration of Helsinki.

2.2. Apparatus

A 100 Hz eye tracking device (Pro Glassems 2, Tobii, Danderyd, Sweden) was used to measure and record eye movements during smooth pursuit tasks. Prior to the experiment, a single target calibration routine was performed in the Tobii Pro Glasses Controller (Tobii Pro Glasses Controller, Tobii, Danderyd, Sweden). Participants were required to track a red dot target (size 0.5° of visual angle) projected on a white screen using a projector (Optoma ML1050ST LED Projector, Fremont, CA, USA) 150 cm away at eye level. Subjects were sitting on a custom-made rotatable chair with upper body fixed to the back support. Hip angle was 80° of flexion, while their feet were placed flat on the floor. Measurements were conducted by the same examiner.

2.3. Experiment

Patients and healthy subjects answered Dizziness Handicap Inventory and were required to fill out a VAS of pain intensity. The testing protocol consisted of 3 different chair positions: (1) facing forward position (their trunk and head were in a neutral position of 0° in the transverse plane), (2) eccentric rotation of the neck of 45° to the left and (3) to the right, respectively. The order of chair rotations was pseudo-randomized across subjects. In the neutral position the chair was aligned so that the participant was facing forward to the middle of the screen. During trunk rotation their head was in a neutral position while their trunk and lower body were rotated. All tests were performed in an isolated room with dim light.

Before the test, all subjects performed 5 familiarization warm up cycles. For each condition subjects were required to track 10 cycles of cyclic sinusoidal target movements with 60 s rest intervals. Subjects were tested at 3 different maximal target speeds (20°/s, 30°/s and 40°/s) and 3 different amplitudes of 30°, 40° and 50° in all 3 different chair positions, namely, neutral and rotation left and right, respectively. All tasks were performed in a random order. Each chair rotation was followed by a 5 min rest and a recalibration of the eye-tracking device. Participants completed the second oculomotor assessments with an average test-retest interval of 4 d (range 2–13 d).

2.4. Data Analysis

The eye movement data were filtered for blinks, saccades and fixations using Tobii Pro Lab software (Tobii Pro lab 1.145, Tobii, Danderyd, Sweden). The square waves (saccades directed counter to each other and having an interval of relative standstill) were removed from the eye movement data using custom-written software in Matlab (R2017b, MathWorks, Natick, MA, USA). The eye movement data were fitted with a corresponding reference sinusoid with synchronized signal acquisition starting points. Each fitted sinusoid consisted of 10 cycles with correspondingly fixed amplitude (converted from angular degrees to pixels) and frequency that matched the profile for each individual condition. The horizontal eye movements were analyzed using gain, calculated as the ratio between fitted eye velocity amplitude and visual target velocity amplitude as described by Tjell et al. [5]. Average gain from the 6th to 9th cycle from each task was used for reliability calculations. In addition, smooth pursuit neck torsion difference (SPNTdiff) was calculated as presented in Equation (1). The calculation was adapted and is similar to that described by Tjell et al. [5]

$$\text{SPNTdiff} = \text{Gain neutral} - (\text{Gain torsion L} + \text{Gain torsion R})/2 \quad (1)$$

Equation (1) gain neutral represents the average gain in the neutral position from the 6th to 9th cycle, Gain torsion L represents the average gain during the left neck torsion position from the 6th to 9th cycle and Gain torsion R represents the average gain during the right neck torsion position from the 6th to 9th cycle.

2.5. Statistical Analysis

Statistical analysis was performed in SPSS (SPSS 23.0 software, SPSS Inc., Chicago, IL, USA). Descriptive statistics (average and standard deviation) were calculated. Normality of distribution was analyzed separately using the Shapiro–Wilk test for each condition at each visit. A two-way mixed effect intraclass correlation coefficient for absolute agreement (ICC(3.1)) and a 95% confidence interval were used to ascertain reliability [16]. An ICC < 0.5 was treated as poor reliability, ICC 0.5–0.75 as moderate reliability, ICC 0.75–0.9 as good reliability and ICC > 0.9 as excellent reliability [17]. In addition, coefficient of variation (CV), standard error of measurement and smallest detectable change group (SDCg) were calculated.

3. Results

In total, 32 healthy subjects and 32 patients with chronic neck pain were included for the inter-visit reliability study. However, one of the patients with chronic neck pain decided not to continue with further assessment after the first visit. Gain and SPNTdiff parameters were normally distributed in all conditions observed.

3.1. Gain in Healthy Controls

The results of the reliability analysis for the healthy subjects are presented in Table 1. The ICC proved to vary from moderate to excellent. In general, the ICC was higher for the neutral position as compared to trunk rotated positions. The highest ICC (moderate to excellent) was observed for the 40° and 50° amplitude of target movement and at velocities of 20°/s and 30°/s. The lowest (moderate) reliability was observed for the 30° amplitude of target movement regardless of the target movement velocity. The SDCg ranged from 0.019 to 0.043 and did not show any changes with regard to the amplitude or velocity of the target movement.C[1]

Table 1. Average gain reliability for each task in healthy subjects.

Amplitude (°)	Velocity (°/s)	Position	ICC [1]	CI [2]	CV [3]	SEM [4]	SDCg [5]	Mean 1 [6]	Mean 2 [7]	SD 1 [8]	SD 2 [9]
30	20	N	0.759	0.541–0.925	0.018	0.009	0.022	0.952	0.933	0.013	0.015
30	20	L45	0.618	0.562–0.858	0.019	0.015	0.031	0.945	0.951	0.014	0.016
30	20	R45	0.723	0.607–0.834	0.018	0.021	0.038	0.948	0.966	0.013	0.016
30	30	N	0.776	0.621–0.847	0.013	0.012	0.034	0.922	0.937	0.010	0.010
30	30	L45	0.778	0.642–0.944	0.016	0.017	0.042	0.938	0.911	0.014	0.013
30	30	R45	0.761	0.508–0.884	0.014	0.016	0.037	0.906	0.919	0.012	0.012
30	40	N	0.681	0.557–0.822	0.019	0.011	0.031	0.889	0.902	0.012	0.015
30	40	L45	0.624	0.344–0.701	0.016	0.016	0.029	0.864	0.893	0.015	0.013
30	40	R45	0.596	0.403–0.694	0.017	0.022	0.041	0.875	0.841	0.016	0.012
40	20	N	0.764	0.654–0.853	0.015	0.008	0.019	0.946	0.977	0.013	0.012
40	20	L45	0.752	0.477–0.875	0.014	0.015	0.027	0.968	0.971	0.011	0.012
40	20	R45	0.757	0.632–0.826	0.015	0.023	0.034	0.940	0.962	0.012	0.013
40	30	N	0.813	0.617–0.924	0.013	0.013	0.029	0.939	0.968	0.011	0.010
40	30	L45	0.783	0.667–0.907	0.014	0.017	0.024	0.919	0.954	0.013	0.012
40	30	R45	0.802	0.684–0.955	0.018	0.016	0.041	0.922	0.960	0.012	0.013
40	40	N	0.753	0.606–0.891	0.018	0.010	0.031	0.906	0.922	0.016	0.014
40	40	L45	0.697	0.534–0.784	0.017	0.024	0.043	0.887	0.903	0.014	0.015
40	40	R45	0.737	0.502–0.901	0.020	0.017	0.026	0.895	0.916	0.015	0.015
50	20	N	0.863	0.554–0.787	0.012	0.007	0.024	0.971	0.965	0.010	0.011
50	20	L45	0.801	0.641–0.911	0.013	0.022	0.036	0.944	0.959	0.010	0.012
50	20	R45	0.761	0.531–0.839	0.011	0.014	0.040	0.936	0.924	0.009	0.010
50	30	N	0.9	0.832–0.980	0.013	0.010	0.033	0.968	0.951	0.010	0.011
50	30	L45	0.908	0.815–0.979	0.014	0.028	0.027	0.945	0.962	0.013	0.012
50	30	R45	0.871	0.811–0.937	0.017	0.021	0.031	0.960	0.943	0.012	0.014
50	40	N	0.773	0.586–0.892	0.019	0.013	0.025	0.897	0.914	0.015	0.016
50	40	L45	0.83	0.647–0.962	0.020	0.017	0.031	0.883	0.905	0.014	0.016
50	40	R45	0.693	0.337–0.924	0.016	0.020	0.028	0.903	0.921	0.016	0.014

[1] ICC—intraclass correlation coefficient; [2] CI—95% confidence interval; [3] CV—coefficient of variation; [4] SEM—standard error of measurement; [5] SDCg—smallest detectable change of a group; [6] Mean 1—group average at the first visit; [7] Mean 2—group mean at the second visit; [8] SD 1—group standard deviation at the first visit; [9] SD 2—standard deviation at the second visit.

3.2. Gain in Patients with Neck Pain

Table 2 presents the results of the reliability analysis for the group of neck pain patients. In this group the ICC varied from moderate to good and showed similar trends as in the healthy group. The most reliable conditions were the eye movement amplitudes of 40° and 50°, especially the 50° amplitude. The neutral position showed somewhat higher ICC compared to the trunk rotated positions, except for the condition of 50° amplitude and velocity of 20°/s. The SDCg was higher as in control group ranging from 0.028 to 0.083 and with no specific trend of increase or decrease regarding the amplitude and velocity of eye movement.

Table 2. Average gain reliability for each task in chronic neck pain patients.

Amplitude (°)	Velocity (°/s)	Position	ICC [1]	CI [2]	CV [3]	SEM [4]	SDCg [5]	Mean 1 [6]	Mean 2 [7]	SD 1 [8]	SD 2 [9]
30	20	N	0.691	0.421–0.751	0.025	0.011	0.032	0.830	0.817	0.018	0.019
30	20	L45	0.543	0.324–0.708	0.026	0.035	0.067	0.784	0.821	0.017	0.018
30	20	R45	0.594	0.440–0.752	0.032	0.028	0.064	0.761	0.745	0.016	0.023
30	30	N	0.739	0.653–0.888	0.024	0.015	0.039	0.696	0.724	0.021	0.016
30	30	L45	0.694	0.433–0.788	0.019	0.024	0.079	0.658	0.666	0.019	0.011
30	30	R45	0.701	0.612–0.775	0.022	0.037	0.083	0.673	0.727	0.024	0.012
30	40	N	0.758	0.622–0.874	0.032	0.010	0.028	0.703	0.686	0.020	0.021
30	40	L45	0.647	0.482–0.810	0.041	0.027	0.065	0.713	0.623	0.019	0.025
30	40	R45	0.606	0.457–0.723	0.045	0.042	0.058	0.736	0.595	0.014	0.022
40	20	N	0.762	0.640–0.851	0.014	0.014	0.040	0.798	0.805	0.014	0.011
40	20	L45	0.753	0.527–0.884	0.025	0.024	0.071	0.766	0.793	0.014	0.017
40	20	R45	0.751	0.600–0.841	0.023	0.019	0.069	0.774	0.791	0.019	0.018
40	30	N	0.788	0.594–0.902	0.226	0.012	0.033	0.720	0.735	0.014	0.016
40	30	L45	0.765	0.630–0.842	0.046	0.034	0.082	0.705	0.677	0.017	0.029
40	30	R45	0.757	0.651–0.924	0.031	0.031	0.067	0.691	0.700	0.018	0.021
40	40	N	0.733	0.522–0.834	0.045	0.007	0.036	0.639	0.629	0.017	0.028
40	40	L45	0.662	0.472–0.767	0.042	0.026	0.072	0.637	0.617	0.019	0.025
40	40	R45	0.581	0.389–0.656	0.033	0.029	0.068	0.631	0.621	0.013	0.019
50	20	N	0.744	0.609–0.833	0.021	0.012	0.029	0.837	0.820	0.013	0.015
50	20	L45	0.88	0.768–0.917	0.018	0.024	0.073	0.829	0.828	0.012	0.013
50	20	R45	0.864	0.783–0.950	0.015	0.022	0.064	0.809	0.818	0.013	0.009
50	30	N	0.879	0.831–0.940	0.042	0.090	0.036	0.737	0.716	0.025	0.030
50	30	L45	0.801	0.715–0.879	0.018	0.019	0.055	0.753	0.748	0.017	0.012
50	30	R45	0.774	0.622–0.861	0.030	0.025	0.069	0.613	0.658	0.024	0.017
50	40	N	0.759	0.652–0.876	0.023	0.013	0.030	0.669	0.670	0.017	0.016
50	40	L45	0.684	0.548–0.792	0.032	0.034	0.066	0.684	0.693	0.021	0.022
50	40	R45	0.735	0.576–0.874	0.031	0.032	0.075	0.614	0.593	0.012	0.018

[1] ICC—intraclass correlation coefficient; [2] CI—95% confidence interval; [3] CV—coefficient of variation; [4] SEM—standard error of measurement; [5] SDCg—smallest detectable change of a group; [6] Mean 1—group average at the first visit; [7] Mean 2—group mean at the second visit; [8] SD 1—group standard deviation at the first visit; [9] SD 2—standard deviation at the second visit.

3.3. SPNT Difference

Results of the reliability study for the SPNTdiff in both groups are presented in Table 3. In general, the ICC of SPNTdiff for both groups was lower (moderate to good) as compared to ICC for gain. In general, the ICC was higher for the control group as compared to the neck pain patient group. Similarly, ICC was higher at 40° and 50° amplitudes.

Table 3. Reliability of smooth pursuit neck torsion difference for both groups.

	Amplitude	Velocity (°/s)	ICC [1]	CI [2]	CV [3]	SEM [4]	SDCg [5]	Mean 1 [6]	Mean 2 [7]	SD 1 [8]	SD 2 [9]
Patients	30	20	0.642	0.417–0.804	1.467	0.018	0.051	0.056	0.011	0.082	0.069
	30	30	0.638	0.503–0.744	2.078	0.033	0.091	0.073	−0.014	0.080	0.074
	30	40	0.589	0.343–0.733	1.836	0.043	0.118	0.052	0.013	0.103	0.091
	40	20	0.746	0.437–0.811	1.283	0.038	0.107	−0.067	0.045	0.068	0.054
	40	30	0.751	0.494–0.819	2.856	0.018	0.049	0.001	0.006	0.046	0.057
	40	40	0.497	0.181–0.682	2.524	0.021	0.059	−0.021	0.092	0.100	0.067
	50	20	0.762	0.597–0.901	2.281	0.039	0.075	−0.031	0.046	0.107	0.122
	50	30	0.759	0.532–0.906	−5.233	0.048	0.133	−0.026	−0.037	0.119	0.126
	50	40	0.673	0.510–0.821	1.460	0.030	0.083	0.065	0.086	0.099	0.139
Healthy	30	20	0.689	0.504–0.916	1.322	0.014	0.015	0.004	0.009	0.077	0.062
	30	30	0.721	0.578–0.879	1.507	0.025	0.020	0.010	0.001	0.064	0.058
	30	40	0.701	0.527–0.821	2.013	0.037	0.051	0.040	−0.009	0.086	0.062
	40	20	0.812	0.699–0.972	1.750	0.022	0.017	0.002	0.005	0.042	0.065
	40	30	0.781	0.517–0.905	1.406	0.034	0.022	0.005	−0.004	0.059	0.080
	40	40	0.683	0.521–0.783	1.943	0.017	0.009	0.010	0.004	0.072	0.094
	50	20	0.78	0.685–0.921	−1.447	0.019	0.010	−0.001	−0.010	0.096	0.075
	50	30	0.773	0.573–0.961	1.612	0.041	0.025	0.008	−0.001	0.092	0.101
	50	40	0.751	0.494–0.887	1.818	0.023	0.019	0.002	0.001	0.073	0.097

[1] ICC—intraclass correlation coefficient; [2] CI—95% confidence interval; [3] CV—coefficient of variation; [4] SEM—standard error of measurement; [5] SDCg—smallest detectable change of a group; [6] Mean 1—group average at the first visit; [7] Mean 2—group mean at the second visit; [8] SD 1—group standard deviation at the first visit; [9] SD 2—standard deviation at the second visit.

4. Discussion

Based on the results, it can be concluded that overall there is moderate to good inter-visit reliability for average gain in most conditions for both groups as presented in Tables 1 and 2. SPNTdiff showed similar results with moderate and good reliability achieved for majority of conditions where patients with neck pain presented slightly lower ICC (Table 3). Results of our study show specific trends that could indicate amplitude rather than velocity as being more differentiating when reporting on the level of reliability. In addition, SDCg was higher in patients than in healthy controls, however, this was not related to amplitude or velocity of the target movement.

Most conditions with 50° amplitude of target movement showed superior reliability in both groups. This could be partially explained by the functional connections between extraocular and cervical muscle activity. In the study by Bexander and Hodges [18], neck muscle activity was investigated during eye movements in healthy subjects and in patients with whiplash associated disorders (WAD). Their findings imply that healthy subjects present with bilateral activation of obliquus capitis inferior (OI) when their eyes are moving in each direction while keeping their head in a neutral position. The OI is an important stabilizer of the atlanto-axial joint that contributes towards the first 45° of head rotation [19]. Moreover, Bexander and Hodges [18] report greater OI activity with increase in eye movement amplitude, suggesting higher co-contraction, possibly increasing stiffness and sensory feedback. Increased stiffness would generally lead to a more stable system and less spontaneous oscillations [20,21]. The latter could indicate more accurate control over head and neck posture providing less mechanical and sensory noise to the eye movements. This could possibly lead to higher reliability in the SPNT test which was in accordance with the results from our study where reliability of the SPNT test was superior at 50° amplitude and the lowest at 30° amplitude.

Results from our study show that neck pain patients had slightly poorer reliability than healthy individuals, but showed a similar trend where 50° amplitude of the SPNT test was most reliable. In addition to amplitude, eye movement velocity gives some further insights into reliability characteristics. Interestingly, both groups from our study presented with highest reliability in a neutral position when the target was moving at 30°/s that slightly increased when the trunk was rotated, which is in line with the above hypothesis. Similar findings about the reliability of the target movement velocity were found in the study by Ettinger et al. [11]. Both groups in our study showed highest gain at 20°/s, which is in line with the results from the study by Schalen et al. [22], however, this was not an indicator for superior reliability in our study.

In the study by Bargary et al. [12] reliability throughout three different speeds was assessed in healthy individuals, however, only overall reliability was reported. Their results presented slightly higher reliability than the results from our study. One of the reasons could be the use of a chin rest in their study. The latter is desirable and frequently used when assessing patients with neurological and psychological deficits [23,24] with the focus on excluding all external influences other than the observed pathology. However, these laboratory settings exclude possible head oscillations that are present in everyday tasks and could influence eye movement control [25]. An important contributor to accurate eye movement tracking and visual image stabilization is sufficient stability of the head [26]. It is well researched that patients with neck pain present with poor stability of the head and neck. In cases where a chin rest is used, impairments of the cervical spine afferent input and its effect on oculomotor control are less visible [27].

According to the study by Treleaven et al. [10], pain in the neck was not the main contributor to altered oculomotor functions. In their study, subjective symptoms of dizziness and unsteadiness related more to the deficits in eye movement control. These symptoms are suggested to be a result of sensory mismatch, commonly seen in those with cervical spine involvement. The limitation of our study was that the level of dizziness was not considered in the analysis, however, a cut-off score of at least 36 on the Dizziness Handicap Inventory out of 100 was required for enrolment of patients with neck pain in this study. Dizziness is suggested to be related to sensory impairments, therefore other neck pain disorder pathologies were not considered in our study, such as myelopathy [28–30], should be investigated in future studies in relation to eye movement control.

An additional parameter investigated in this study was SPNTdiff. Based on the results, inter-visit reliability for SPNTdiff was lower than for gain in different conditions. In the patient group, reliability of SPNTdiff was moderate, while healthy controls presented with moderate to good ICC. These results were expected as SPNTdiff is calculated from average gain in neutral and in trunk rotated positions. By including three different parameters with their own errors of measurement, the cumulative error could increase and consequently weaken reliability. The most reliable conditions in both groups were at velocities of 20°/s and 30°/s and at amplitudes of 40° and 50°. This is in line with the above observations describing possible factors contributing to reliability of gain. As SPNTdiff is calculated for both sides and described as percentage of difference, possible unilateral structural abnormalities could influence results not considered in our study.

Additionally, SDCg for gain was lower in healthy controls and higher in group of patients with chronic neck pain with no differences between conditions. Future studies should implement SDCg in smooth pursuit sensitivity studies comparing different groups of patients and healthy controls or effects of rehabilitation interventions. A similar trend was observed for SPNTdiff in patients with neck pain presenting with higher SDCg.

5. Conclusions

Although an attempt was made to recruit a homogenous group of patients, neck pain disorders have heterogenous pathologies with interconnected signs and symptoms. Therefore, reliability of the SPNT test might vary across different neck pain pathologies. Future studies should include the most reliable parameters and use them for further assessments of the most sensitive parameters across different traumatic and non-traumatic neck pain incidences.

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2.1.2 The influence of neck torsion and sequence of cycles on intra-trial reliability of smooth pursuit eye movement test in patients with neck pain disorders

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Abstract

The sensory mismatch commonly observed in patients with neck pain disorders could alter intra-trial reliability in simple implicit smooth pursuit eye movement tasks. This could be more pronounced when neck is in torsioned position (SPNT). The aim of this study was to explore the effects of neck torsion, target movement velocity and amplitude on intra-trial reliability of smooth pursuit eye movements in patients with neck pain disorders and healthy individuals. SPNT test was evaluated in thirty-two chronic neck pain patients and thirty-two healthy controls. Ten cycles were performed using video-oculography at three different velocities (20°s-1, 30°s-1 and 40°s-1) and at three different amplitudes (30°, 40° and 50°) of target movement. Intra-trial reliability and differences between average gain and SPNT difference from 2nd to 5th cycle and from 6th to 9th cycle were assessed using ICC3.1 and factorial analysis of variance respectively. Intra-trial reliability for gain and SPNT difference at all target movement amplitudes and velocities proved to be good to excellent in both observed groups. Patients with neck pain disorders presented with a trend of inferior gain performance between 6th to 9th cycle at 30°s-1 of target movement as compared to healthy individuals which was only evident when neck was in torsioned position. Although intra-trial reliability of smooth pursuit neck torsion test is good to excellent, the effects of learning are not as pronounced in patients with neck pain disorders.

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RESEARCH ARTICLE

The influence of neck torsion and sequence of cycles on intra-trial reliability of smooth pursuit eye movement test in patients with neck pain disorders

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Abstract
The sensory mismatch commonly observed in patients with neck pain disorders could alter intra-trial reliability in simple implicit smooth pursuit eye movement tasks. This could be more pronounced when neck is in torsioned position (SPNT). The aim of this study was to explore the effects of neck torsion, target movement velocity and amplitude on intra-trial reliability of smooth pursuit eye movements in patients with neck pain disorders and healthy individuals. SPNT test was evaluated in 32 chronic neck pain patients and 32 healthy controls. Ten cycles were performed using video-oculography at three different velocities (20° s^{-1}, 30° s^{-1} and 40° s^{-1}) and at three different amplitudes (30°, 40° and 50°) of target movement. Intra-trial reliability and differences between average gain and SPNT difference from the second to fifth cycle and from the sixth to ninth cycle were assessed using $ICC_{3,1}$ and factorial analysis of variance, respectively. Intra-trial reliability for gain and SPNT difference at all target movement amplitudes and velocities proved to be good to excellent in both observed groups. Patients with neck pain disorders presented with a trend of inferior gain performance between the sixth and ninth cycle at 30° s^{-1} of target movement as compared to healthy individuals which was only evident when neck was in torsioned position. Although intra-trial reliability of smooth pursuit neck torsion test is good to excellent, the effects of learning are not as pronounced in patients with neck pain disorders.

Keywords Head position · Neck pain patients · Oculomotor functions

Introduction

Patients with neck pain disorders suffer from a variety of subjective complaints and functional deficits (Kristjansson and Treleaven 2009), of which visual disturbances are frequently reported and have a negative effect on patient's quality of life such as difficulty reading and driving a car (Gimse et al. 1997; Takasaki et al. 2013; Teo et al. 2019).

Functional screening in neck pain disorder patients commonly reveal oculomotor deficits and difficulty smoothly following a target with their eyes, even more so when their neck is in a torsioned position (Tjell and Rosenhall 1998). Smooth pursuit neck torsion test (SPNT) presents with moderate to good inter-visit reliability (Majcen Rosker et al. 2021) and high sensitivity to differentiate between patients with neck pain disorders and healthy individuals (Gimse et al. 1996; Treleaven et al. 2005, 2011); however, some studies did not report differences between the two groups (Prushansky et al. 2004; Kongsted et al. 2007; Dispenza et al. 2011). Amongst other previously reported methodological inconsistencies (Centeno and Freeman 2008; Treleaven 2008), the number of cycles used for analysis of SPNT test varied between the studies and could potentially influence intra-trial reliability. While some studies did not report on the number of cycles patients were required to track a target (Prushansky et al. 2004), the majority of studies required patients to perform eye movement tracking

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during ten cycles of cyclic sinusoidal target movement (Gimse et al. 1996; Tjell and Rosenhall 1998; Tjell et al. 2002; Treleaven et al. 2005, 2011). In addition, some inconsistencies were present across the studies regarding the number of cycles used for further analysis. While some studies averaged all performed cycles (Janssen et al. 2015), Tjell et al. (2002) and Treleaven et al. (2005) averaged the sixth to ninth cycle and used them for further analysis. In general, intra-trial reliability is subjected to processes of motor learning and sensory–motor integration. When performing simple cyclic oculomotor tasks, short-term adaptations in eye movement control between individual cycles can take place (Herzfeld et al. 2020).

Smooth pursuit eye movement task is regarded as an implicit oculomotor control learning paradigm (Künzell et al. 2016), therefore improvements due to learning can take place. During smooth pursuit eye movements, new mapping from sensory input to motor output can take place (Braun et al. 2009). This new mapping can be subjected to fast-occurring and short-lasting adaptations in eye movement control, which can occur between consecutive cycles (Herzfeld et al. 2020). In the SPNT test, this could potentially lead to learning effects during the first few cycles, leading to improvements in eye movement control in the last few cycles. This is in accordance with results from the study by Kristjansson et al. (2004), where healthy subjects improved in kinaesthetic awareness on trial to trial basis; however this was not the case in those with disturbed cervical spine afferent input. The authors proposed that this could supposably be due to impaired sensory feedback from the cervical spine. This altered sensory feedback is believed to contribute significantly to sensory–motor mismatch. Due to direct neurophysiological connections between cervical spine afferent input, vestibular and visual system, sensory mismatch can affect eye movement control.

The main aim of this study was to assess intra-trial reliability between the first and the last half of the cycles performed during the SPNT test. Based on the results from the inter-visit reliability study by Majcen Rosker et al. (2021), differences in intra-trial reliability between different target movement amplitudes and velocities could be expected. We additionally hypothesize that patients with neck pain disorders will present with inferior reliability than healthy controls and show decrease in their performance over the last few cycles as compared to the first few cycles which would differ in different amplitudes and velocities of target movement.

Materials and methods

Participants

Patients with chronic neck pain and healthy individuals were enrolled in the study. Healthy individuals were recruited among university staff, doctoral students and their friends. Patients with neck pain were referred by an orthopaedic surgeon and were previously assessed for suitability via a telephone interview. Each patient with neck pain enrolled in the study previously underwent magnetic resonance imaging assessment. Patients with neck pain had to experience pain in the neck for at least 6 months to 5 years to be considered for the study and were required to present with a minimum of 50° of cervical rotation to each side. Inclusion criteria for both groups were age range between 18 and 55 years. Patients were required to mark pain intensity on a 10 cm horizontal line with ends marked "no pain" (left) and the "worst pain imaginable" (right) on the visual analogue scale (VAS) (Boonstra et al. 2014). For enrolment in the study patients with neck pain had to present with a minimum score of 4 on VAS. All participants were excluded if they reported any previous injuries to the head or neck, pain in the shoulder or upper extremities and any neurological or vestibular disorders. Prior to participating in the study, participants were required to be free from any medication or alcohol for at least 30 h. In a case of corrected vision (e.g. use of glasses or contact lenses) subjects were not included in the study. All participants were required to read and sign a consent form prior to participation. The study was approved by the national medical ethics committee (number: 0120–47/2020/6) and was performed in accordance with the Declaration of Helsinki.

Equipment

Smooth pursuit eye movements were measured using infrared video-oculography that has previously been recognized as valid and reliable tool (Leube et al. 2017; Stuart et al. 2019; Niehorster et al. 2020). A 100 Hz infrared eye-tracking device (Pro Glasses 2, Tobii, Danderyd, Sweden) was used to measure and record eye movements during smooth pursuit tasks. A single target calibration routine was performed in the Tobii Pro Glasses Controller (Tobii Pro Glasses Controller, Tobii, Danderyd, Sweden) prior to measurement. Individuals were required to track a horizontally moving target of a red dot (size 0.5° of visual angle) which was projected on a white screen 150 cm away at an eye level. Subjects were sitting on a custom-made rotatable chair with upper body fixed to the back support. Hip angle was 80° of flexion, while their feet were placed flat on the floor. All measurements were conducted by the same examiner.

Experiment

Patients with neck pain were required to mark pain intensity on VAS. The testing protocol consisted of three trunk rotations: (i) facing forward position (the trunk and head were in a neutral position), (ii) rotation of the trunk for 45° to the left and (iii) rotation of the trunk for 45° to the right under the stationary head. The order of chair rotations was pseudo-randomized across subjects. In the neutral position the anterior–posterior longitudinal axis of the chair was aligned in parallel to the line running from the middle of the screen and the middle of the chair. During trunk rotation their head was in a neutral position while their trunk was rotated. All tests were performed in an isolated room with dim light.

Before the test, all subjects performed five familiarizations warm-up cycles. For each condition, subjects were required to track ten cycles of cyclic sinusoidal target movements with 60 s rest intervals. Subjects were tested at three different maximal target speeds (20° s^{-1}, 30° s^{-1} and 40° s^{-1}) and three different amplitudes of 30°, 40° and 50° in all three different chair positions. All tasks were performed in a random order. Each chair rotation was followed by a 5 min rest and a recalibration of the eye-tracking device.

Data analysis

The eye movement data were filtered for blinks, saccades and fixations using Tobii Pro Lab software (Tobii Pro lab 1.145, Tobii, Danderyd, Sweden). Saccades directed counter to each other (the square waves) and having an interval of relative standstill were removed from the eye movement data using custom-written software in Matlab (R2017b, MathWorks, Natick MA, USA). The eye movement data were fitted with a corresponding reference sinusoid with synchronized signal acquisition starting points. Each fitted sinusoid consisted of ten cycles with correspondingly fixed amplitude (converted from angular degrees to pixels) and frequency that matched the profile for each individual condition. The horizontal eye movements were analysed using gain, calculated as the ratio between fitted eye velocity amplitude and visual target velocity amplitude as described by Tjell et al. (2002), gain torsion L represents the average gain during the left trunk rotation (right neck torsion) and gain torsion R represents the average gain during right trunk rotation (left neck torsion). Gain was averaged for the first half of the ten cycles (2nd to 5th cycle) and for the last half of the ten cycles (6th to 9th cycle). In addition, smooth pursuit neck torsion difference ($SPNT_{diff}$) was calculated as presented in Eq. (1). The calculation was adapted and is similar to that described by Tjell et al. (2002):

$$SPNT_{diff} = \text{gain neutral} - (\text{gain torsion L} + \text{gain torsion R})/2. \quad (1)$$

Equation (1): gain neutral represents the average gain in the neutral position, gain torsion L represents the average gain during the left neck torsion position and gain torsion R represents the average gain during the right neck torsion position. The average gains in neutral position and both trunk rotations were calculated from the second to fifth cycle or from the sixth to ninth cycle.

Statistical analysis

Statistical analysis was performed in SPSS (SPSS 23.0 software, SPSS Inc., Chicago, USA). Descriptive statistics (averages and standard deviations) were calculated. The normality of distribution was analysed separately for each condition using skewness and kurtosis. The homogeneity of variance was analysed with Levene's test. Data for gain were log transformed and data for $SPNT_{diff}$ were transformed using square-root transformation to achieve normal data distribution. A two-way mixed effect intra-class correlation coefficient for absolute agreement ($ICC_{3.1}$) and a 95% confidence interval were used to ascertain reliability (Koo and Li 2016). Poor reliability was regarded when ICC < 0.5, ICC 0.5–0.75 as moderate reliability, ICC 0.75–0.9 as good reliability and ICC > 0.9 as excellent reliability (Portney and Watkins 2009). In addition, standard error of measurement (SME) and smallest detectable change group (SDCg) were calculated. The differences between the average gain of the first and last few cycles were analysed with a factorial analysis of variance. For analysing difference in gain, four factors were used: trunk rotation (neutral and trunk rotations for 45° to the left and right), target movement amplitude (30°, 40° and 50°), target movement velocity (20° s^{-1}, 30° s^{-1} and 40° s^{-1}) and cycles (averaged first and last cycles). For analysing difference in $SPNT_{diff}$, three factors were included: target movement amplitude (30°, 40° and 50°), target movement velocity (20° s^{-1}, 30° s^{-1} and 40° s^{-1}) and cycles (averaged first and last cycles). A two-tailed *T* test for dependent samples was used for post hoc analysis. All *p* values in *T* test were adjusted for multiple comparisons according to the Benjamin and Hochberg procedure. The level of statistical significance (*p*) was set at $p < 0.05$. The effect size in *T* tests was calculated using Cohen's *d* (*d*).

Results

Sixty-four individuals participated in the study, 32 patients with chronic neck pain and 32 healthy individuals (demographic data are presented in Table 1). In the neck pain group, cervical spine magnetic imaging assessment presented disc protrusions or herniations at the levels from C4 to Th1 in 24 patients, 9 patients presented with facet joints osteoarthritis at the levels from C5 to Th1, 11 patients presented with low-grade spondylolisthesis and 9 patients presented with cervical spinal stenosis. Twenty-five patients presented with a combination of at least two types of structural deformities; however in 7 patients, only one type of

Table 1 Demographic data

	Idiopathic neck pain patients ($n=32$)	Asymptomatic controls ($n=32$)
Gender	23 women/9 men	19 women/13 men
Average age (age range)	46.2 ± 4.8 years (27–53 years)	37.8 ± 6.1 years (23–49 years)
Average pain duration	13.6 ± 8.3 months	

structural impairment was present. The average VAS score in neck pain patients was 6 ± 1.2.

Reliability analysis

The results of the reliability analysis for gain and $SPNT_{diff}$ are presented in Tables 2 and 3, respectively. ICC for gain in both observed groups ranged from good to excellent in neutral and left trunk rotation positions and moderate to excellent for right trunk rotation. No amplitude or velocity-specific trends in ICC were observed in any of the studied groups. Comparable results were observed for $SPNT_{diff}$; however, the ICC tended to be smaller as compared to ICC for gain.

The SDCg for gain during neutral position ranged from 0.071 to 0.335 in patients with neck pain disorders and from 0.141 to 0.253 in healthy controls and was slightly higher for heathy controls in most of the conditions observed. In neck torsioned positions the SDCg was slightly higher in both groups (from 0.067 to 0.399 in neck

Table 2 Reliability analysis for gain

Position	A	V	Patients with neck pain				Healthy subjects			
			ICC	CI	SEM	SDCg	ICC	CI	SEM	SDCg
N	50	20	0.887	0.731–0.953	0.013	0.038	0.888	0.660–0.964	0.022	0.061
		30	0.926	0.823–0.969	0.003	0.009	0.899	0.681–0.968	0.011	0.032
		40	0.848	0.630–0.937	0.012	0.033	0.819	0.455–0.941	0.004	0.013
	40	20	0.980	0.851–0.974	0.003	0.011	0.814	0.446–0.939	0.025	0.071
		30	0.907	0.778–0.961	0.030	0.084	0.904	0.699–0.969	0.004	0.012
		40	0.854	0.646–0.940	0.018	0.052	0.780	0.694–0.930	0.006	0.017
	30	20	0.889	0.733–0.954	0.030	0.083	0.930	0.786–0.977	0.001	0.003
		30	0.905	0.768–0.961	0.006	0.018	0.901	0.701–0.968	0.008	0.022
		40	0.629	0.122–0.847	0.014	0.039	0.815	0.357–0.947	0.012	0.035
L 45	50	20	0.911	0.778–0.964	0.031	0.086	0.302	0.532–0.795	0.006	0.018
		30	0.913	0.724–0.968	0.021	0.058	0.915	0.726–0.974	0.007	0.019
		40	0.834	0.529–0.941	0.012	0.035	0.951	0.837–0.986	0.002	0.006
	40	20	0.833	0.572–0.935	0.008	0.023	0.975	0.920–0.992	0.001	0.004
		30	0.848	0.603–0.941	0.006	0.019	0.643	0.253–0.893	0.007	0.020
		40	0.825	0.518–0.937	0.013	0.037	0.910	0.712–0.972	0.003	0.009
	30	20	0.765	0.362–0.913	0.012	0.035	0.367	0.396–0.915	0.005	0.016
		30	0.959	0.892–0.984	0.0181	0.050	0.707	0.385–0.917	0.012	0.035
		40	0.993	0.917–1	0.005	0.016	0.981	0.835–0.997	0.007	0.020
R 45	50	20	0.732	0.310–0.895	0.010	0.029	0.915	0.727–0.974	0.024	0.068
		30	0.685	0.192–0.876	0.016	0.044	0.53	0.333–0.895	0.004	0.012
		40	0.846	0.605–0.940	0.012	0.035	0.83	0.454–0.948	0.004	0.012
	40	20	0.759	0.367–0.908	0.029	0.080	0.383	0.537–0.809	0.010	0.028
		30	0.867	0.650–0.950	0.012	0.034	0.878	0.615–0.962	0.005	0.014
		40	0.712	0.207–0.893	0.014	0.039	0.773	0.269–0.933	0.005	0.014
	30	20	0.937	0.830–0.977	0.017	0.049	0.949	0.834–0.984	0.009	0.024
		30	0.829	0.505–0.938	0.017	0.048	0.781	0.260–0.934	0.018	0.051
		40	0.799	0.337–0.707	0.011	0.031	0.966	0.886–0.990	0.001	0.005

This table presents the results of the reliability analysis, where N—neutral neck position; L—neck rotation for 45° to the left; R—neck rotation for 45° to the right; A—target movement amplitude; V—target movement velocity; ICC—Intra-class correlation coefficient; CI—confidence interval; SEM—standard error of measurement; SDCg—smallest detectable change

Table 3 Reliability analysis for $SPNT_{diff}$

A	V	Patients with neck pain				Healthy subjects			
		ICC	CI	SEM	SDCg	ICC	CI	SEM	SDCg
50	20	0.648	0.588–0.862	0.013	0.037	0.797	0.658–0.938	0.005	0.015
	30	0.641	0.604–0.859	0.011	0.031	0.897	0.677–0.968	0.004	0.011
	40	0.848	0.597–0.943	0.005	0.015	0.850	0.702–0.956	0.007	0.019
40	20	0.687	0.577–0.880	0.014	0.040	0.542	0.501–0.854	0.009	0.026
	30	0.760	0.653–0.912	0.006	0.018	0.686	0.761–0.911	0.005	0.016
	40	0.619	0.641–0.869	0.009	0.026	0.911	0.706–0.973	0.003	0.010
30	20	0.891	0.700–0.961	0.004	0.013	0.867	0.582–0.959	0.004	0.014
	30	0.820	0.520–0.934	0.007	0.021	0.938	0.796–0.981	0.002	0.008
	40	0.701	0.457–0.846	0.012	0.034	0.762	0.522–0.875	0.006	0.018

This table presents the results of the reliability analysis, where A—target movement amplitude; V—target movement velocity; ICC—intra-class correlation coefficient; CI—confidence interval; SEM—standard error of measurement; SDCg—smallest detectable change

pain patients and from 0.088 to 0.334 in healthy controls), but no systematic differences between the two groups were observed. For $SPNT_{diff}$, SDCg ranged from 0.151 to 0.676 in patients and from 0.096 to 0.220 in healthy subjects. No amplitude or velocity specific trends were observed; however, $SPNT_{diff}$ at 40° amplitude and 20° s^{-1} velocity presented with the highest SEM and SDCg.

Differences between the first and last cycles

The results of the factorial analysis of variance for gain are presented in Table 4 and for $SPNT_{diff}$ in Table 5. In patients with neck pain, statistically significant differences between average gain of the first and last cycles, at different target movement velocities and at different trunk rotations, were observed. In healthy controls, no statistically significant differences were observed. No statistically significant

Table 4 Factorial analysis of variance for gain

Factor	Patients with neck pain			Healthy subjects		
	F	*p*	η^2	*F*	*p*	η^2
Trunk_rotation	18.715	0.000	0.035	2.418	0.090	0.007
Amplitude	1.631	0.196	0.003	0.564	0.569	0.002
Velocity	51.544	0.000	0.092	21.185	0.041	0.087
First_last	0.020	0.043	0.000	0.560	0.454	0.001
Trunk_rotation * Amplitude	1.285	0.274	0.005	0.392	0.815	0.002
Trunk_rotation * Velocity	0.321	0.864	0.001	0.843	0.498	0.005
Trunk_rotation * First_last	0.217	0.047	0.042	0.223	0.800	0.001
Amplitude * Velocity	2.032	0.088	0.008	0.292	0.883	0.002
Amplitude * First_last	0.161	0.852	0.000	0.155	0.857	0.000
Velocity * First_last	0.436	0.647	0.001	0.134	0.874	0.000
Trunk_rotation * Amplitude * Velocity	2.183	0.027	0.017	0.826	0.579	0.010
Trunk_rotation * Amplitude * First_last	0.770	0.174	0.003	0.294	0.882	0.002
Trunk_rotation * Velocity * First_last	0.467	0.260	0.002	0.258	0.905	0.002
Amplitude * Velocity * First_last	0.293	0.883	0.001	0.076	0.989	0.000
Trunk_rotation * Amplitude * Velocity * First_last	0.187	0.993	0.001	0.245	0.982	0.003

This table presents the results of the 3×3×3×2 factorial analysis of variance, where factor—represents individual factor; trunk rotation—represents three different trunk rotations (neutral and trunk rotation for 45° to the left and right); amplitude—represents three different target movement amplitudes (30°, 40° and 50°); velocity—represents three different target movement velocities (20°/s, 30°/s and 40°/s); First_last—represents the average gain for the first few cycle and for the last few cycles; *F*—f statistics; *p*—statistical significance; η^2—partial eta square for the group of patients with neck pain disorders and the group of healthy participants

Table 5 Factorial analysis of variance for $SPNT_{diff}$

Factor	Patients with neck pain			Healthy subjects		
	F	*p*	*n2*	*F*	*p*	*n2*
Amplitude	1.401	0.248	0.010	0.118	0.889	0.001
Velocity	0.023	0.977	0.000	2.297	0.103	0.022
First_last	0.350	0.555	0.001	0.108	0.742	0.001
Amplitude * Velocity	2.620	0.055	0.035	0.985	0.417	0.019
Amplitude * First_last	0.588	0.556	0.004	0.598	0.551	0.006
Velocity * First_last	0.463	0.630	0.003	0.387	0.680	0.004
Amplitude * Velocity * First_last	0.794	0.530	0.011	0.293	0.883	0.006

This table presents the results of the 3×3×2 factorial analysis of variance, where Factor—represents individual factor; Amplitude—represents three different target movement amplitudes (30°, 40° and 50°); Velocity—represents three different target movement velocities (20°/s, 30°/s and 40°/s); First_last—represents the average $SPNT_{diff}$ for the first few cycle and for the last few cycles; *F*—f statistics; *p*—statistical significance; η^2—partial eta square for the group of patients with neck pain disorders and group of healthy participants

differences using the factorial analysis of variance were observed for $SPNT_{diff}$ except for target movement velocity.

In Figs. 1 and 2, averages and standard deviations for the pairs of the first and last cycles at each target movement amplitude and velocity for both groups are presented for gain and $SPNT_{diff}$, respectively. In addition, the result for statistically significant post hoc tests are presented. Post hoc tests revealed statistically significant differences between average gain in the first and last cycles for the left and right trunk rotation at 50° target movement amplitude and for right trunk rotation at 30° target movement amplitude. At 40° target movement amplitude, no statistically significant differences were observed; however a trend of decreased average gain was present. No statistically significant differences between the first and the last cycles were observed for $SPNT_{diff}$.

Discussion

The main purpose of the study was to assess intra-trial reliability of the SPNT test and differences in eye movement performance between the first and the last part of the ten cycles in patients with neck pain disorders and healthy individuals. Both groups presented with good to excellent intra-trial reliability for gain in the neutral as well as in both neck torsioned positions. Additionally, there were no differences presented in gain performance between the first and the last cycles in the neutral position, which was evident for both groups. However, a trend was observed in that patients with neck pain disorders presented with lower gain performance in the last few cycles when performing the SPNT test in both neck-torsioned positions. $SPNT_{diff}$ presented with lower reliability as compared to gain; however, no differences between the first and the last cycles were observed.

SPNT test has been frequently applied in clinical and research settings for many years (Tjell and Rosenhall 1998; Della Casa et al. 2014). Intra- and inter-examiner reliability of clinical tests has been suggested to vary from moderate to substantial (Jørgensen et al. 2014); however, automated stimuli presentation is generally more desirable to use in patients with neck pain disorders as it has been shown to present with superior validity, sensitivity and specificity (Daly et al. 2018). As the automated stimuli are presented in a more controlled environment, it is expected to be more reliable, which is in line with the results of our study where good to excellent intra-trial reliability was observed for both gain and $SPNT_{diff}$ at all target movement amplitudes and velocities regardless of the neck torsion position and the observed group. Patients from our study presented with comparable reliability to healthy subjects regardless of the pain and impairments that patients with neck pain experienced. A possible explanation for good to excellent reliability in patients with neck pain disorders could be the lack of movement variability generally observed in this group of patients (Alsultan et al. 2019). Consequently, lack of movement variability could present with more stereotypical head positioning and therefore decreased information flow for adjusting eye movement relative to head oscillations, which would be more evident in the neck torsion position. Interestingly, Kristjansson et al. (2004) found that in their study assessing neck movement control patients with cervicogenic deficit presented with higher reliability than asymptomatic subjects. This is in line with the above speculations and was partially confirmed from the results of our study, where patients presented with slightly superior ICC and lower SDCg for gain in the neutral position as compared to healthy subjects.

Regardless of the high intra-trial reliability, some differences were observed in gain performance between the first and last part of the analysed cycles during the SPNT test; however, this was not observed in the neutral position.

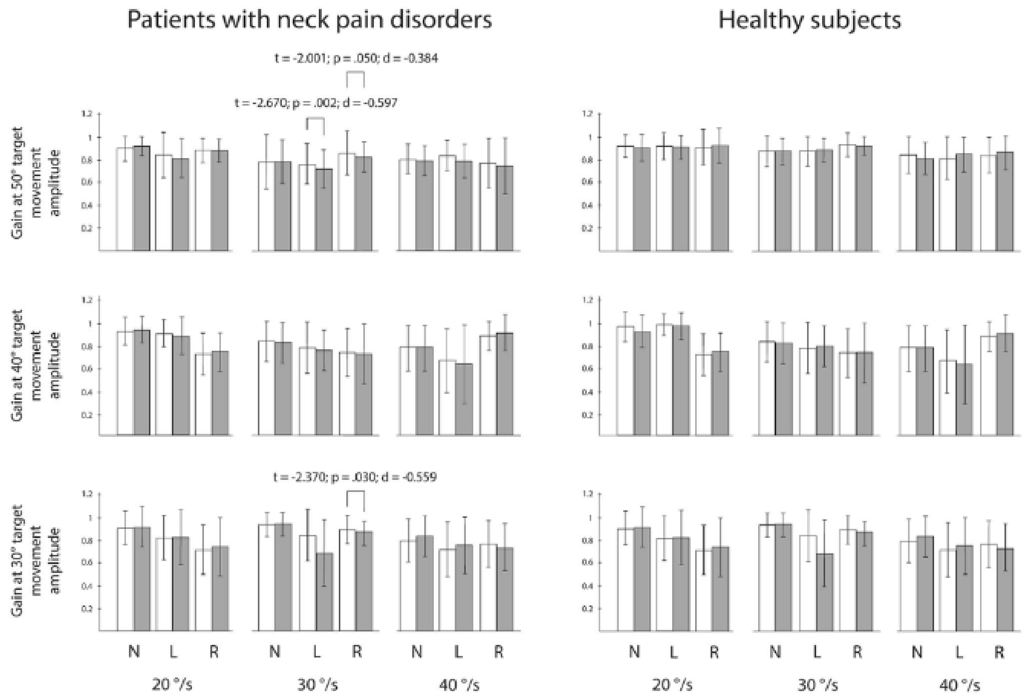

Fig. 1 Differences in gain between the first part and the second part of the SPNT test. This figure presents the averages and standard deviations of the first and the second set of cycles (white and grey columns, respectively) and results of the post hoc tests for both groups, where vertical axis represents the average gain at different target movement amplitudes; horizontal axis represents the different target movement velocities and head positions; N—neutral neck position; L—neck rotation for 45° to the left; R—neck rotation for 45° to the right; t—represents the t statistics; p—statistical difference and; d—effect size expressed as Cohen d

Patients with neck pain disorders are suggested to present with poorer performance when their neck is in torsioned position (Tjell et al. 2002; Treleaven et al. 2005). A proposed reason is altered kinaesthetic awareness which can be a consequence of sensory mismatch resulting primarily from central processes. Abundance of muscle spindles found in the upper cervical spine acts as important contributors towards kinaesthetic senses, responding to ramp-and-hold stretch with a rate of discharge that is proportional to the magnitude of the stretch (Proske and Gandevia 2012). Consequently, prolonged time spent in a neck torsioned position could additionally alter sensory–motor control, possibly further affecting eye movement control. The latter was observed in our study, but only when the neck was in torsioned position, as the last few cycles showed decreased gain in patients with neck pain, but not in healthy controls.

Neck muscles that possess high muscle spindle density can influence coordination of extraocular muscles and consequently oculomotor control (Velay et al. 1994). In addition, proprioceptive information from the extraocular muscles and sensory retinal information presents an important sensory source for detecting target movement direction and speed (Madelain and Krauzlis 2003). Integration of this information amongst others takes place in the brainstem, cerebellum and pons and can be modified via learning processes. Herzfeld et al. (2020) have proposed a model of neurological processes governing cerebellar learning during smooth pursuit eye movement test. This model predicts faster and delayed adaptations during smooth pursuit eye movements. Delayed adaptations involve visual and memory adaptations that slowly develop with higher volume of repetitions. On the contrary, faster adaptations enable online changes in oculomotor control with a limited duration. This is partially in line with the results from our study where healthy subjects presented with improvements in eye movement performance during the last few cycles; however, neck pain patients presented with a trend of decrease in eye movement performance during the last few cycles especially

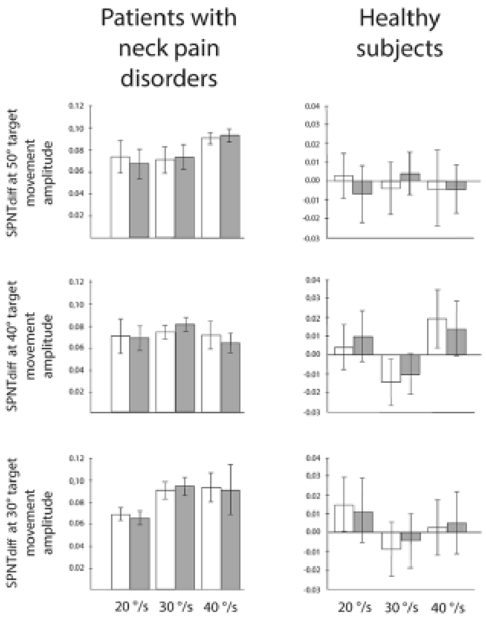

Fig. 2 Differences in $SPNT_{diff}$ between the first part and the second part of the SPNT test. This figure presents averages and standard deviations of the first and the second set of cycles (white and grey columns, respectively) and results of the post hoc tests for both groups, where the vertical axis represents the average $SPNT_{diff}$ at different target movement amplitudes; the horizontal axis represents the different target movement velocities

during neck torsion position. The results from our study are in line with findings from other authors where both faster and delayed adaptations were present in healthy subjects but not in patients with neck pain (Kristjansson et al. 2004). Patients with neck pain disorders have been shown to present with altered sensory–motor integration as a result of changes in sensory input (Andrew et al. 2018). This maladaptation has been shown to be nonresponsive to faster and delayed motor learning process, leading to preservation of altered movement patterns. Although to date these processes have not been directly studied in oculomotor functions, inability to improve oculomotor control during tasks such as SPNT test in patients with neck pain disorders could be present. In our study, this was observed as a trend of decreased gain in the last as compared to first few cycles in neck pain patients, but not in healthy controls. No such trends were observed for $SPNT_{diff}$. Consequently, the parameter of gain could be more sensitive to such alterations in sensory control as compared to $SPNT_{diff}$. Since $SPNT_{diff}$ is calculated from gain, it is still suggested to use the last few cycles for further analysis in clinical practice.

Smooth pursuit eye movements consist of smooth eye movements and sporadic saccadic jumps of focal vision, which can be less accurate. The parameter of gain gathered during the SPNT test is calculated as the ratio between the amount of smooth pursuit tracking without the saccadic intrusions relative to the target movement amplitude. Less accurate saccades prevent longer periods of smooth pursuit target tracking and consequently decrease gain. Therefore, the direction and amplitude of saccades are important to enable smoother target pursuit. According to Land (2006), smooth pursuit system works on its own at lower target velocities of up to 15° s^{-1}. Above this velocity, the smooth pursuit eye movement is supplemented by saccadic eye movement system. The results of our study showed that differences in gain between the first and the last few cycles in patients with neck pain disorders were present at the target movement velocity of 30° s^{-1} during neck torsion position, irrespective of the target movement amplitude. Decreased gain during velocity of 30° s^{-1} in the last few cycles could indicate a deficit in smooth pursuit and saccadic eye movement system interplay. Since both gain and $SPNT_{diff}$ showed moderate to excellent itra-trial reliability, it is advisable that velocities of 30° s^{-1} should be used in future studies.

Although some new findings for better understanding the SPNT test have been presented in our study, the heterogeneity of patients with neck pain could have influenced the results. In addition to different structural impairments, symptoms such as dizziness and unsteadiness could importantly influence these results and should be sub-grouped in future studies. Moreover, patients with neck pain as a consequence of traumatic event, such as whiplash-associated disorders, could present with further impairments and possibly different results.

Conclusion

The SPNT test presented with good to excellent intra-trial reliability in patients with neck pain disorders and in healthy individuals. In addition, results from our study suggest that gain and $SPNT_{diff}$ during the sixth to ninth cycle should be averaged and used consistently throughout the studies and in clinical practice to provide a more efficient test for assessing oculomotor performance in patients with neck pain.

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Declarations

Conflict of interest The authors declare no conflict of interest.

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2.1.3 Oculomotor performance in patients with neck pain: does it matter which angle of neck torsion is used in smooth pursuit eye movement test and is the agreement between angles dependent on target movement amplitude and velocity?

Majcen Rosker Z., Vodicar M., Kristjansson E. 2022. Oculomotor performance in patients with neck pain: does it matter which angle of neck torsion is used in smooth pursuit eye movement test and is the agreement between angles dependent on target movement amplitude and velocity? Musculoskeletal Science and Practice, 59: 10235, doi: 10.1016/j.msksp.2022.102535: 9 p

ABSTRACT

Neck torsion manoeuvre is thought to affect eye movement control via afferent sensory drive in neck pain disorders patients. Literature reports inconsistencies regarding the angle of neck torsion most commonly used across the studies. The goal of this study was to determine the level of agreement in oculomotor performance between two most commonly used neck torsion angles during smooth pursuit neck torsion test (SPNT). A cross-sectional design was used in thirty-two neck pain patients and thirty-two healthy individuals. Gain and SPNTdiff were measured during SPNT test at 30° and 45° of neck torsion angle, at 30°, 40° and 50° of target movement amplitudes and three different target movement velocities (20°s-1, 30°s-1 and 40°s-1) using eye tracking device. Bland-Altman plots and correlation analysis were used to study the agreement between the two angles. Small to medium correlations and wide bias confidence intervals suggest medium level of agreement in gain or SPNTdiff between the two neck torsion angles for chronic neck pain patients, but higher in healthy individuals. Higher agreement in gain was observed at lager target movement amplitudes and at slower target movement velocities, however this trend was not observed for SPNTdiff. Level of agreement between the two angles in SPNT test depends on the amplitude and velocity of the moving target. In cases when subjects within the same study are not able to perform 45° of neck torsion, 50° amplitude and 20°s-1 velocity of target movement are more suitable to reach higher agreement between the angles.

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Original article

Oculomotor performance in patients with neck pain: Does it matter which angle of neck torsion is used in smooth pursuit eye movement test and is the agreement between angles dependent on target movement amplitude and velocity?

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Smooth pursuit neck torsion test
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ABSTRACT

Background: Neck torsion manoeuvre is thought to affect eye movement control via afferent sensory drive in neck pain disorders patients. Literature reports inconsistencies regarding the angle of neck torsion most commonly used across the studies.
Objectives: The goal of this study was to determine the level of agreement in oculomotor performance between two most commonly used neck torsion angles during smooth pursuit neck torsion test (SPNT).
Design: A cross-sectional design was used in thirty-two neck pain patients and thirty-two healthy individuals.
Method: Gain and $SPNT_{diff}$ were measured during SPNT test at 30° and 45° of neck torsion angle, at 30°, 40° and 50° of target movement amplitudes and three different target movement velocities ($20°s^{-1}$, $30°s^{-1}$ and $40°s^{-1}$) using eye tracking device. Bland-Altman plots and correlation analysis were used to study the agreement between the two angles.
Results: Small to medium correlations and wide bias confidence intervals suggest medium level of agreement in gain or $SPNT_{diff}$ between the two neck torsion angles for chronic neck pain patients, but higher in healthy individuals. Higher agreement in gain was observed at lager target movement amplitudes and at slower target movement velocities, however this trend was not observed for $SPNT_{diff}$.
Conclusion: Level of agreement between the two angles in SPNT test depends on the amplitude and velocity of the moving target. In cases when subjects within the same study are not able to perform 45° of neck torsion, 50° amplitude and $20°s^{-1}$ velocity of target movement are more suitable to reach higher agreement between the angles.

1. Introduction

Patients with neck pain disorders frequently experience a plethora of symptoms that cannot be found from any other region of the body (Bogduk and Govind, 2009; Janssen et al., 2015; Treleaven, 2017). The uniqueness of the cervical spine has been proposed by the direct neurophysiological connection between proprioceptive information from various structures of the cervical spine, vestibular and visual system (Peterson, 2004). As suggested by Bexander and Hodges (2019), eye movement amplitude and velocity can influence neck muscle activity and consequently their proprioceptive feedback, that is important for oculomotor control during smooth pursuit eye movements. It is therefore not surprising that visual disturbances commonly present during daily activities when tracking moving objects with their eyes (e.g. while driving a car, riding a bicycle, observing traffic while crossing a road and others) are frequently reported in those with cervical spine disorders (Gimse et al., 1997; Treleaven and Takasaki, 2014).

In 1998 Tjell and Rosenhall (1998) proposed a clinical test to assess eye movement control that was shown to present with high sensitivity and specificity (90% and 91% respectively) in discriminating between patients with cervical spine disorders and the control group; consisting of patients with central vertigo, Meniere's disease and healthy controls.

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The test is usually performed in a neutral position and when the trunk is rotated underneath a stationary head to 45° to the left and to the right, called smooth pursuit neck torsion test (SPNT). The test is considered positive when the accuracy of smooth pursuit eye movements (gain) is worse in the torsioned positions compared to the neutral position, causing an increased difference in gain between the neutral and torsioned positions, called smooth pursuit neck torsion difference ($SPNT_{diff}$). Deficiencies in eye movement control during SPNT test result from altered proprioceptive reflexes of the neck, the cervico-collic and cervico-ocular reflexes. Positive SPNT test typically indicate error in proprioceptive information derived from the neck, transmitted by these reflexes (Tjell and Rosenhall, 1998).

Although SPNT test has been proposed as a specific test for detecting cervical spine related oculomotor dysfunction (Treleaven et al., 2008) some controversy remains regarding the specificity of the test, as some studies failed to detect differences in the SPNT test between those with cervical spine disorders and healthy individuals (Dispenza et al., 2011; Kongsted et al., 2007; Prushansky et al., 2004). These could be due to methodological inconsistencies found throughout different studies (Dispenza et al., 2011; Kongsted et al., 2007; Treleaven et al., 2005) which include investigating oculomotor disfunction in SPNT test by using different target movement amplitudes and velocities (Janssen et al., 2015; Treleaven et al., 2005). This has partially been confirmed by a recent study presenting with higher reliability of the SPNT test when using target movement amplitudes of 40° and 50° and lower reliability when applying 30° of target movements amplitude (Majcen Rosker et al., 2021). In addition, target movement velocities of $20°s^{-1}$ and $30°s^{-1}$ presented with higher reliability as opposed to $40°s^{-1}$. However, it is still unknown how changes in amplitude and velocity during different neck torsion positions affect gain and $SPNT_{diff}$ during SPNT test (Prushansky et al., 2004; Tjell and Rosenhall, 1998).

Reduced cervical spine range of motion is a frequent functional impairment reported by patients with neck pain (Prushansky et al., 2004). Consequently, patients may struggle to complete the SPNT test at 45° of neck torsion and require testing at a reduced range such as 30° of neck torsion. While most studies focused on investigating eye movement control at 45° of neck torsion (Tjell and Rosenhall, 1998; Treleaven et al., 2005), some studies applied 30° (Dispenza et al., 2011; Prushansky et al., 2004) reporting different results. To our knowledge, only one study has investigated eye movement control in neck pain patients using different angles of neck torsion with a standardised target movement amplitude and velocity (Janssen et al., 2015). Their results indicated poorer performance of the SPNT test with larger neck torsion angles. Therefore, it could be suggested, that using different neck torsion angles or using them interchangeably may reduce sensitivity of the test findings for identifying a positive SPNT test.

To our knowledge no study has systematically evaluated the agreement between these two test angles. Hence, the main goal of this study was to determine which target movement amplitudes and velocities would provide with highest level of agreement between the two neck torsion angles (i.e. 45° versus 30°) in patients with neck pain disorders and healthy individuals.

2. Materials and methods

2.1. Participants

Patients with chronic neck pain were referred from an orthopaedic outpatient clinic and were previously assessed for suitability via a telephone interview. Asymptomatic controls were recruited among university staff, doctoral students and their friends. All participants had to present with a minimum of 50° of cervical rotation to each side, had to be free from previous traumatic injury to the neck or head, shoulder or upper extremities pain, any neurological or vestibular disorders, and were required to take no medication or alcohol for 30 h prior to participating in the study. Participants were not included in the study in a case of corrected vision (e.g. use of glasses or contact lenses) in order to avoid any potential eye detection inaccuracies. In addition, they were required to read and sign a consent form prior to participation. The study was approved by the national medical ethics committee (number: 0120–47/2020/6) and was performed in accordance with the declaration of Helsinki.

2.2. Assessment

Patients completed the Dizziness handicap inventory (DHI) and mark pain intensity using a visual analogue scale (VAS). Each patient enrolled in the study underwent magnetic resonance imaging assessment. The SPNT testing protocol consisted of five different neck positions: (i) facing forward position (the trunk and head were in a neutral position), (ii) right neck torsion position at 30° (rotation of the trunk underneath the stationary head to 30° to the left), (iii) left neck torsion position at 30° (rotation of the trunk underneath the stationary head to 30° to the right), (iv) right neck torsion position at 45° (rotation of the trunk underneath the stationary head to 45° to the left) and (v) left neck torsion position at 45° (rotation of the trunk underneath the stationary head to 45° to the right). The order of neck torsion positions was pseudo-randomized across subjects. In the neutral position the anterior-posterior longitudinal axis of the chair was aligned in parallel to the line running from the middle of the screen and the middle of the chair. Hip angle during sitting on a chair was 80° of flexion, while feet were placed flat on the floor. All measurements were conducted by the same examiner in an isolated room with dim light.

Before the test, all subjects performed 5 familiarizations warm up cycles. For each condition subjects were required to track 10 cycles of cyclic sinusoidal target movements with their eyes followed by 60 s rest interval. Subjects were tested at 3 different maximal target movement velocities ($20°s^{-1}$, $30°s^{-1}$ and $40°s^{-1}$) and 3 different target movement amplitudes of 30°, 40° and 50° in all 5 different neck positions. All conditions (different target movement velocities and amplitudes during all neck positions) were performed in a random order. After completing SPNT test at each neck position, recalibration of the eye-tracking device was performed during a 5 min rest.

2.3. Equipment

Smooth pursuit eye movements were measured using infrared video-oculography that has previously been recognized as valid and reliable tool (Leube et al., 2017; Niehorster et al., 2020; Stuart et al., 2019). A 100 Hz infrared eye tracking device (Pro Glasses 2, Tobii, Danderyd, Sweden) was used to measure and record eye movements during smooth pursuit tasks. Prior to the experiment, a single target calibration routine was performed in the Tobii Pro Glasses Controller (Tobii Pro Glasses Controller, Tobii, Danderyd, Sweden). Individuals were required to track a horizontally moving target of a red dot (size 0.5° of visual angle) which was projected (Optoma ML1050ST LED Projector, Fremont, USA) with a 100-Hz refresh rate on a white screen 150 cm away at an eye level (Deravet et al., 2018). Subjects were sitting on a custom-made rotatable chair with upper body fixed to the back support.

2.4. Data analysis

The eye movement data were filtered for blinks, saccades and fixations using Tobii Pro Lab software (Tobii Pro lab 1.145, Tobii, Danderyd, Sweden). The square waves (saccades directed counter to each other and having an interval of relative standstill) were removed from the eye movement data using custom-written software in Matlab (R2017b, MathWorks, Natick, MA, USA). The eye movement data were fitted with a corresponding reference sinusoid with synchronized signal acquisition starting points. Each fitted reference sinusoid consisted of 10 cycles with correspondingly fixed amplitude (converted from angular degrees to pixels) and frequency that matched the profile for each individual condition. First and last 10% of the amplitude in each eye movement cycle were removed from further analysis. The horizontal eye movements were analysed using gain, calculated as the ratio between eye velocity amplitude and visual target velocity amplitude as described by Tjell et al. (2002). Gain torsion R represents the average gain during right neck torsion position from the 6th to 9th cycle and gain torsion L represents the average gain during left neck torsion position from the 6th to 9th cycle (Majcen Rosker et al., 2022). In addition, smooth pursuit neck torsion difference ($SPNT_{diff}$) was calculated as presented in Equation (1). The calculation was adapted and is similar to that described by Tjell et al. (2002):

$$SPNT_{diff} = \text{Gain neutral} - (\text{Gain torsion L} + \text{Gain torsion R})/2 \quad (1)$$

Equation (1): gain neutral represents the average gain in the neutral position from the 6th to 9th cycle, gain torsion L represents the average gain during the left neck torsion position from the 6th to 9th cycle and gain torsion R represents the average gain during the right neck torsion position from the 6th to 9th cycle.

2.5. Statistical analysis

Statistical analysis was performed using SPSS (SPSS 26.0 software, SPSS Inc., Chicago, USA). Age differences between groups were analysed using T-test and the effect size calculated using Cohen d. Skewness and kurtosis were calculated in order to analyse data distribution. Due to non-normality of data distribution median and interquartile range (IQR) were calculated for each gain and $SPNT_{diff}$ parameter in order to provide descriptive statistics (Supplementary Table 1). A Spearman correlation coefficient (r) was used to analyse the correlation between gain or $SPNT_{diff}$ at 30° and 45° of neck torsion angle for each individual pair of target movement amplitude and velocity separately. The r was treated as no correlation for $r < 0.3$, small correlation for $0.29 < r < 0.5$, medium correlation for $0.49 < r < 0.7$ and high correlation for $r > 0.69$ (Field, 2009). For all correlation analysis p values were adjusted for multiple comparisons according to the Benjamin and Hochberg procedure, with statistical significance (p) set at $p < .05$. Further, Bland-Altman analysis was performed as follows (Giavarina, 2015) to study the agreement between the two angles for measuring gain and $SPNT_{diff}$ separately. First, the mean gain or $SPNT_{diff}$ was calculated for two corresponding angles for each individual pair of target movement amplitude and velocity followed by calculating the difference between the two angles that were plotted on a x-y scatterplot as suggested by Bland and Altman (1986) and Giavarina (2015). Furthermore, differences in gain or $SPNT_{diff}$ between the two angles were averaged for each individual pair of target movement amplitude and velocity separately in each group to present measurement bias. Due to non-normally distributed differences between the two angles the confidence intervals were calculated via a quantile regression as suggested by Chen and Kao (2021).

3. Results

3.1. Participants

Thirty-four patients with idiopathic neck pain and thirty-two asymptomatic controls were recruited for the study. Two idiopathic neck pain patients were excluded from the study due to unbearable pain during the test. Twenty-three women and nine men were included in the patient group and nineteen women and thirteen men in the control group. The mean age of the patient's group was 46.2 ± 4.8 years (age range 27–53 years) and the mean age of the control group 37.8 ± 6.1 years (age range 23–49 years). The control group was statistically significantly older as compared to the patient group ($p = .48$; $d = 0.110$). In the neck pain group cervical spine magnetic imaging assessment presented disc protrusions or herniations at the levels from C4 to Th1 in 24 patients, 9 patients presented with facet joint osteoarthritis at the levels from C5 to Th1, 11 patients presented with low-grade spondylolisthesis and 9 patients presented with cervical spinal stenosis. Twenty-three patients had a combination of at least two types of structural deformity, however in 9 patients only one type of structural deformity was present. Average pain duration in the patient's group was 13.6 ± 8.3 months and average VAS score was 4.8 ± 1.3. The average score for DHI in the patient group was 25 ± 3. Control group presented with no pain and no complaints of dizziness.

3.1.1. Correlation analysis

Results of the correlation analysis between gain at the two angles for each of the two groups are presented in Table 1. Correlations between gain at the two angles were positive and statistically significant at all target movement amplitudes and velocities in both groups. Healthy participants showed medium to high correlations at all pursuit amplitudes with highest correlations present at 50°, regardless of the target movement velocity. In the neck pain patient group small to high correlations were observed with no indicated differences between smooth pursuit amplitudes and velocities.

Results of the correlation analysis for $SPNT_{diff}$ at two neck torsion angles for both groups are presented in Table 1. In general, neck pain patient group presented with slightly lower correlations as compared to healthy group. In healthy controls high positive corelations, while in neck pain patient group medium to high positive correlations ($p < .05$) were observed for 50° target movement amplitude at 20°s^{-1} and 30°s^{-1} target movement velocities. At 40° target movement amplitude high correlations were observed when applying velocity of 40°s^{-1} for both groups. Additionally, high correlations were observed for both groups when following a target at 30° amplitude and velocity of 30°s^{-1}.

3.1.2. Bland Altman analysis for gain in healthy subjects

Bland Altman plots for healthy subjects are presented in Fig. 1 and corresponding bias with its confidence intervals in Table 2. Gain of most healthy participants was located above .9 for all target movement

Table 1
Correlations between gain and $SPNT_{diff}$ at 30° and 45° neck torsion angles.

	Amplitude	Velocity	Side	Healthy subjects		Neck pain patients	
				r	*P*	*R*	*p*
Gain	50	20	R	.747	.000	.558	.000
			L	.549	.001	.673	.000
		30	R	.717	.000	.684	.000
			L	.545	.001	.507	.001
		40	R	.685	.000	.632	.000
			L	.492	.003	.677	.000
	40	20	R	.578	.000	.572	.000
			L	.508	.002	.482	.001
		30	R	.480	.004	.690	.000
			L	.556	.010	.558	.000
		40	R	.467	.005	.505	.000
			L	.693	.000	.473	.002
	30	20	R	.453	.006	.708	.000
			L	.345	.043	.543	.000
		30	R	.517	.023	.693	.000
			L	.590	.000	.490	.001
		40	R	.435	.010	.646	.000
			L	.411	.017	.780	.000
$SPNT_{diff}$	50	20		.836	.001	.773	.005
		30		.927	.000	.641	.046
		40		.555	.077	.509	.110
	40	20		.336	.312	.489	.127
		30		.518	.102	.497	.120
		40		.764	.006	.847	.001
	30	20		.536	.890	.434	.183
		30		.836	.001	.808	.003
		40		.457	.623	.547	.164

$SPNT_{diff}$ – smooth pursuit neck torsion difference; L – left neck torsion; R – right neck torsion; *r* – Spearman correlation coefficient; p – p value.

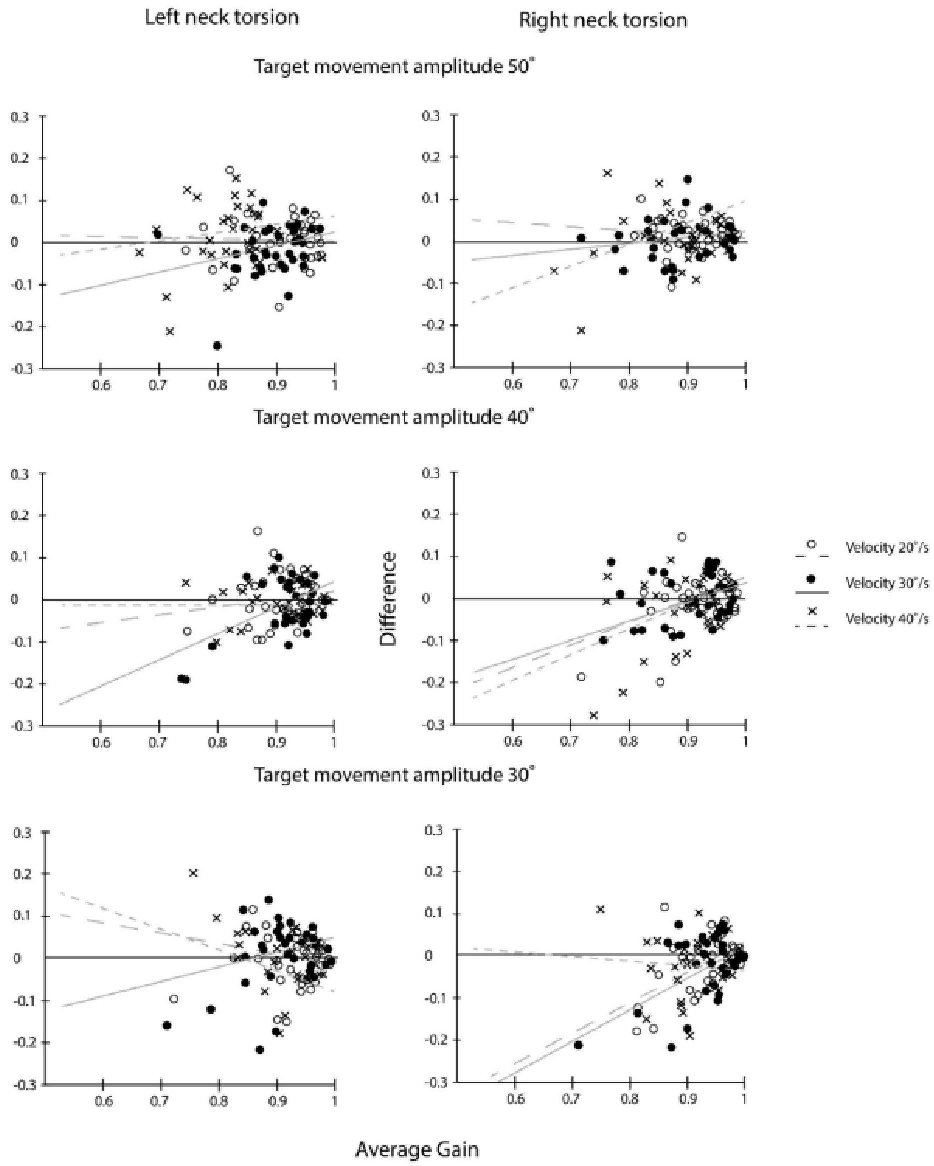

Fig. 1. Bland Altman plots for gain in SPNT task in healthy subjects.
Fig. 1 depicts Bland Altman plots for the right (right side plots) and left (left side plots) neck torsion positions. The first row of plots represents 50° amplitude, the second row 40° amplitude and the third row 30° of target movement amplitude during SPNT test. At each graph differences between gain at the two neck torsion positions are plotted against average gain for the two angles for each individual subject. In addition, each plot contains data for all three target movement velocities used in the SPNT test.

amplitudes and velocities. As indicated by bias, the two angles proved to be relatively similar, with a trend of slightly lower gain at 45° of neck torsion when using 50° amplitude during smooth pursuit task. At 40° amplitude and especially 30° amplitude, the gain tended to be higher when applying 45° of neck torsion which is indicated by negative bias. As presented by trend lines in Fig. 1, bias increased with lower average gain, indicating larger differences in gain between the two observed neck torsion angles.

3.1.3. Bland Altman analysis for gain in neck pain patients

Bland Altman plots for neck pain patients are presented in Fig. 2 and corresponding bias with its confidence intervals in Table 2. Average gain

Table 2
Bias and confidence intervals for determining agreement in gain and $SPNT_{diff}$ between 30° and 45° of neck torsion.

	A	V	Side	Healthy subjects			Neck pain patients		
				Bias	Upper	Bias	Lower	Upper	Lower
Gain	50	20	R	.014	.082	-.047	-.021	.135	-.187
			L	.005	.103	-.092	-.015	.141	-.166
		30	R	.040	.147	-.076	.004	.250	-.243
			L	.019	.110	-.083	-.006	.203	-.208
		40	R	-.011	.104	-.097	.014	.233	-.191
			L	.001	.075	-.075	.025	.247	-.275
	40	20	R	.004	.128	-.099	-.024	.187	-.236
			L	-.014	.057	-.094	-.032	.211	-.267
		30	R	-.022	.078	-.122	.029	.242	-.207
			L	-.011	.084	-.118	.077	.309	-.185
		40	R	-.020	.051	-.100	.108	.336	-.124
			L	-.000	.076	-.085	.110	.374	-.176
	30	20	R	-.022	.094	-.113	-.006	.189	-.188
			L	-.009	.099	-.107	.083	.247	-.092
		30	R	-.023	.064	-.121	.080	.222	-.059
			L	.016	.120	-.074	.097	.399	-.193
		40	R	-.043	.048	-.099	.075	.347	-.202
			L	-.046	.049	-.124	.019	.387	-.357
$SPNT_{diff}$	50	20		-.001	-.022	.019	.004	-.030	.039
		30		.002	-.023	.019	-.001	-.070	.067
		40		-.003	-.104	.097	-.009	-.085	.006
	40	20		.006	-.029	.042	.003	-.075	.082
		30		.013	-.063	.090	-.017	-.126	.091
		40		.005	-.030	.041	-.006	-.058	.045
	30	20		.004	-.031	.041	-.019	-.013	.094
		30		.005	-.037	.048	-.008	-.088	.072
		40		.010	-.010	.012	-.002	-.065	.060

$SPNT_{diff}$ – smooth pursuit neck torsion difference; *A – amplitude of the target movement in the smooth pursuit neck torsion test; V – velocity of the target movement in the smooth pursuit neck torsion test; L – left neck torsion; R – right neck torsion; Bias – average difference between gain at 30° and 45° of neck torsion for the specific group; Upper – upper boundary of the confidence interval; Lower – lower boundary of the confidence interval.*

in neck pain patients was distributed between 0.7 and 0.9. Bias in neck pain patients indicated less systematic differences between gain in the two observed angles at different target movement amplitudes of SPNT test. As compared to healthy participants, neck pain patients presented with larger bias, especially at 40° and 30° amplitude of the SPNT test. The trend lines for individual SPNT test velocities showed less consistent behaviour but tended to indicate slightly larger positive bias at lower average gain. This observation primarily indicates lower gain at 45° of neck torsion as compared to 30° of neck torsion.

3.1.4. Bland Altman analysis for $SPNT_{diff}$ in both groups

Bland Altman plots for $SPNT_{diff}$ in both groups are presented in Fig. 3 and corresponding bias with its confidence intervals in Table 2. As compared to healthy participants, average $SPNT_{diff}$ distribution in neck pain patients was wider (also indicated by larger IQR in Supplementary Table 1). Bias for the $SPNT_{diff}$ in neck pain patients was comparable to healthy participants and proved to be smaller at 50° of target movement amplitude. The trend lines for individual target movement velocities showed less consistent behaviour but indicate larger bias when $SPNT_{diff}$ moves away from 0.

4. Discussion

The goal of our study was to determine which target movement amplitudes and velocities would provide with highest level of agreement in gain and $SPNT_{diff}$ between 30° and 45° of neck torsion positions during SPNT test in patients with neck pain disorders and healthy individuals. Based on small to high level of correlations and wide bias confidence intervals it could be suggested that there is moderate agreement for gain and $SPNT_{diff}$ between the two neck torsion angles for patients with chronic neck pain but larger agreement in healthy individuals. While 30° of target movement amplitude presented with small level of agreement between the two angles in both groups, 40° and 50° target movement amplitudes showed larger overall agreement for gain. In addition, level of agreement for gain at target movement velocities of 20°s^{-1} and 30°s^{-1} was larger than during 40°s^{-1}. These results suggest that the level of agreement in gain between the two angles depends on the amplitude and velocity of the moving target. Moreover, a trend of larger differences between the two neck torsion angles (smaller agreement) was observed in participants with lower gain performance in both groups. On the contrary, agreement in $SPNT_{diff}$ did not seem to be as affected by amplitude or velocity, with largest agreement observed for target movement amplitude of 50° and velocity of 20°s^{-1} in neck pain patients. Based on the aforementioned suggestions, it could be recommended that neck torsion angles should not be used interchangeably when measuring oculomotor control in idiopathic neck pain patients.

4.1. Neck torsion angle

Results from our study indicate that the two neck torsion angles do not necessarily present with the same outcome during SPNT test. This is evident for both parameters (gain and $SPNT_{diff}$) in neck pain patient group but less in healthy individuals. A possible reason for moderate agreement in patients with neck pain disorders might be explained by the pathological mechanisms affecting afferent sensory drive, that may arise from stimulation of different cervical spine structures during the two neck torsion angles used in our study and consequently alter oculomotor control.

Mechanoreceptive and nociceptive nerve endings in the cervical facet capsules contribute towards forming kinaesthetic awareness and pain sensation of the cervical spine (McLain, 1993). Dysfunction of facet joints can contribute towards decreased range of motion, possibly stimulating facet capsule proprioceptors at smaller angles of neck torsion. Consequently, patients may only be able to perform SPNT test at angles of up to 30° of neck torsion (Prushansky et al., 2004). On the contrary, in those with no limitations in cervical spine range of motion, test can be performed at 45° of neck torsion which would present with additional stimulation of muscle spindles as they respond with the

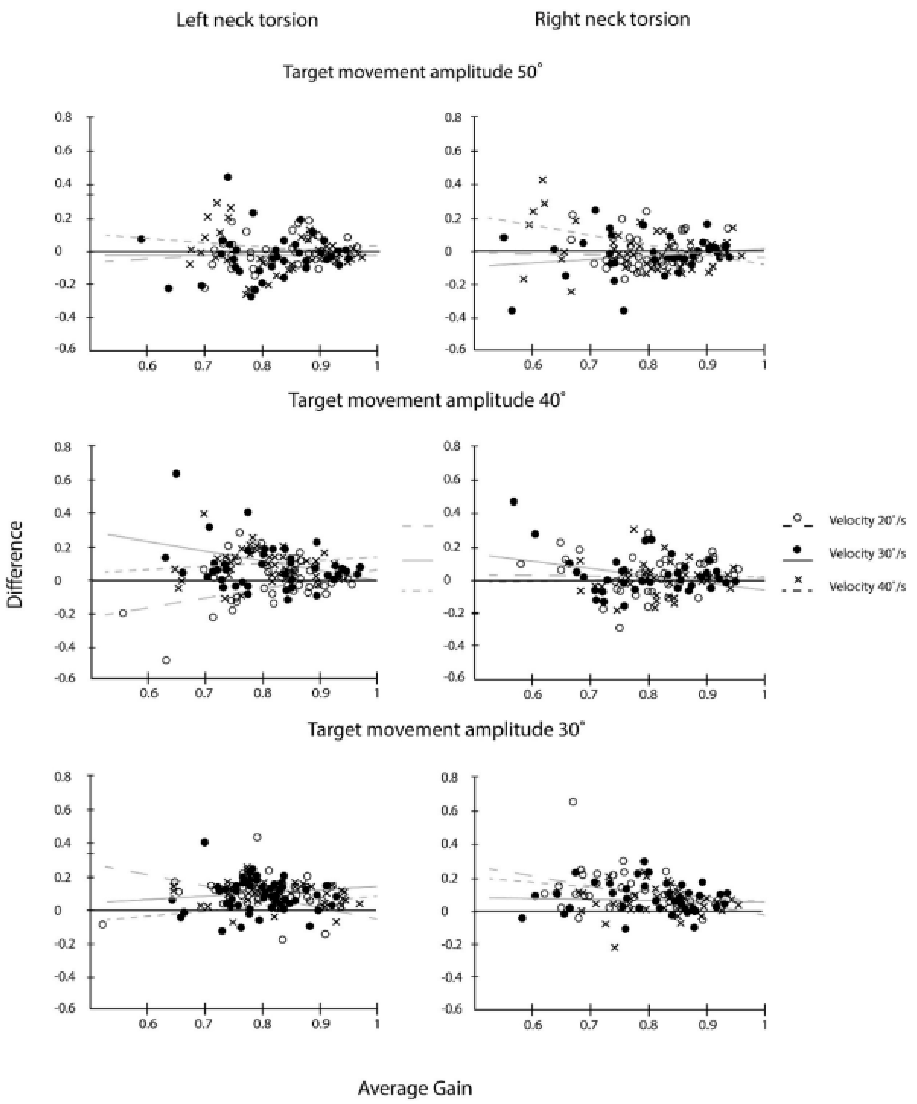

Fig. 2. Bland Altman plots for gain in SPNT task in neck pain patients.
Fig. 2 depicts Bland Altman plots for the right (right side plots) and left (left side plots) neck torsion positions. The first row of plots represents 50° amplitude, the second row 40° amplitude and the third row 30° of target movement amplitude during SPNT test. At each graph differences between gain at the two neck torsions plotted against average gain for the two angles for each individual subject. In addition, each plot contains data for all three target movement velocities used in the SPNT test.

discharge rate that is proportional to the magnitude of the stretch (Proske and Gandevia, 2012). According to Proske and Gandevia (2012) joint receptors do not play as significant role in kinaesthesia as muscle spindles. In patients with neck pain disorders muscle spindles are additionally stimulated via increased activity of the III and IV afferent nociceptive drive (Liu et al. 2021). Increased sensitivity of muscle spindles can lead to erroneous proprioceptive signals, especially when high density cervical spine muscle spindles (Kulkarni et al., 2001) are unevenly sensitized, causing asymmetrical effect on kinaesthesia (Liu et al. 2021). In addition, increased torsion of the cervical spine stimulates Pacinian and Ruffini corpuscles located in the anulus fibrosis of the degenerated intervertebral discs, providing dysfunctional signalling of head and neck movements (Liu et al. 2021). Based on the aforementioned suggestions proprioceptive information available for the head and eye movement control differs between the two neck torsion angles.

The notion of less abundant proprioceptive drive at smaller angles of

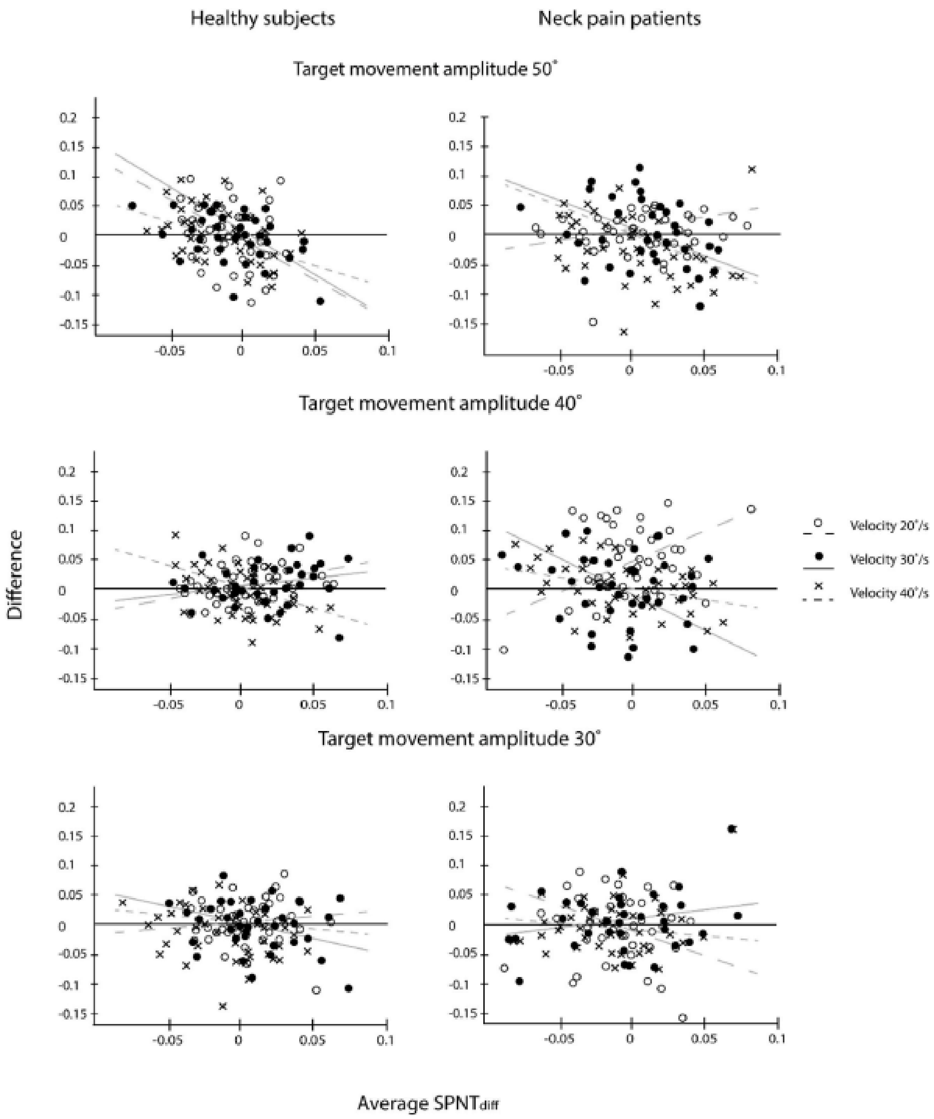

Fig. 3. Bland Altman plots for SPNT$_{diff}$.
Fig. 3 depicts Bland Altman plots for the healthy subjects (left side plots) and neck pain patients (right side plots). The first row of plots represents 50° amplitude, the second row 40° amplitude and the third row 30° of target movement amplitude during SPNT test. At each graph difference between SPNT$_{diff}$ at the two neck torsion positions are plotted against average SPNT$_{diff}$ for the two angles for each individual subject. In addition, each plot contains data for all three speeds used in the SPNT test.

neck torsion has been supported by up-to-date research where those performing SPNT test at the neutral and at 30° of neck torsion angle found no differences between neck pain patients and healthy individuals. While some studies reported that this was the maximum angle tolerated by their patients (Prushansky et al., 2004), Dispenza et al. (2011) did not give clear justification as to why they have used this angle. On the contrary, other studies (Tjell et al. 2002; Tjell and Rosenhall 1998; Treleaven et al. 2005) using 45° of neck torsion were able to identify differences between neck pain patients and the control group. This line of reasoning has been further supported by the study performed by Janssen et al. (2015). Their study suggested that gain decreased while increasing angle of neck torsion in the neck pain patient group but not in healthy individuals. Although in their study no statistical analysis were done to compare differences between the angles, figures from their results indicated that gain at 30° of neck torsion was similar to the gain in the neutral position, but higher than gain at 45° of neck torsion. This suggests that 30° and 45° neck torsion angles do not present with the same results, which has also been confirmed by the results of our study.

4.2. Target movement amplitude

According to the results of this study, target movement amplitude applied during SPNT test is related to the agreement between the two neck torsion angles for gain but less for $SPNT_{diff}$. Target movement amplitudes of 40° and 50° for gain and 50° for $SPNT_{diff}$ presented with superior agreement between the two angles than target movement amplitude of 30°. According to Majcen Rosker et al. (2021) 30° of target movement amplitude is characterized by inferior reliability, which could additionally decrease the level of agreement between the two angles when applying lower target movement amplitudes. This could be partially explained by the influence of eye movement amplitude on neck muscle activity and consequently proprioceptive information available for oculomotor control (Velay et al., 1994). According to Bexander and Hodges (2019) bilateral activation of obliquus capitis inferior is observed when head is stationery and eyes are moving laterally which increases with larger eye movement amplitudes, suggesting higher co-contraction. Based on these suggestions, increased activation of obliquus capitis inferior due to lateral eye movements could provide more accurate sensory feedback counteracting sensory mismatch and improving oculomotor control resulting in higher agreement between the two angles applied in our study.

4.3. Target movement velocity

Based on the results from our study velocities of $20°s^{-1}$ and $30°s^{-1}$ for gain and $20°s^{-1}$ for $SPNT_{diff}$ indicated larger agreement between the two observed neck torsion angles in both observed groups. Higher agreement at lower velocities could be explained by the interplay of smooth pursuit and saccadic eye movement systems. In general, smooth pursuit system works on its own up to target movement velocities of $15°s^{-1}$, above this velocity smooth pursuit is supplemented by saccadic eye movement system (Land, 2006). Higher velocities would be accompanied by more saccadic eye movements, which could decrease the amount of smooth pursuit eye movements and consequently gain. Therefore, it was somehow expected that larger agreement between the two neck torsion angles would be observed for lower velocities as compared to higher target movement velocities. This is in line with the previous reliability study by Majcen Rosker et al. (2021) where target movement velocities of $20°s^{-1}$ and $30°s^{-1}$ were characterised with superior reliability than higher target movement velocities. Results of our study support to-date literature investigating patients with neck pain disorders where target movement velocities of $20°s^{-1}$ have been most commonly applied (Dispenza et al., 2011; Janssen et al., 2015; Tjell et al. 2002; Tjell and Rosenhall 1998; Treleaven et al. 2005).

4.4. Study limitations and future considerations

Based on the moderate agreement between the two neck torsion angles, they should not be used interchangeably in clinical practice and research settings. Although a parameter of gain has reached better agreement between the angles, parameter of $SPNT_{diff}$ provides a more valid measure of SPNT test outcome. Therefore, based on the results of our study when both angles are applied interchangeably, target movement amplitude of 50° and target movement velocity of $20°s^{-1}$ should be used. Although this amplitude and velocity would allow us to reach better agreement between the two neck torsion angles it is still unclear whether those with decreased range of motion of the cervical spine could be compared to those without such limitations. In order to gain better insight into the sensitivity of SPNT test, future research should investigate diagnostic accuracy when using different angles of neck torsion, target movement amplitude and velocity in patients with neck pain disorders. Future studies should also consider the variety of different symptoms in patients with neck pain disorders of traumatic and nontraumatic origin as they differ in functional impairments and self-reported characteristics of symptoms (Ris et al., 2017). Additional limitations of our study were the age difference between the two studied groups and large number of tests that participants had to perform. Future studies should investigate whether gain and $SPNT_{diff}$ are altered in middle aged adult group in a reduced number of target movement profiles.

An important limitation of our study was that a variety of patients with neck pain disorders were included in the analysis altogether. Results of our study indicate higher dispersion in average gain and $SPNT_{diff}$ as well as differences between the two neck torsion angles in the neck patient group. Therefore, future studies should subgroup them based on the level of pain, passive and active range of motion, structural impairments, and other related symptoms to gather a more in-depth insight into the underlying mechanisms influencing oculomotor disfunction.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.msksp.2022.102535.

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2.1.4 Video-oculographic measures of eye movement control in the smooth pursuit neck torsion test can classify idiopathic neck pain patients from healthy individuals: a datamining based diagnostic accuracy study

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Abstract

Idiopathic neck pain patients frequently experience oculomotor disfunctions with deficits in eye movement control between neutral and neck torsion position (SPNT test) being commonly investigated in clinical and research settings. The aim of the study was to determine accuracy of SPNT test in classifying idiopathic neck pain patients. The study was conducted on a referred sample of 38 chronic neck pain patients from orthopaedic outpatient clinic and 40 healthy controls. Video-oculography was used to study gain and SPNTdiff during SPNT test under three target movement velocities and amplitudes and two different angles of neck torsion. A Naïve Bayesian predictive model was used to classify neck pain patients based on gain or SPNTdiff. Gain during two target movement profiles at velocities of 30°s-1 and amplitudes of 30° and 40° under 45° of neck torsion presented with highest area under the curve (.837), specificity (92%), sensitivity (94%), highest true positive and lowest false negative predicted value. Highest area under the curve (.760), specificity (50%), sensitivity (71%), highest true positive and lowest false negative values were observed for SPNTdiff at velocities of 30°s-1 and amplitude of 30° applying 45° of neck torsion. SPNT test provides useful diagnostic tool for classifying neck pain patients when using single or combination of two target movement profiles. Neck torsion of 45° as opposed to 30° should be used during SPNT test when investigating patients with neck pain disorders.

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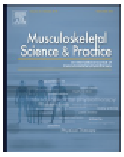

Original article

Video-oculographic measures of eye movement control in the smooth pursuit neck torsion test can classify idiopathic neck pain patients from healthy individuals: A datamining based diagnostic accuracy study

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ABSTRACT

Background: Idiopathic neck pain patients frequently experience oculomotor disfunctions with deficits in eye movement control between neutral and neck torsion position (SPNT test) being commonly investigated in clinical and research settings.
Objectives: The aim of the study was to determine accuracy of SPNT test in classifying idiopathic neck pain patients.
Design: a datamining based diagnostic accuracy study.
Methods: The study was conducted on a referred sample of 38 chronic neck pain patients from orthopaedic outpatient clinic and 40 healthy controls. Video-oculography was used to study gain and $SPNT_{diff}$ during SPNT test under three target movement velocities and amplitudes and two different angles of neck torsion. A Naïve Bayesian predictive model was used to classify neck pain patients based on gain or $SPNT_{diff}$.
Results: Gain during two target movement profiles at velocities of $30°s^{-1}$ and amplitudes of 30° and 40° under 45° of neck torsion presented with highest area under the curve (0.837), specificity (92%), sensitivity (94%), highest true positive and lowest false negative predicted value. Highest area under the curve (0.760), specificity (50%), sensitivity (71%), highest true positive and lowest false negative values were observed for $SPNT_{diff}$ at velocities of $30°s^{-1}$ and amplitude of 30° applying 45° of neck torsion.
Conclusion: SPNT test provides useful diagnostic tool for classifying neck pain patients when using single or combination of two target movement profiles. Neck torsion of 45° as opposed to 30° should be used during SPNT test when investigating patients with neck pain disorders.

1. Introduction

Visual disturbances have been demonstrated in patients with neck disorders (Kristjansson and Treleaven, 2009). The cause of these disturbances is likely to be associated with impairments in the proprioceptive system attributed to various structures of the cervical spine, consequently causing mismatch with information from vestibular and visual system (Brandt, 1996). Along with characteristics of visual disturbances such as difficulty judging distance, concentrating to read, visual fatigue and others (Treleaven and Takasaki, 2014), patients with neck pain disorders exhibit altered cervico-colic and cervico-ocular reflexes that importantly contribute to changes in eye movement control (de Vries et al., 2016).

Eye movement control in patients with neck pain disorders is often assessed as the ability to follow horizontally moving target with their eyes expressed as the difference between the neutral and neck torsioned positions, called smooth pursuit neck torsion (SPNT) test. To date, number of studies have proposed differences between healthy individuals and neck pain patients (Janssen et al., 2015; Treleaven et al., 2005, 2011) with majority of studies reporting poorer performance in patients, even more so when neck is in torsioned position. Despite all the evidence of functional connections between cervical proprioceptors, visual system and vestibular apparatus (Treleaven, 2008), results from studies during SPNT test in patients with neck pain disorders remain inconclusive (de Zoete et al., 2020b; Janssen et al., 2015; Kongsted et al., 2007, 2007, 2007; Prushansky et al., 2004; Tjell et al., 2002).

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A possible reason for inconsistencies in results between studies could be the lack of consensus in methodology used such as different target movement velocities and amplitudes applied during testing conditions and different neck torsion positions (Janssen et al., 2015; Kongsted et al., 2007; Majcen Rosker et al., 2022a; Prushansky et al., 2004). Neck pain patients generally present with increased number of saccades that could exponentially grow with increasing target movement velocity, therefore higher velocities could possibly present with superior sensitivity between neck pain patients and asymptomatic individuals. Moreover, wider target movement amplitudes may present with additional proprioceptive feedback (Bexander and Hodges, 2019) possibly affecting smooth pursuit eye movements. This was partially confirmed by Majcen Rosker et al. (2021), where wider amplitudes presented with superior reliability and lower amplitudes with inferior reliability. Based on the aforementioned rationales, target movement amplitude, velocity and neck torsion position could affect sensitivity and specificity of the SPNT test.

An attempt to show SPNT test as a useful diagnostic tool when differentiating those with whiplash associated disorders (WAD) and those without has been made by Tjell et al. (2002). In the control group, patients with fibromyalgia, cervical spondylolysis and those with cervical dizziness were combined with healthy subjects. Based on the results from their study those with fibromyalgia, cervical spondylolysis and cervical dizziness differed from those with WAD but it is inconclusive whether they differed from healthy individuals. Cervical spondylolysis as well as cervicogenic dizziness are commonly seen in patients with neck pain disorders. According to research (Daly et al., 2018; de Vries et al., 2016) patients with nontraumatic neck pain also present with oculomotor impairments that could influence eye movement control.

Our study aimed to explore classification accuracy of SPNT test for idiopathic neck pain patients based on their gain performance using a datamining predictive model. SPNT test under different target movement profiles was applied, using three target movement velocities and amplitudes as well as two different angles of neck torsion. Additionally, difference in gain between the neutral and neck torsion positions ($SPNT_{diff}$) was taken into the predictive model. We hypothesized that SPNT test provides useful diagnostic tool in classifying patients with neck pain disorders from asymptomatic individuals.

2. Materials and methods

2.1. Participants

Patients with chronic neck pain and asymptomatic controls were enrolled in the study. Asymptomatic controls were recruited among university staff, doctoral students and their friends. Patients with chronic neck pain were referred to the study from orthopaedic outpatient clinics. Prior to undertaking the study, their suitability was assessed via the telephone interview. Patients experiencing neck pain for a minimum of 6 months to 5 years were considered for the study. Additionally, they were required to present with a minimum 50° of cervical rotation to each side. Inclusion criteria for each group was age range 18–55 years. Patients were required to mark pain intensity on 10-cm horizontal line of visual analogue scale (VAS) (Boonstra et al., 2014). To be considered in the study, neck pain patients had to present a minimum of 4 on VAS. Subjects had to be free from previous traumatic injury to the neck or head, shoulders or upper extremities pain, any neurological or vestibular disorders, and were required to take no medication or alcohol for 30-h prior to participating in the study. Participants were not included in the study in a case of corrected vision. All participants were required to read and sign a consent form. The study was approved by the national medical ethics committee (number: 0120–47/2020/6) and was performed in accordance with the declaration of Helsinki.

2.2. Equipment

A 100-Hz infrared eye tracking device (Pro Glasses 2, Tobii, Danderyd, Sweden)[a] was used to measure and record eye movements during SPNT test. Prior to experiment, a single target calibration routine was performed (Tobii Pro Glasses Controller, Tobii, Danderyd, Sweden)[b]. Individuals were required to track a horizontally moving target of a red dot (size 0.5° of visual angle) which was projected (Optoma ML1050ST LED Projector, Fremont, USA)[c] with a 100-Hz refresh rate on a white screen 150 cm away at an eye level as suggested by Deravet et al. (2018). Subjects were sitting on a custom-made rotatable chair with upper body fixed to the back support (Fig. 1). Hip angle was 80° of flexion, their feet were placed flat on the floor. All measurements were conducted by the same examiner.

2.3. Experiment

Testing protocol consisted of five trunk positions: neutral position with the trunk and head facing forward, rotation of the trunk for 30° to the left and to the right under the stationary head and rotation of the trunk for 45° to the left and to the right under the stationary head. The order of trunk rotations was pseudo-randomized across subjects. In the neutral position the anterior-posterior longitudinal axis of the chair was aligned in parallel to the line running from the middle of the screen and the middle of the chair.

For each condition subjects were required to track 10 cycles of cyclic sinusoidal target movements with 60 s rest intervals. Subjects were tested at 3 different maximal target speeds ($20°s^{-1}$, $30°s^{-1}$ and $40°s^{-1}$) and 3 different target movement amplitudes (30°, 40° and 50°) in all 5 different trunk positions. All tasks were performed in a random order.

2.4. Data analysis

Eye movement data were filtered for blinks, saccades and fixations using Tobii Pro.

Lab software (Tobii Pro lab 1.145, Tobii, Danderyd, Sweden)[d]. Square waves (saccades directed counter to each other and having an interval of relative standstill) were removed from the eye movement data using custom-written software in Matlab (R2017b, MathWorks, Natick, MA, USA)[e]. Eye movement data were fitted with a corresponding reference sinusoid with synchronized signal acquisition starting points. Each fitted sinusoid consisted of 10 cycles with correspondingly fixed amplitude (converted from angular degrees to pixels) and frequency that matched the profile for each individual condition. Horizontal eye movements were analysed using gain, calculated as the ratio between fitted eye velocity, amplitude and visual target velocity amplitude as described by Tjell et al. (2002). Gain torsion L represents the average gain during the left trunk rotation (right neck torsion) and gain torsion R represents the average gain during right trunk rotation (left neck torsion) all from the 6th to 9th cycle (Majcen Rosker, et al., 2022b). In addition, SPNT difference ($SPNT_{diff}$) was calculated as presented in Equation (1). The calculation was adapted and is similar to that described by Tjell et al. (2002):

$$SPNT_{diff} = \text{Gain neutral} - (\text{Gain torsion L} + \text{Gain torsion R})/2 \quad (1)$$

Equation (1): gain neutral represents the average gain in the neutral, gain torsion L represents the average gain during the left neck torsion and gain torsion R represents the average gain during the right neck torsion all averaged from the 6th to 9th cycle.

2.5. Statistical analysis

Statistical analysis was performed in Orange data mining software (Orange 3.26.0, Ljubljana, Slovenia). To analyse accuracy of classifying patients with neck pain, Naïve Bayes machine learning approach was

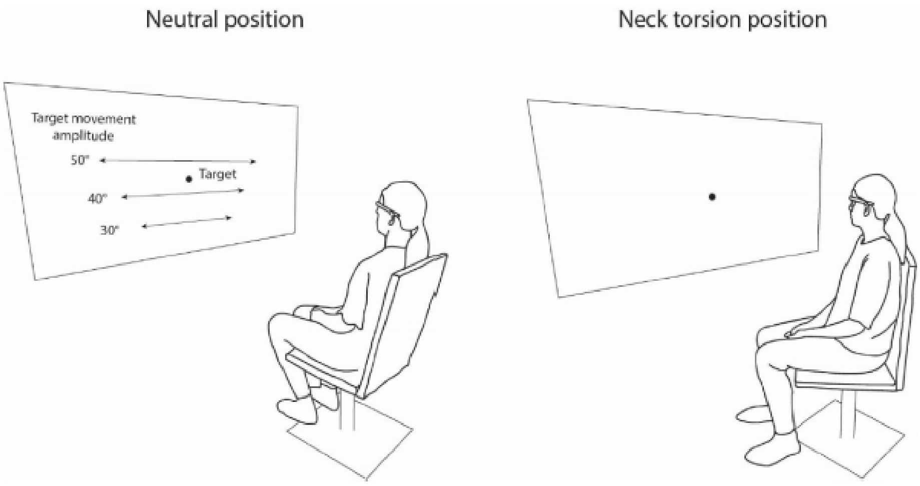

Fig. 1. Experimental setup.

used (Rudner, 2019; Y. Zhang et al., 2017). Gain and $SPNT_{diff}$ at different target movement profiles (three amplitudes and velocities of target movement as well as five trunk positions) were used as predictor variables, and the group as predicted class.

Two different approaches were used to analyse classification accuracy of target movement profiles used in this study. In the first approach, all target movement profiles were separately fed into the Naïve Bayes machine learning algorithm (one amplitude and velocity for each angle of left and right trunk rotation) to determine participants that classify into a group of patients with idiopathic neck pain. To develop machine learning classifier, data from 78 participants were randomly split into five folds. Four folds were used for model training and cross-validated with the remaining fold, repeating the procedure for all folds. Performance of the machine learning classifier for each target movement profile was described by the receiver operating curve (ROC), area under the curve (AUC), sensitivity, specificity, predictive value as a true

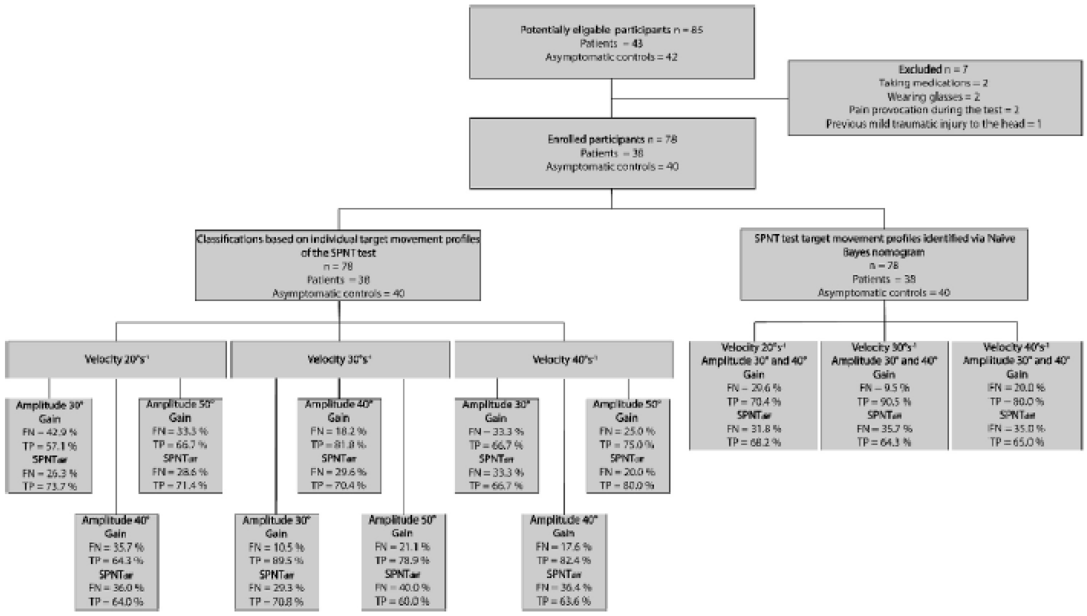

Fig. 2. STRAD flow diagram
N – number of participants; FN - Predictive value as a false negative rate; TP - predictive value as a true positive rate; $SPNT_{diff}$ – smooth pursuit neck torsion difference between the neutral trunk position and the torsioned positions.

positive test and predictive value as a false negative test.

In the second approach, two target movement profiles were fed into the Naïve Bayes machine learning algorithm simultaneously to enable multidimensional classification and to study whether using two target movement profiles can improve classification performance. The two movement profiles were identified via a nomogram using Naïve Bayes classifier that ranked the target movement profiles according to their prediction performance (Shariat et al., 2009; H. Zhang and Su, 2004). These two highest ranking target movement profiles were combined and fed into the Naïve Bayes algorithm simultaneously.

Finally, target movement profiles were evaluated individually according to their importance in the machine learning classifier that the Naïve Bayes method created. These were classified by Information Gain and Gini index (Liu, 2004).

In addition, minimal clinically important difference (MCID) was calculated between the two observed groups for each individual target movement profile separately and treated as small (MIDC >0.2), moderate (MIDC >0.5) and large (MIDC >0.8) (Wright et al., 2012).

3. Results

3.1. Participants

The flow of participants throughout the study as well as diagnostic accuracy are presented in Fig. 2. The mean age of the patient's group was 42.6 ± 5.8 years (age range 25–51 years) and the mean age of the control group 39.1 ± 6.3 years (age range 23–49 years). Average pain duration in the patient's group was 13.6 ± 8.3 months and average VAS score was 4.8 ± 1.3.

3.2. Classifications using gain performance at 45° of neck torsion

Performance of Naïve Bayes classifications while applying individual target movement profile or pair of target movement profiles using gain are presented in Table 1 and Fig. 2 with corresponding ROC curves presented in Supplementary Fig. 1. Target movement profiles at 45° of neck torsion using velocities of 30°s^{-1} and amplitudes of 30° or 40° presented with highest AUC, specificity, sensitivity, predictive value as a true positive test and lowest predicted value as a false negative test. Naïve Bayes classification improved when velocity of 30°s^{-1} with both 30° and 40° amplitudes were simultaneously fed into the classification algorithm. On the contrary, inferior classification performance was observed at velocities of 20°s^{-1} and 40°s^{-1}.

The highest contribution to classification performance from all the above models indicated by Information gain and Gini index was observed by target movement profiles at 30°s^{-1} and amplitudes of 30° or 40° or when they were simultaneously included into the classification model.

3.3. Classifications using gain performance at neutral position and during 30° of neck torsion

Target movement profiles at 30° of neck torsion were presented with inferior classification performance as compared to all classifications during 45° of neck torsion and were therefore not included in further analysis. Similarly, classifications using target movement profiles at neutral position presented with no classification ability regardless of the target movement velocity or amplitude.

3.4. Classifications using $SPNT_{diff}$

Results of classification performance using $SPNT_{diff}$ are presented in Table 2, Fig. 2 and corresponding ROC curves in Supplementary Fig. 2. Lower classification performance was observed when using $SPNT_{diff}$ as compared to classifications when using gain. No velocity or amplitude specific trends were observed and no combination of $SPNT_{diff}$ at two

Table 1
Sensitivity and specificity values for gain.

Features included in the model			AUC	Sensitivity	Specificity	Information Gain	Gini index
Velocity (°s^{-1})	Trunk position	Amplitude (°)					
30	L45	40	.837	.947	.929	.464	.232
	R45	40				.396	.198
	L45	30				.305	.198
	R45	30				.589	.294
30	L45	40	.808	.889	.857	.464	.232
	R45	40				.396	.198
30	L45	30	.868	.895	.857	.305	.153
	R45	30				.589	.294
30	L45	50	.708	.651	.500	.092	.046
	R45	50				.243	.122
20	L45	40	.720	.667	.571	.183	.091
	R45	40				.159	.079
	L45	30				.183	.091
	R45	30				.146	.073
20	L45	40	.697	.739	.571	.183	.091
	R45	40				.159	.079
20	L45	30	.680	.650	.500	.183	.091
	R45	30				.146	.073
20	L45	50	.708	.667	.500	.092	.046
	R45	50				.243	.122
40	L45	40	.643	.800	.857	.263	.129
	R45	40				.259	.131
	L45	30				.190	.121
	R45	30				.094	.062
40	L45	40	.652	.824	.786	.094	.047
	R45	40				.190	.095
40	L45	30	.573	.667	.714	.263	.133
	R45	30				.259	.129
40	L45	50	.673	.750	.714	.269	.135
	R45	50				.222	.111

AUC – area under the Roc curve; L45 – left trunk rotation for 45°; R45 – right trunk rotation for 45°.

Table 2
Sensitivity and specificity values for $SPNT_{diff}$.

Features included in the model				AUC	Sensitivity	Specificity	Information Gain	Gini index
Velocity (°s⁻¹)	Trunk position		Amplitude (°)					
30	45		40	.703	.700	.571	.080	.040
	45		30				.183	.091
30	45		40	.603	.682	.500	.080	.040
30		45	30	.760	.708	.500	.183	.091
30		45	50	.502	.600	.429	.065	.042
20		45	40	.635	.682	.500	.033	.021
		45	30				.033	.021
20		45	40	.612	.640	.357	.033	.021
20		45	30	.617	.737	.643	.033	.021
20		45	50	.735	.714	.429	.057	.038
40	45		40	.700	.650	.500	.153	.096
	45		30					
40	45		40	.652	.636	.429	.153	.096
40	45		30	.598	.667	.357	.052	.036
40	45		50	.755	.800	.714	.162	.102

AUC – area under the Roc curve; 45 – trunk rotation for 45°.

different target movement profiles resulted in improved classification performance. $SPNT_{diff}$ calculated for 45° of neck torsion presented with superior classification performance as compared to $SPNT_{diff}$ calculated for 30° of neck torsion.

3.5. *Minimal clinically important difference*

Data on MCID for gain and $SPNT_{diff}$ are presented in Table 3. Largest values for gain were observed at target movement profiles of 30° and 40° amplitude and velocity of 30°s^{-1}. Similar trend was observed for $SPNT_{diff}$ with additional target movement profiles of 30° and 50° amplitude and velocity of 40°s^{-1}.

Table 3
Minimal clinically important difference.

Velocity (°s-1)	Minimal clinically important difference			
	Amplitude (°)	Left rotation 45°	Right rotation 45°	$SPNT_{diff}$
30	40	1.384	3.294	−1.059
	30	1.796	3.273	−1.584
	50	0.754	2.492	−0.502
20	40	0.655	0.307	−0.288
	60	0.342	1.234	−0.277
	50	0.802	0.334	−0.624
40	40	0.825	0.692	−0.798
	30	0.394	1.468	−1.513
	50	0.793	1.592	−1.121

$SPNT_{diff}$ – smooth pursuit neck torsion difference between the neutral trunk position and the torsioned positions.

4. Discussion

In the present study our goal was to explore sensitivity and specificity of the SPNT test (gain and $SPNT_{diff}$) for classifying chronic neck pain patients, using different target movement profiles and neck torsion positions. Based on the results from our study higher sensitivity and specificity for neck patients was observed for gain than for $SPNT_{diff}$. Moreover, our study showed differences in sensitivity and specificity between different target movement profiles with highest classification performance observed when applying a pair of profiles. No such trends were observed for $SPNT_{diff}$. Based on the Naïve Bayes build nomogram, all target movement profiles during 30° of neck torsion were inferior classifiers than target movement profiles during 45° of neck torsion, therefore it can be concluded that target movement profiles during 30° of neck torsion are less favourable to use in clinical and research settings.

To date, eye movements during SPNT test have been examined visually by individual examiners (Daly et al., 2018; Della Casa et al., 2014) but its relevance as a diagnostic tool remained questionable with 27.3% sensitivity and 79.3% specificity, while more objective methods presented with superior sensitivity (63.6%) and specificity (89.6%) for differentiating between idiopathic neck pain patients and asymptomatic individuals (Daly et al., 2018). Our study applied Naïve Bayes based classification approach using video-oculographic measures, which presented with 94% sensitivity and 92% specificity in combination when applying pair of profiles at velocity of 30°s^{-1} and amplitude of 30° and at velocity of 30°s^{-1} and amplitude of 40°. On the contrary, single target movement profile failed to reach equally favourable sensitivity and specificity with the highest prediction performance observed for velocity of 30°s^{-1} and amplitude of 30°. These profiles also presented with highest MCID between groups.

To date, research settings most commonly applied target movement profile with velocity of 20°s^{-1} and amplitude of 40° (Tjell et al., 2002; Tjell and Rosenhall, 1998; Treleaven et al., 2005, 2011) and are shown to present with statistically significant differences between healthy individuals and WAD patients. Although WAD patients present with more severe impairments than idiopathic neck pain patients (Anstey et al., 2016) as well as they differ in the performance of SPNT test (Janssen et al., 2015; Tjell et al., 2002), there is however evidence that oculomotor control is altered in neck patients and that it differs from healthy individuals which is confirmed by the results of our study. However, above mentioned most commonly used target movement profile showed much inferior classification performance using Naïve Bayes classification approach in our study. Aforementioned observations, along with the results from our study suggest that most commonly used target movement profile may not present with differences between idiopathic neck pain patients and healthy individuals. Recent study by de Zoete et al. (2020a) supports these suggestions, where no differences were reported between idiopathic neck pain patients and healthy individuals which could be the result of using less sensitive target movement profile with velocity of 20°s^{-1} and amplitude of 40°. Therefore, more specific target movement profiles should be used to provide more useful clinical and research tool with excellent sensitivity and specificity. This is of importance as approximately 50% of neck pain patients suffer from some type of subjective visual complaints (Treleaven and Takasaki, 2014). Thus, valid diagnostic methods could provide clinicians with more objective identification of cervical spine related oculomotor deficits. These findings provide important impetus for future research in chronic neck patients and opportunity to develop more targeted rehabilitation approaches.

In the study by Majcen Rosker et al. (2021) superior reliability was observed for tasks involving amplitudes of 50°. Authors proposed that this might be due to increased stiffness of cervical spine during SPNT test using larger target movement amplitudes consequently improving accuracy of eye movement control. According to Kristjansson et al. (2004) task has to be challenging enough to present with sufficient sensitivity and specificity which is in line by the results of our study where the most reliable parameters found in the study by Majcen Rosker et al. (2021) presented with inferior specificity and sensitivity in our study. Results of our study reported that gain at amplitudes of 30° and 40° presented with superior classification performance which has previously been presented with moderate to good reliability (Majcen Rosker et al., 2021). Although amplitude of 40° presents with superior reliability, combination of 30° and 40° amplitudes should be used in future studies.

Previous studies investigating neck disorders using SPNT test most commonly applied target movement velocities of 20°s^{-1} (Tjell et al., 2002; Treleaven et al., 2005), which according to Majcen Rosker et al. (2021) presents with moderate to good inter-visit reliability of gain during SPNT test in chronic neck patients. Results from our study proposed that velocity of 30°s^{-1} present with superior sensitivity and specificity than 20°s^{-1} but according to Majcen Rosker et al. (2021) present with similar reliability. Based on these observations, future studies should apply velocity of 30°s^{-1} when studying chronic neck pain patients. Moreover, target movement velocity could affect smoothness of pursuit eye movements and saccadic intrusions as at velocities exceeding 15°s^{-1}, number of saccades increases (Land, 2006). Saccades have to preserve their spatial accuracy and initiation latency and could be altered in neck pain patients, which should be analysed in future studies.

In addition to gain, $SPNT_{diff}$ has been commonly used in patients with neck pain disorders (Janssen et al., 2015; Tjell et al., 2002). According to Tjell et al. (2002) the parameter of $SPNT_{diff}$ was able to classify WAD patients with 92% specificity and 72% sensitivity. Results from our study showed that $SPNT_{diff}$ in idiopathic neck pain patients presents with inferior sensitivity and specificity. This is partially in line with the study by Janssen et al. (2015) where $SPNT_{diff}$ did not show differences between groups of WAD, chronic neck pain patients and healthy controls. In their study, post-hoc tests were not performed between pairs of groups, however based on the figures presented in their research paper there could be differences present between WAD and healthy individuals, but not between idiopathic neck pain patients and healthy controls. Results from our study showed that parameter of $SPNT_{diff}$ provides sufficient sensitivity (70.8%) and specificity (50%) when using an amplitude of 30° and velocity of 30°s^{-1} and should be applied in clinical settings. Parameter of $SPNT_{diff}$ along with parameter of gain could provide useful tool for future research in neck pain patients.

4.1. Study limitations

Correlations between oculomotor impairments and subjective symptoms related to neck disorders including visual characteristics survey should be studied in the future. Due to heterogeneity of neck disorders patients, future studies should subgroup them according to the level and type of impairments. In addition, across studies different patients recruitment techniques were observed such as advertising in local newspapers, social media, local physiotherapy clinics and orthopaedic outpatient clinics etc. (Daly et al., 2018; de Zoete et al., 2020a; Majcen Rosker et al., 2022a). These could have resulted in enrolling different cohorts of neck pain patients with bigger variability in their functional impairments which decreases the ability to summarize the results between studies. Additional limitations of our study were the significant age difference between the two studied groups and large number of tests that participants had to perform. Significant age difference resulting from younger asymptomatic individuals (i.e. doctoral students) could have influenced SPNT test results possibly resulting in more accurate eye movement control as compared to older heathy asymptomatic individuals.

5. Conclusion

According to the results of our study combination of two target movement profiles with velocity of 30°s^{-1} and amplitude of 30° and at velocity of 30°s^{-1} and amplitude of 40° provide with excellent sensitivity and specificity for classifying subjects with chronic neck pain. Based on these results, both target movement profiles should be used in research but might be too time consuming for using in everyday clinical practice. Gain and $SPNT_{diff}$ during SPNT test provide valid parameters for studying cervical spine related oculomotor deficits in neck pain patients. Neck torsion of 45° as opposed to 30° should be used during SPNT test when investigating subjects with neck pain disorders. Our research showed that Naïve Bayes approach provides promising results in the research targeting neck pain patients which has also been suggested by other studies (Liew et al., 2019, 2020, 2021).

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Declaration of competing interest

Author declare no conflict of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.msksp.2022.102588.

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2.1.5 Is altered oculomotor control during smooth pursuit neck torsion test related to subjective visual complaints in patients with neck pain disorders

Majcen Rosker Z., Vodicar M., Kristjansson E. 2022. Is altered oculomotor control during smooth pursuit neck torsion test related to subjective visual complaints in patients with neck pain disorders. International Journal of Environmental Research and Public Health, 19: 1-10

Abstract

Subjective visual complains are commonly reported in patients with neck pain, but their relation to objectively measured oculomotor functions during smooth pursuit neck torsion test (SPNT) has not yet been investigated. The aim of the study was to analyse classification accuracy of visual symptom´s intensity and frequency based on SPNT test results. Forty-three patients with neck pain were referred by orthopaedic outpatient clinics where they were required to fill out 16-item proforma of visual complaints. Infrared video-oculography was used to measure smooth pursuit eye movements during neutral and neck torsion positions. Parameters of gain and SPNT difference (SPNTdiff) were taken into Naïve Bayes model as classifiers, while intensity and frequency of visual symptoms were taken as predicted class. Intensity but less frequency of visual symptoms previously associated with neck pain or focal vision disorders (computer vision syndrome) showed better classification accuracy using gain at neck torsion position, indicating cervical driven visual disturbances. Moreover, SPNTdiff presented with slightly lower classification accuracy as compared to gain at neck torsion position. Our study confirmed relationship between cervical driven oculomotor deficits and some visual complaints (concentrate to read, words moving on page, blurred vision, difficulty judging distance, sore eyes, heavy eyes, red eyes and eyes strain).

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Is Altered Oculomotor Control during Smooth Pursuit Neck Torsion Test Related to Subjective Visual Complaints in Patients with Neck Pain Disorders?

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Abstract: Subjective visual complaints are commonly reported in patients with neck pain, but their relation to objectively measured oculomotor functions during smooth pursuit neck torsion tests (SPNTs) has not yet been investigated. The aim of the study was to analyse classification accuracy of visual symptom intensity and frequency based on SPNT results. Forty-three patients with neck pain were referred by orthopaedic outpatient clinics where they were required to fill out 16-item proformas of visual complaints. Infrared video-oculography was used to measure smooth pursuit eye movements during neutral and neck torsion positions. Parameters of gain and SPNT difference ($SPNT_{diff}$) were taken into the Naïve Bayes model as classifiers, while intensity and frequency of visual symptoms were taken as predicted class. Intensity and, to a lesser degree, frequency of visual symptoms previously associated with neck pain or focal vision disorders (computer vision syndrome) showed better classification accuracy using gain at neck torsion position, indicating cervical driven visual disturbances. Moreover, $SPNT_{diff}$ presented with slightly lower classification accuracy as compared to gain at neck torsion position. Our study confirmed the relationship between cervical driven oculomotor deficits and some visual complaints (concentrating to read, words moving on page, blurred vision, difficulty judging distance, sore eyes, heavy eyes, red eyes, and eyes strain).

Keywords: visual disturbances; neck pain; oculomotor functions; eye movements

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1. Introduction

The cervical spine has undergone scientific scrutiny for many years. From university professors to highly skilled clinicians, many attempts have been made to concur about interconnected signs and symptoms, but the overall understanding remains based on the assumptions that "In the cervical spine, everything is possible". Many unfortunate people, therefore, suffer from a variety of different symptoms attributed to neck pain disorders [1,2]. While some relationship exists between functional signs and symptoms, such as in cervicogenic headaches [3], radiculopathy [4] and dizziness [5], visual disturbances remain poorly understood.

Visual disturbances have been reported over the years in those with neck pain disorders [5–7]. While some visual complaints, such as blurred vision, words jumping on the page, difficulty concentrating to focus and read, are more notably reported in those with neck pain disorders then others (i.e., double vision). It wasn't until 2014 that Treleaven and Takasaki [8] presented more a comprehensive analysis of visual disturbances reported by individuals with neck pain. Their study presented a 16-item proforma to determine visual symptoms of which the most prevalent and troublesome visual complaints were identified. Out of these 16 items, some are suggested to be associated with cervical spine driven deficits [2,9] and some with focal vision disorders [10], whereas others that are not so commonly observed in patients with neck pain disorders are associated with vestibular pathology, ambient vision, and neurological disorders [11,12].

While visual symptoms associated with neck pain have received some attention in the literature [8], focal vision disorders and their relation to neck pain have been seldomly investigated. Focal vision disorder, also called computer vision syndrome, could co-exist in those with neck pain disorders. Moreover, computer vision syndrome can lead to occurrences of neck pain, and neck pain can contribute to the development of computer vision syndrome [13]. On the contrary, some other symptoms, such as double vision, could be a red flag condition found in patients with neck pain disorders (i.e., vertebral artery disfunction). To date, it is unknown which of the visual complaints and to what extent they are attributed to cervicogenic driven oculomotor deficits.

Oculomotor control of which the ability to smoothly follow a moving target with one's eyes has been frequently investigated in clinical and research practice [6] and is altered in patients with neck pain disorders [5]. This is especially evident when the neck is torsioned to 45° to the left and to the right [14,15], called the smooth pursuit neck torsion test (SPNT) that has previously been identified as a reliable tool [16,17]. Neck pain patients frequently exhibit more sporadic saccadic jumps and lack the ability to focus their gaze on a moving target during the SPNT. Consequently, altered eye movement velocity as compared to target movement velocity (gain) is observed, especially in neck torsion position as compared to the neutral position expressed as the SPNT difference ($SPNT_{diff}$) [18].

As to date, no well-established link has been identified between visual symptoms and oculomotor deficits in neck pain patients; it would be of clinical importance to assess such relationship. Visual disturbances remain subjective visual complaints that are often dismissed in clinical practice due to the lack of ability to identify concurrent gaze-related cervicogenic driven functional signs. Therefore, the aim of this study was to investigate whether oculomotor control during the SPNT is related to different visual symptoms commonly described by patients with neck pain disorders.

2. Materials and Methods

2.1. Participants

Patients with chronic neck pain were referred from orthopaedic outpatient clinics and were assessed for suitability via telephone interviews prior to participating in the study. All patients had to present with a minimum of 50° of cervical rotation to each side and be free from previous traumatic injury to the neck or head, shoulder or upper extremities pain, and any neurological or vestibular disorders, and were required to have not taken any medication or alcohol for the last 30 h prior to participating in the study. Prior to participation, they read and signed a consent form. The study was approved by the national medical ethics committee (number: 0120-47/2020/6) and was performed in accordance with the Declaration of Helsinki.

2.2. Assessment

Patients were required to mark pain intensity on a visual analogue scale (VAS). Each patient underwent a magnetic resonance imaging assessment prior to the initial screening at the orthopaedic outpatient clinic. This information was used to describe the extent and variability of cervical spine structural impairments. The SPNT protocol consisted of three different neck positions: (i) facing forward position (the trunk and head were in a neutral position), (ii) right neck torsion position at 45° (rotation of the trunk underneath the stationary head to 45° to the left), and (iii) left neck torsion position at 45° (rotation of the trunk underneath the stationary head to 45° to the right). Hip angle during sitting on a chair was 80° of flexion while feet were placed flat on the floor. All measurements were conducted by the same examiner in an isolated room with dimmed lights.

Before the test, all patients performed five familiarization warm-up cycles. For each condition patients were required to track 10 cycles of cyclic sinusoidal target movements with their eyes, followed by 1-min rest interval. Patients were tested at two different target movement profiles (40° of target movement amplitude with velocity of $30°s^{-1}$ and 30° of target movement amplitude with velocity of $30°s^{-1}$) at all three different neck positions. Different target movement velocities and amplitudes during all neck positions were performed in random order. After completing the SPNT at each neck position, recalibration of the eye-tracking device was performed during a 5-min rest.

Patients were required to complete a proforma of visual disturbances and complaints consisting of 16 items, as described by Treleaven and Takasaki [8]. The proforma included the following items: focal disorders (heavy eyes, sore eyes, red eyes, eye strain, visual fatigue, squinting, itchy eyes, and hard to focus on close work), vestibular pathology, migraines, ambient vision disturbances, or vertebral artery insufficiency (double vision, spots in eyes, sensitivity to light, and dizziness when reading) and symptoms associated with neck pain (blurred vision, words or objects moving, needing to concentrate to read, and difficulty judging distances). Patients were required to specify the average intensity of visual symptoms on a 3-level scale and average frequency on a 4-level scale. An examiner was present during the filling out of the proforma to ensure no items were left out unintentionally.

2.3. Equipment

Infrared video-oculography (Pro Glasses 2, Tobii, Danderyd, Sweden) was used to measure smooth pursuit eye movements at a sampling rate of 100 Hz [18–20]. A single target calibration routine was performed prior to measurements in the Tobii Pro Glasses Controller (Tobii Pro Glasses Controller, Tobii, Danderyd, Sweden). Patients were required to track a horizontally moving target of a red dot (size 0.5° of visual angle) projected (Optoma ML1050ST LED Projector, Fremont, CA, USA) on a white screen 150 cm away at an eye level with a 100-Hz refresh rate [21]. Patients were sitting on a custom-made rotatable chair with upper body fixed to the back support (Figure 1). A 16 item proforma was adapted as described by Teo et al. and Treleaven and Takasaki [8,13].

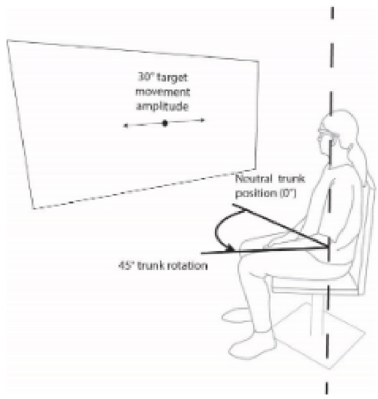

Figure 1. Patient setup.

2.4. Data Analysis

The eye movement data were filtered for blinks and fixations using Tobii Pro Lab software (Tobii Pro lab 1.145, Tobii, Danderyd, Sweden). The square waves (saccades directed counter to each other and having an interval of relative standstill) and saccades were removed from the eye movement data using custom-written software in Matlab (R2017b, MathWorks, Natick, MA, USA). The eye movement data were fitted with a corresponding reference sinusoid with synchronized signal acquisition starting points. Each fitted reference sinusoid consisted of 10 cycles with correspondingly fixed amplitude (converted from angular degrees to pixels) and frequency that matched the profile for each individual condition. The first and last 10% of the amplitude in each eye movement cycle were removed from further analysis. The horizontal eye movements were analysed using gain, calculated as the ratio between eye velocity amplitude and visual target velocity amplitude, as described by Tjell et al. [18]. Gain torsion R represents the average gain during right neck torsion position from the 6th to 9th cycle, and gain torsion L represents the average gain during left neck torsion position from the 6th to 9th cycle [17]. In addition, smooth pursuit neck torsion difference ($SPNT_{diff}$) was calculated, as presented in Equation (1). The calculation was adapted and is similar to that described by Tjell et al. [18]:

$$SPNT_{diff} = \text{Gain neutral} - (\text{Gain torsion L} + \text{Gain torsion R})/2 \quad (1)$$

Equation (1): gain neutral represents the average gain in the neutral position, gain torsion L represents the average gain during the left neck torsion position, and gain torsion R represents the average gain during the right neck torsion position.

For the 16-item proforma, the intensity of the visual symptoms was scaled as 1—mild, 2—moderate, 3—severe and for frequency as 1—rare, 2—occasional, 3—frequent, 4—always. If no visual symptoms were present, patients were instructed to leave the specific item blank (treated as zero score).

2.5. Statistical Analysis

Median and interquartile range were calculated for intensity and frequency score for each visual symptom as well as the percentage of patients reporting presence of individual visual complaints. Classification analysis was performed in Orange data-mining software (Orange 3.26.0, Ljubljana, Slovenia). To analyse the accuracy of the classifying intensity or frequency of visual disturbances using gain or $SPNT_{diff}$, the Naïve Bayes machine-learning approach was used [22,23]. Gain and $SPNT_{diff}$ at the most reliable and specific target movement profiles were used as predictor variables [24,25] and the score for intensity or frequency of each visual disturbance symptom as predicted class.

To develop the machine-learning classifier, data from 43 patients were randomly split into four folds. Three folds were used for model training and cross-validated with the remaining fold, repeating the procedure for all folds. Performance of the machine-learning classifier for each target movement profile was described by the area under the curve (AUC), sensitivity, and specificity.

3. Results

3.1. Participants

The mean age of 43 patients (31 females and 12 males) enrolled in this study was 41.3 ± 6.7 years (age range 25–51 years) with average pain duration of 13.4 ± 9.1 months and average VAS score 4.9 ± 1.7. The cervical spine magnetic-imaging assessment presented disc protrusions or herniations at the levels from C4 to Th1 in 27 patients, 9 patients presented with facet joints osteoarthritis at the levels from C5 to Th1, 12 patients presented with low-grade spondylolisthesis, and 9 patients presented with cervical spinal stenosis. Thirty-four patients presented with a combination of at least two types of structural deformities; however, in nine patients only one type of structural impairment was present.

Percentage of patients as well as median score with interquartile range for intensity and frequency of each visual symptom are presented in Table 1. As no patient reported presence of double vision, sensitivity to light, or spots in eyes, these symptoms were not included for further analysis. The highest percentage of patients reported presence of blurred vision and visual fatigue followed by sore eyes, heavy eyes, and other symptoms. Majority of reported visual symptoms showed mild (1) to moderate (2) intensity and rare (1) to frequent (3) frequency.

Table 1. Median, interquartile range, and percentage of patients reporting presence of each individual visual complaint.

	Intensity [1]		Frequency [2]		
Visual Symptom	**Median [3]**	**IQR [4]**	**Median [3]**	**IQR [4]**	**% of Patients [5]**
Concentrating to read	2	2	2	2	63.6%
Words moving on page	0	2	0	3	45.5%
Blurred vision	1	1.5	3	2	81.8%
Difficulty judging distance	2	2	2	2.5	63.6%
Sore eyes	1	1.5	3	3.5	72.7%
Heavy eyes	2	2.5	2	3	72.7%
Harder to do close work	1	2	2	2.5	54.5%
Visual fatigue	2	1	3	1.5	81.8%
Itchy eyes	1	1	1	2.5	63.6%
Red eyes	1	1.5	2	3	63.6%
Eye strain	1	1.5	2	4	63.6%
Squinting	1	2	2	3	54.5%

[1] Intensity—intensity score for an individual visual symptom; [2] Frequency—frequency score for an individual visual symptom; [3] Median—median score for individual visual symptom; [4] IQR—interquartile range for individual visual symptom; [5] % of patients—percentage of patients reporting individual visual symptom.

3.2. *Classification Analysis*

Results of the classification analysis are presented in Table 2. Classification accuracy (AUC) based on gain at neck torsion position proved to be higher for intensity as compared to frequency of visual symptoms. In addition, gain at neck torsion position proved to have higher classification accuracy as compared to gain at neutral position for both intensity and frequency of visual symptoms. The classification accuracy based on $SPNT_{diff}$ proved to be slightly lower as compared to gain at neck torsion position for both intensity and frequency of visual symptoms. In general, classification accuracy was medium to low or non-present.

Table 2. Relation between visual symptoms, gain, and $SPNT_{diff}$.

		Gain Torsion [1]			Gain Neutral [2]			$SPNT_{diff}$ [3]		
	Visual Symptom	**AUC [4]**	**Se [5]**	**Sp [6]**	**AUC [4]**	**Se [5]**	**Sp [6]**	**AUC [4]**	**Se [5]**	**Sp [6]**
Intensity	Dizzy reading	0.340	0.282	0.438	0.296	0.388	0.339	0.440	0.482	0.638
	Concentrating to read	0.734	0.763	0.814	0.513	0.614	0.716	0.634	0.563	0.814
	Words moving on page	0.652	0.746	0.753	0.489	0.475	0.361	0.638	0.746	0.853
	Blurred vision	0.545	0.464	0.758	0.427	0.352	0.583	0.515	0.444	0.708
	Difficulty judging distance	0.578	0.611	0.893	0.353	0.407	0.693	0.498	0.611	0.893
	Sore eyes	0.704	0.667	0.909	0.525	0.375	0.667	0.644	0.667	0.809
	Heavy eyes	0.600	0.589	0.873	0.534	0.450	0.714	0.586	0.539	0.873
	Harder to do close work	0.493	0.328	0.838	0.389	0.448	0.762	0.481	0.310	0.638
	Visual fatigue	0.477	0.417	0.600	0.279	0.483	0.500	0.462	0.411	0.602
	Itchy eyes	0.297	0.225	0.683	0.348	0.319	0.702	0.255	0.264	0.483
	Red eyes	0.539	0.473	0.836	0.366	0.329	0.604	0.515	0.273	0.833
	Eye strain	0.629	0.518	0.867	0.431	0.455	0.758	0.525	0.618	0.859
	Squinting	0.366	0.436	0.606	0.415	0.401	0.723	0.301	0.236	0.703
Frequency	Dizzy reading	0.412	0.406	0.716	0.176	0.273	0.408	0.347	0.209	0.581
	Concentrating to read	0.626	0.718	0.640	0.486	0.519	0.572	0.614	0.518	0.713
	Words moving on page	0.536	0.520	0.687	0.361	0.242	0.400	0.622	0.608	0.748

Table 2. *Cont.*

	Gain Torsion [1]			Gain Neutral [2]			$SPNT_{diff}$ [3]		
Visual Symptom	**AUC [4]**	**Se [5]**	**Sp [6]**	**AUC [4]**	**Se [5]**	**Sp [6]**	**AUC [4]**	**Se [5]**	**Sp [6]**
Blurred vision	0.682	0.606	0.833	0.466	0.145	0.681	0.693	0.515	0.815
Difficulty judging distance	0.484	0.509	0.481	0.347	0.382	0.412	0.463	0.494	0.569
Sore eyes	0.337	0.281	0.734	0.331	0.091	0.611	0.512	0.545	0.769
Heavy eyes	0.433	0.373	0.538	0.308	0.182	0.749	0.376	0.242	0.675
Harder to do close work	0.679	0.582	0.698	0.428	0.397	0.494	0.454	0.545	0.768
Visual fatigue	0.572	0.573	0.644	0.473	0.432	0.532	0.472	0.114	0.651
Itchy eyes	0.353	0.114	0.538	0.372	0.300	0.580	0.321	0.273	0.623
Red eyes	0.357	0.327	0.645	0.480	0.361	0.544	0.357	0.364	0.722
Eye strain	0.462	0.321	0.561	0.458	0.364	0.577	0.496	0.364	0.720
Squinting	0.383	0.421	0.525	0.410	0.339	0.465	0.500	0.455	0.628

[1] Gain torsion—gain measured at left and right neck torsion position with two target movement profiles (40° amplitude/30°s^{-1} velocity and 30° amplitude/30°s^{-1} velocity); [2] Gain neutral—gain measured at neutral position measured with two target movement profiles (40° amplitude/30°s^{-1} velocity and 30° amplitude/30°s^{-1} velocity); [3] $SPNT_{diff}$—smooth pursuit neck torsion difference; [4] AUC—area under the receiver operating characteristic curve; [5] Se—true positive rate (sensitivity); [6] Sp—true negative rate (specificity).

The highest classification accuracy of symptom intensity was observed for need to concentrate to read, followed by sore eyes, words moving on page, eye strain, heavy eyes, difficulty judging distance, blurred vision, and red eyes. A similar trend was observed for classifications using $SPNT_{diff}$ but for a smaller number of visual symptoms for both intensity and frequency.

4. Discussion

The aim of this study was to investigate the relation between oculomotor control during the SPNT and different visual symptoms described by patients with neck pain disorders. Based on the results from our study, it can be concluded that intensity as opposed to frequency of visual symptoms is more related to the parameters of gain and $SPNT_{diff}$, with both presenting with either moderate or low classification accuracy. Moreover, gain during neck torsion manoeuvre seems to have a more pronounced relation as compared to gain during neutral position, indicating that functional deficits of the cervical spine are related to some subjective visual complaints. $SPNT_{diff}$ presented with slightly lower classification accuracy as compared to gain during neck torsion position. The highest classification accuracy based on gain was observed for the following visual symptoms: need to concentrate to read, sore eyes, words moving on page, eye strain, heavy eyes, difficulty judging distance, blurred vision, and red eyes. Similar trends were observed for $SPNT_{diff}$, but fewer symptoms presented with at least low classification accuracy.

The results of our study confirm a stronger relationship between intensity of visual symptoms and SPNT performance than between frequency of visual symptoms and SPNT performance. This is in line with other studies reporting that intensity of subjective symptoms correlates to objective measures of neuromuscular functions of the neck in patients with neck pain disorders [26]. On the other hand, higher frequency of the symptoms would likely be present in those experiencing chronic symptoms. Chronic adaptations in those with spinal pain could lead to central nervous system adaptations that persist for a prolonged time even after alleviation of subjective symptoms of pain [27]. Such adaptations in the central nervous system could lead to alterations in oculomotor function that might be less dependent on symptomatic visual complaints. This notion is partially confirmed by studies reporting changes in oculomotor functions in asymptomatic subjects [28].

Functional connections between cervical spine deficits at neck torsion position and sensory mismatch commonly observed in neck pain patients could explain the relationship between gain at neck torsion position as well as $SPNT_{diff}$ and certain visual complaints. These deficits might be related to errors in proprioceptive information derived from the neck, transmitted by the cervico-collic and cervico-ocular reflexes [14], which can only be observed if patients are actively holding their head while performing cyclic smooth pursuit eye movements. On the opposite these are likely not present when the head is supported by chin rest [29]. Neck muscles that possess high muscle spindle density can influence coordination of extraocular muscles and consequently oculomotor control [30]. In addition, proprioceptive information from extraocular muscles and sensory retinal information presents an important sensory source for detecting target movement direction and speed [29], where extraocular sensory feedback has been shown to be the primary source of information in environments with structured background [30,31]. The perception of target movement is an important driver for the control of smooth pursuit eye movements, which can be altered in patients with neck pain.

Symptoms that have previously been associated with neck pain disorders, concentrating to read, words moving on page, difficulty judging distance, and blurred vision [32,33] showed moderate relationships with gain at neck torsion angle and slightly less with $SPNT_{diff}$. This information adds to findings reported by Gimse et al. [34] where moderate correlations were found between reading ability and $SPNT_{diff}$. The presence of pain in the neck region would generally lead to stiffening of the neck muscles [35], which is accompanied by decreased eyes–head–shoulders coordination and consequently decreased ability to maintain focal vision on a target [36]. Increased focal vision oscillations would prevent steady-state gaze, which might result in an increased number of saccades. This could lead to blurred vision, which would demand higher concentration while reading or keeping the gaze on a moving target. The symptom, "words moving on page", also called oscillopsia, can appear resulting from abnormal eye movements caused by upper cervical spine instability or by impaired vestibulo-ocular reflex [37] that can also be found in patients with neck pain disorders [38]. Difficulty judging distance is a common symptom reported by patients with neck pain disorders and can result from altered eye vergence. Our study found a relationship between difficulty judging distance and gain in neck torsion position. This is in accordance with other studies that found decreased vergence abilities when the neck was placed in torsion compared to the neutral position [39].

Prolonged time spent in the position where focal vision has to be frequently maintained could lead to focal vision disorders that are suggested to worsen with prolonged use of computers and mobile devices [10]; therefore, focal vision disorders are also called computer vision syndrome. Our study found a more pronounced relationship between gain during neck torsion position and some of the symptoms commonly associated with focal vision disorders (sore eyes, heavy eyes, red eyes, and eye strain), indicating the influence of cervical driven deficits on focal vision disturbances. The notion of the contribution of neck pain on symptomatic visual disturbances has also been confirmed by the study performed by Teo et al. [13]. Based on the results from their study, intensity of visual symptoms was more pronounced in the neck pain group than in the control group, regardless of similarities in daily computer use. Although growing evidence is emerging that musculoskeletal conditions, such as neck pain, might be related to computer vision syndrome, that relationship is poorly explained. It is currently still unknown whether computer vision syndrome causes neck pain or neck pain causes computer vision syndrome.

None of the patients from our study reported double vision or diplopia, sensitivity to light, and spots in eyes; therefore, these symptoms were not further analysed. Although Treleaven and Takasaki [8] reported on the possibilities that sensitivity to light and spots in eyes could be related to neck pain disorders, double vision should be considered as part of a differential diagnosis, such as vertebral artery insufficiency [40,41].

Important limitations of the study were that a heterogenous group of neck pain patients were included in the analysis, altogether possibly influencing the results of our study. Future studies should subgroup patients based on the level and region of pain [42] and traumatic and nontraumatic origin of neck pain disorders [43]. It could be expected that the relations between subjective visual complaints and the SPNT would be greater when investigating whiplash associated disorder patients due to the involvement of upper cervical spine trauma and its direct neurophysiological connection to the visual and vestibular systems [2]. In our study, only one aspect of oculomotor control was studied (continuous smooth pursuit eye movements) and did not address other connections between oculomotor control and subjective visual complaints in neck pain patients. Visual symptoms should therefore also be studied in relation to other oculomotor functions, such as smooth pursuit initiation, eye vergence, saccade accuracy, and other daily visual demanding tasks [44]. Another limitation of our study was that the amount of time individuals spent using computers or similar devices was not considered, which could have importantly influenced classification accuracy reported in our study. Therefore, future studies should gather this information for further analysis.

5. Conclusions

Our study confirmed the relationship between cervical driven oculomotor deficits measured during the SPNT and some of the commonly reported visual complaints in patients with neck pain disorders. Intensity of visual symptoms should be considered in clinical practice as it might show a more pronounced relationship to oculomotor control deficits measured during neck torsion positions. Although some relationship was found between visual complaints and oculomotor deficits related to cervical spine, other potential causes not investigated in our study should be considered.

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2.1.6 Cervicocephalic kinaesthetic sensibility measured during dynamic unpredictable head movements presents with different relationship with eye movement control and postural balance than traditional measures of position sense in neck pain patients

Majcen Rosker Z., Vodicar M., Kristjansson E. 2022. Cervicocephalic kinaesthetic sensibility measured during dynamic unpredictable head movements presents with different relationship with eye movement control and postural balance than traditional measures of position sense in neck pain patients. International Journal of Environmental Research and Public Health, 19: 1-10

Abstract

Cervical afferent input is believed to affect postural balance and oculomotor control in neck pain patients but relationship to cervicocephalic kinaesthesia describing movement sense has not yet been studied. The aim of this study was to analyse the relationship of two aspects of cervi-cocephalic kinaesthesia to postural balance and oculomotor control, both in neck torsion positions. Forty-three idiopathic neck pain patients referred from orthopaedic outpatient clinics and for-ty-two asymptomatic controls were enrolled in the study. Force plate was used to measure cen-ter-of-pressure movements during parallel stances under neutral and neck torsion manoeuvres. Video-oculography was used to assess eye movements during smooth pursuit neck torsion test (SPNTT), while kinaesthetic awareness was measured using Butterfly test and head-to-neutral re-location test. Multiple regression was used to describe relationships between tests. Body sway in anterior-posterior direction was related to Butterfly parameters but less to head-to-neutral test. Medium relationship between Butterfly parameters and gain during SPNTT but less SPNT-difference was observed, but not for the head-to-neutral test. It can be concluded that spe-cific aspect of neck kinaesthetic functions (i.e. movement sense) importantly contributes towards oculomotor and balance control which is more evident under neck torsion position in neck pain patients but less in asymptomatic individuals.

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Article

Relationship between Cervicocephalic Kinesthetic Sensibility Measured during Dynamic Unpredictable Head Movements and Eye Movement Control or Postural Balance in Neck Pain Patients

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Abstract: Cervical afferent input is believed to affect postural balance and oculomotor control in neck pain patients, but its relationship to cervicocephalic kinesthesia, describing movement sense, has not yet been studied. The aim of this study was to analyze the relationship of two aspects of cervicocephalic kinesthesia to postural balance and oculomotor control in neck torsion positions. Forty-three idiopathic neck pain patients referred from orthopedic outpatient clinics and forty-two asymptomatic controls were enrolled in the study. A force plate was used to measure center-of-pressure movements during parallel stances under neutral and neck torsion maneuvers. Video-oculography was used to assess eye movements during smooth pursuit neck torsion test (SPNTT), while kinesthetic awareness was measured using the Butterfly test and head-to-neutral relocation test. Multiple regression was used to describe relationships between tests. Body sway in the anterior–posterior direction was related to Butterfly parameters but less to the head-to-neutral test. A medium relationship between Butterfly parameters and gain during SPNTT, with less SPNT-difference, was observed, but not for the head-to-neutral test. It can be concluded that specific aspect of neck kinesthetic functions (i.e., movement sense) importantly contributes towards oculomotor and balance control, which is more evident under neck torsion positions in neck pain patients, but is less pronounced in asymptomatic individuals.

Keywords: sensorimotor functions; neck pain patients; balance; oculomotor control; proprioception

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1. Introduction

Neck pain disorders have been identified as one of the most challenging chronic medical conditions with an exponentially increasing number of cases in years lived with disability [1]. While over the last three decades one of the most commonly reported outcome measures in clinical and research practice was pain, it is now clear that the elimination of pain itself does not prevent reoccurrence and chronicity [2]. Possible reasons for reoccurrence and chronicity might be disturbances in the sensorimotor control system commonly observed in patients with neck pain disorders [3].

Sensorimotor disturbances affect multiple functional subsystems of which altered postural balance [4], eye movement control [5,6], kinaesthesia [7] and others are commonly identified in patients with neck pain disorders. A possible reason for sensorimotor disturbances in neck pain patients is suggested to be due to mismatch of sensory information derived from the cervical spine, visual and vestibular systems, which are neurophysiologically interconnected at the level of the brainstem [8]. The present mismatch is reflected as an altered ability of the accurate perception of head, neck and whole body position and movement in space (i.e., kinesthetic awareness) [9,10].

Alterations in cervicocephalic kinesthetic sensibility have been identified in previous studies investigating neck pain patients, confirming disturbances in position sense [11]. As position sense measures only one aspect of proprioception [12] applying more complex tests measuring movement sense and movement control during dynamically changing position is of importance [13]. Sensory information from different structures (i.e., muscle spindles, Ruffini corpuscles, Pacinian corpuscles and others) are integrated in movement sense [12,14]. This is of importance as idiopathic neck pain patients may suffer from multiple structural and functional impairments [7,15,16]. In addition, the pathological ingrowth of certain proprioceptors (Ruffini corpuscles) into cervical structures (i.e., intervertebral discs) can produce false sensory information, consequently influencing coordination of alpha and gamma motor neuron activity [16]. This is important for muscle spindle function which can negatively influence head and neck movement sense and consequently decrease their movement control [9,10].

Cervical afferent input is believed to importantly contribute to postural balance [17,18] and eye movement control [19]. Abnormal cervical afferent input is suggested to cause disturbances in the cervico-collic and cervico-ocular reflexes, consequently negatively influencing eye movement control, especially in neck torsion maneuvers [20,21]. Same trends of poorer performance during neck torsion maneuvers have been proposed for postural balance tasks [22] but their relationship to afferent input reflected in dynamic cervicocephalic kinesthesia has not yet been measured in neck pain patients. Although the literature implies that the aforementioned aspects of sensorimotor control present different functional characteristics [23], some evidence exists that suggests they are interrelated [3]. Recent articles describe existing correlations between postural balance, eye movement control and dynamic cervicocephalic kinesthesia [19,24]. However, this relationship was only studied in healthy athletes where habitual postural adaptations were proposed as possible reason for asymmetrical tonic activity of neck muscles, causing sensory mismatch. As described above, sensory mismatch is suggested as one of the main reasons for sensorimotor impairments in patients with neck pain disorders. Therefore, the aim of this study was to analyze the relationship of two aspects of cervicocephalic kinesthesia (head-to-neutral relocation test and Butterfly test) with postural balance and oculomotor control, in neck torsion positions in both neck pain patients and asymptomatic individuals.

2. Methods

2.1. Participants

Asymptomatic controls and idiopathic chronic neck pain patients were referred to the study. Patients were recruited from the orthopedic clinic of the national University medical center, and three private orthopedic outpatient clinics and were assessed for suitability via a telephone interview prior to participation by an experienced physiotherapist. In addition, healthy subjects were recruited for the study and were randomly selected between university staff, doctoral students and their friends. To be enrolled, all participants had to present with the following inclusion criteria: more than 50° of cervical rotation to each side, age between 18 and 55 years, and the group of idiopathic neck pain patients had to present with a minimum of four for pain in the neck on a visual analogue scale. Participants were excluded if they reported: previous traumatic injuries to the head or neck, shoulder, upper or lower extremity pain within the last two years, any neurological or vestibular disorders, type II diabetes, diagnosed psychiatric disorders. Furthermore, all participants were required to refrain from taking medication or alcohol 30 h prior to the study. Participants had to read and sign a consent form and were free to withdraw at any time. The study was approved by the national medical ethics committee (number: 0120-47/2020/6) and was performed in accordance with the declaration of Helsinki and its later additions.

2.2. *Measurement Procedures*

Patients were required to mark pain intensity on a visual analogue scale and underwent magnetic resonance imaging assessment prior to an initial screening at the orthopedic outpatient clinics. This information was used to describe the extent and variability of cervical spine structural impairments. Tests of body sway, smooth pursuit neck torsion test (SPNTT), neck kinesthesia using the dynamic kinesthetic awareness test (Butterfly test) and position sense (head-to-neutral) were performed by an experienced physiotherapist.

Reliable and valid measures of postural balance [25] were assessed in randomly ordered postural tasks; upright quiet parallel stance with feet positioned parallel at the hips' width parallel stance with neck torsioned to 45° to the left and right. During all stances, participants were instructed to place their hands on the hips and to keep their knees straight. All balance tasks were performed standing on a force plate measuring the center of pressure (CoP) movement (9260AA, Kistler Instruments AG, Winterthur, Switzerland). During testing, participants had to maintain their vision on a target positioned at a 2-metwe distance. Each stance was repeated three times for 30 s separated by 60 s rest intervals.

A reliable and valid SPNTT protocol [5,6,26] was conducted as described in the study by Majcen Rosker et al. [6]. Tracking of a horizontally moving target was performed at three different neck positions: facing forward (the trunk and head were in a neutral position), right neck torsion at 45° and left neck torsion at 45°. Eye movements were measured using infrared video-oculography (Pro Glasses 2, Tobii, Danderyd, Sweden) at a sampling rate of 100 Hz [27–29].

Participants were sitting on a custom-made rotatable chair and were required to track 10 cycles of cyclic sinusoidal target movements with their eyes for each condition, followed by 60 s rest interval. A horizontally moving target was projected (Optoma ML1050ST LED Projector, Fremont, CA, USA) on a white screen 150 cm away at eye level. Participants were tested at a target movement profile using 40° of target movement amplitude with a velocity of 30°/s at all three neck positions in a random order.

Valid measurements of cervicocephalic kinesthetic awareness were taken using the Butterfly test (formally the Fly test) [13,30] and head-to-neutral relocation test [31–33]. During the Butterfly test, participants were instructed to accurately follow a dynamic unpredictable target with their neck. Cervicocephalic kinesthesia was measured using an inertial measurement unit (NeckSmart, NeckCare Holding ehf., Reykjavik, Iceland). Two repetitions of three different movement paths of increasing difficulty (easy, medium and difficult) were used. Target movement path characteristics and test duration were predefined by the NeckCare software (NeckSmart, NeckCare Holding ehf., Reykjavik, Iceland).

A head-to-neutral relocation test was used to measure error in the position sense of the cervical spine. Prior to the initiation of each measurement trial, participants had to position their head and neck into a self-selected neutral position, serving them as a reference position. While blindfolded, each participant performed three repetitions of slow head movements to both rotations, flexion, or extension and back to the predetermined neutral position. The head-to-neutral relocation test was performed using the same inertial measurement unit and software as described in the Butterfly test.

2.3. *Data Analysis*

Signals derived from CoP movement were sampled at 1000-Hz and filtered (0.04–10 Hz band-pass, Butterworth zero-lag fourth order). Analysis was performed with Kistler MARS software (MARS 5.0, Kistler Instruments AG, Winterthur, Switzerland). The average velocity of CoP movement in the anterior–posterior (AP) direction and the mean frequency of changes in CoP movement during AP postural sway were used for further analysis of CoP movement during balance tests as suggested by previous research [34].

The accuracy of head and neck movements during the Butterfly test was analyzed using the NeckSmart software applying the following parameters: mean and standard deviation of the relative time spent on the target during each trial expressed as a percentage of total trial time (time-on-target), relative time spent behind the target (undershoot), and time spent in front of the target (overshoot). Averages and standard deviations for all conditions were used for further analysis.

Accuracy of the head-to-neutral relocation, representing position sense in angular degrees (°) was analyzed in NeckSmart software. The following parameters were calculated: mean of the absolute deviation from the neutral position over the three trials for each measured direction (absolute error), average magnitude of both under and overestimation of target position (constant error) and variability of three consecutive repetitions expressed as two standard deviations (variable error).

The procedure of analyzing eye movement data is described in the study by Majcen Rosker et al. [6]. The square waves, saccades and blinks were removed from the eye movement data using custom-written software in Matlab (R2017b, MathWorks, Natick, MA, USA). The sixth to ninth cycles were used for further analysis. Horizontal eye movements were analyzed using gain, calculated as the ratio between eye velocity amplitude and visual target velocity amplitude as described by Tjell et al. [21] during right (gain R) and left (gain L) neck torsion, as well as the difference between gain at neck torsion and neutral position (SPNTdiff).

2.4. *Statistical Analysis*

All statistical analysis was performed in Statistical analysis software (SPSS 23.0 software, SPSS Inc., Chicago, IL, USA). The normality of distribution was analyzed for all independent variables (parameters of the Butterfly and head-to-neutral tests) using skewness and kurtosis and homogeneity of variance using the Lavine's test. Multiple regression with a best fit model was used to analyze relations between dependent variables (individual balance or SPNT test parameter) and independent variables. Multiple regression was performed in two steps. First, clusters of three difficulty levels (easy, medium and difficult) or three precision measures (absolute error, constant error and variable error) for individual parameters of kinesthetic tests were used for linear model building. In the second step, difficulty levels or precision measures presented in statistically significant models for all variables used to assess relationship to one dependent variable were combined to build the final model. The latter was used to describe the relationship between independent variables (for each kinesthetic test separately) and one dependent variable. Before building each model, the level of collinearity was analyzed. For each model, adjusted R2 and p values were calculated (treated as significant when $p < 0.05$).

3. Results

3.1. *Participants Characteristics*

Eighty-five individuals participated in the study, 43 idiopathic neck pain patients and 42 asymptomatic controls (demographic data and results of magnetic imaging assessment are presented in Table 1).

Table 1. Demographic data.

	Idiopathic Neck Pain Patients (n = 43)	Asymptomatic Controls (n = 42)
Gender	31 women/12 men	24 women/18 men
Average age (age range)	41.3 ± 6.7 years (25–51 years)	39.1 ± 6.3 years (23–49 years)
Average pain duration	13.4 ± 9.1 months	
Average VAS score	4.9 ± 1.7	
Disc protrusion or herniation (C4–Th1)	27 patients	
Facet joint osteoarthritis (C5–Th1)	9 patients	
Low grade spondylolisthesis	12 patients	
Cervical spine stenosis	9 patients	
Combination of at least two types of structural deformities	34 patients	
One type of structural deformity	9 patients	

3.2. *Multiple Regression Analysis for Butterfly Test and Postural Balance*

Results of the multiple regression analysis between the Butterfly tests and individual dependent variables (balance Vap or Fap) are presented in Table 2 Only statistically significantly models were presented.

Table 2. Relations between body sway and Butterfly test.

Body Sway Parameter	Group	Butterfly Parameter	Difficulty	Neutral			Left			Right		
				R^2	F	*p*	R^2	F	*p*	R^2	F	*p*
Vap	**Patients**	**ToTsd**	**D**				0.318	8.472	0.011			
		Undsd	**E**				0.477	7.137	0.017			
		Ovrsd	**M**				0.423	9.306	0.032			
			D							0.054	4.288	0.043
		Und	**M**							0.072	8.019	0.023
	Healthy	**ToTsd**	**M**				0.216	3.967	0.000			
		Ovrsd	**M**				0.360	4.436	0.040			
Fap	**Patients**	**ToT**	**M**							0.091	6.783	0.012
		Und	**M**							0.089	6.698	0.012
			D	0.189	4.738	0.046						
	Healthy	**ToTsd**	**M**				0.058	4.588	0.036			
		ToT	**M**	0.135	9.047	0.002	0.055	4.363	0.041			
		Und	**M**	0.088	6.577	0.013	0.098	4.136	0.021			

R^2—adjusted R square, F—F statistic, *p*—statistical significance; Neutral—neutral head position; Left—left neck torsion; Right—right neck torsion; Vap—average velocity of CoP movement in anterior-posterior direction; Fap—average frequency of direction change of CoP movement in anterior-posterior direction; ToTsd—time-on-target standard deviation; Undsd—undershoot standard deviation; Ovrsd—overshoot standard deviation; Und—undershoot; ToT—time-on-target; D—difficult trajectory of the Butterfly test; M—medium trajectory of the Butterfly test; E—easy trajectory of the Butterfly test.

Statistically significant models produced by the first step multiple regression modelling presenting a relationship between the body sway parameters (Vap or Fap) and the butterfly test parameters are presented in Table 1. Vap when performing balance in neutral position proved to have no relation with the Butterfly test in either of the groups. For neck torsion position, the patient group presented with relations to the butterfly test. Such relationships were only observed for the left neck torsion in the control group. Fap proved to have some relations to the Butterfly test parameters in the neutral position in both groups. In the neck torsion position, the patients presented with statistically significant relations when observing the right neck torsion and patients when observing the left neck torsion. In general, all above-described relations tended to be more pronounced in neck pain patients than in healthy controls.

Second level multiple regression was unable to upgrade the models presented at the first level of multiple regression in the neutral position. Under left neck torsion, the multiple regression presented with a superior Vap variability, describing the model using a time-on-target standard deviation at the difficult level and an overshoot standard deviation at the medium level (R^2 = 0.452; F = 6.247; 0.012) in neck pain patients. In the healthy group, no such model was observed for Vap, as no improvement was observed by combining time-on-target standard deviation and overshoot standard deviation at the medium difficulty. At right neck torsion no superior models to the first level multiple regression could be observed for both groups. No collinearity between variables was observed.

3.3. *Multiple Regression Analysis for Head-to-Neutral Position Sense and Postural Balance*

Results of multiple regression analysis between head-to-neutral position sense and individual dependent variables (balance Vap or Fap) are presented in Table 3. Only statistically significantly models are presented.

Table 3. Relations between body sway and head-to-neutral relocation test.

Body Sway Parameter	Group	HTN Direction	HTN	Neutral			Left			Right		
				R^2	F	*p*	R^2	F	*p*	R^2	F	*p*
Vap	Patients	Right	Ae	0.066	5.124	0.027				0.208	4.105	0.040
	Healthy	Right	Ae				0.083	3.629	0.033	0.101	7.551	0.038
Fap	Patients	Forward	Ce	0.055	4.379	0.041						
		Right	Ae									

HTN direction—direction of the head-to-neutral relocation test; HTN—head-to-neutral relocation accuracy parameter; R^2—adjusted R square, F—F statistic, *p*—statistical significance; Neutral—neutral head position; Left—left neck torsion; Right—right neck torsion; Vap—average velocity of CoP movement in anterior-posterior direction; Fap—average frequency of direction change of CoP movement in anterior-posterior direction; Ae—absolute error; Ce—constant error.

Both, patient and control presented with some relations between the head-to-neutral test and the Vap or Fap in the neutral stance. The patient group presented with some but weak relations between the head-to-neutral test and Vap under both neck torsion positions. No second level multiple regression models were built due to only one parameter being significant at the first level for all neck positions in both groups. No collinearities were observed.

3.4. *Multiple Regression Analysis for Butterfly and SPNT Test*

Results of multiple regression analysis between Butterfly parameters and individual dependent variables (Gain at different neck positions or SPNTdiff) are presented in Table 4. Only statistically significantly models were presented.

Table 4. Relations between eye movements during smooth pursuit neck torsion test and the butterfly test.

Group	Butterfly Parameter	Difficulty	Gain_n			Gain_l			Gain_r			SPNTdiff		
			R^2	F	*p*	R^2	F	*p*	R^2	F	*p*	R^2	F	*p*
Patients	ToTsd	E	0.421	8.278	0.018	0.397	9.025	0.031	0.391	8.316	0.041			
	Undsd	E				0.372	9.935	0.022	0.423	8.333	0.018			
	Ovrsd	E	0.529	7.869	0.011							0.293	3.298	0.044
	ToT	E				0.306	5.418	0.045	0.364	6.729	0.029			
	Und	E				0.417	8.164	0.019	0.495	10.804	0.029			
Healthy	ToTsd	D	0.287	2.717	0.042									
	Undsd	M	0.325	2.002	0.034									
	Over	E							0.265	9.932	0.049			

Gain_n—gain in neutral neck torsion position; Gain_l—gain at left neck torsion position; Gain_r—gain at right neck torsion position; R^2—adjusted R square, F—F statistic, p—statistical significance; ToTsd—time-on-target standard deviation; Undsd—undershoot standard deviation; Ovrsd—overshoot standard deviation; Und—undershoot; ToT—time-on-target; Over—overshoot; D—difficult difficulty; M—medium difficulty; E—easy difficulty.

Both patients and the control group presented with some relations between the Butterfly parameters and gain at the neutral position. Such relations under neck torsion position were only observed for the patient group in both neck torsion positions. The SPNTdiff only presented with the relation to the overshoot standard deviation in the patient group. No second level multiple regression models could be built to present superior characteristics as observed at the first level. No collinearity was observed.

3.5. Multiple Regression Analysis for Head-to-Neutral Relocation Test and SPNT Test

Results of the multiple regression analysis between head-to-neutral relocation test parameters and individual dependent variables (gain at different neck positions or SPNTdiff) are presented in Table 5. Only statistically significantly models are presented.

Table 5. Relations between eye movements during smooth pursuit neck torsion test and the head-to-neutral relocation test.

Group	HTN Direction	HTN	Gain_n			Gain_l			Gain_r			SPNTdiff		
			R^2	F	*p*	R^2	F	*p*	R^2	F	*p*	R^2	F	*p*
Patients	**F**	**Ae**	0.476	5.543	0.031									
	R	**Ve**	0.387	7.318	0.024	0.519	11.803	0.007	0.420	8.235	0.018			
	L	**Ae**	0.413	8.92	0.039									
Healthy	**R**	**Ae**										0.138	13.676	0.048

HTN direction—direction of the head-to-neutral relocation test; HTN—head-to-neutral relocation accuracy parameter; Gain_n—gain in neutral neck torsion position; Gain_l—gain at left neck torsion position; Gain_r—gain at right neck torsion position; R^2—adjusted R square, F—F statistic, *p*—statistical significance; F—forward head movement during the head-to-neutral test; R—right head movement during the head-to-neutral relocation test; L—left head movement during the head-to-neutral relocation test; Ae—absolute error; Ve—variable error.

Only the patient group presented with relations between the head-to-neutral relocation test parameters and gain at neutral and neck torsioned position. The control group presented with low relations between right absolute error and SPNTdiff. No superior models were observed at the second level multiple regression model. No collinearity was observed.

4. Discussion

The aim of this study was to investigate the relationship between cervicocephalic kinesthesia using the Butterfly test and the head-to-neutral paradigm and balance under neck torsion positions or oculomotor control during SPNTT in idiopathic neck pain patients and healthy controls. Results from our study confirm a relationship between kinesthetic awareness of the neck measured with both tests and postural balance in neck pain patients, which is less prominent in healthy individuals. A relationship between cervicocephalic kinesthetic awareness and gain during neck torsion maneuver, with less SPNTdiff, was observed in idiopathic neck pain patients, and a smaller relationship was found in healthy individuals.

While cervicocephalic position sense and postural balance have been extensively studied separately in patients with neck pain disorders [35] their relation has been seldom investigated [3]. In the research by Treleaven et al. [3] the relationship between balance and the head-to-neutral relocation test presented with small to medium correlations. Our study importantly upgrades their findings where the relationship between neck position sense and balance was more pronounced in neck torsion maneuvers. This is more evident in neck pain patients and less so in healthy individuals. Assessing balance tasks when the body is rotated underneath the stationary head is thought to stimulate cervical but not vestibular receptors. In patients with neck pain disorders, abnormal cervical afferents can contribute more to sensorimotor disturbances when the neck is in a torsioned position [36]. A previously proposed mechanism of cervical-driven postural balance deficits can therefore be confirmed by the more pronounced relationship between neck kinesthesia and balance in neck torsion position found in our study, which was evident in both observed groups.

Previous studies assessing neck pain patients found a poor ability to control body sway in the AP direction [34]. Our results presented with a medium relationship between average CoP movement velocity and frequency in the AP direction and some of the Butterfly parameters (time-on-target standard deviation, time-on-target and overshoot). The altered inter-trial standard deviation of the Butterfly test parameters could indicate less efficient sensorimotor control of cervical spine movements, which is in line with other studies confirming alterations in head movement variability in patients with neck pain disorders [37]. The altered variability of head and neck movements found during the Butterfly test in our study is related to body sway velocity and frequency in the AP direction. This is partially in line with other studies, where cervical spine injury was associated with altered body stiffness in postural and locomotion tasks [37,38]. In general, postural and locomotor tasks are dependent on a closed-loop mechanism, where movement corrections are based on proprioceptive feedback [39]; however in neck pain patients, this closed-loop system could be hampered due to commonly observed sensory mismatch. Another parameter that was related to body sway control was the overshoot of the head and neck movements while tracking an unpredictable moving target. The largest proportion of overshoot can be caused by a less efficient correction of movement direction. In this instance, it is necessary to accurately reverse the function of the muscles performing the initial impulse from agonists to antagonists in order to accurately decelerate and initiate changes in movement direction. Accurate movement control demands appropriate sensory feedback [40]; therefore, proprioceptive deficits could result in inappropriate sensory motor coupling, consequently affecting balance.

It could be speculated that consistency of the time spent on target in the Butterfly test could be dependent on the variation in adjusting for the cervical kinesthetic perception error, which is an important mechanism in postural control. One of the possible drivers of perception error, besides the pathological ingrowth of proprioceptors into the vertebral disc [16], can be increased tonic activity and altered proprioceptive feedback from dorsal cervical muscles commonly seen in patients with neck pain disorders. This could alter their body sway control, which has been suggested by Pettorossi and Schieppati [10], where proprioceptive alterations induced by vibration of dorsal neck muscles significantly influenced body posture and movement in AP direction.

Neck torsion maneuvers have been thought to affect eye movement control due to disturbed proprioceptive feedback from the cervical spine [41] but the relationship between cervical kinesthesia and oculomotor control has not been thoroughly studied. Treleaven et al. [3] found no correlations between cervical proprioception and eye movement control using only SPNTdiff. Our study in addition to SPNTdiff also analyaed gain. The parameter of gain showed a greater relationship with the head-to-neutral position than SPNTdiff. This is somehow expected, as the gain measured during neck torsion position directly reflects alterations in proprioceptive feedback. SPNTdiff on the other hand reflects the magnitude of disturbances in cervico-ocular and cervico-colic reflexes. To upgrade the current knowledge, the Butterfly test that measures the dynamic head and neck movement control was performed. The results presented a medium relationship with gain but not with SPNTdiff in neck pain patients, but this was less pronounced in asymptomatic individuals. Undershoot and its inter-trial standard deviation were associated with gain performance when neck was torsioned to the left and right. The undershoot parameter could be associated with increased tonic muscular activity via increased muscle spindle firing, which could lead to an inability to react accurately during unpredictable changes in the direction of movement. Increased and asymmetric muscle spindle firing could cause sensory mismatch, consequently influencing oculomotor control via its direct neurophysiological connection to the vestibular and visual system [7,16].

One of the important limitations of our study was a small sample size, which could have affected the level of observed relationships and consequently the models build by the multiple regression method. As patients with neck pain disorders represent a heterogenous group which differs in the type of sensorimotor disturbances, future studies should subgroup them according to the location of pain [16] and the presence of other symptoms such as dizziness and visual disturbances [42].

5. Conclusions

It can be concluded that the specific aspect of neck kinesthetic functions (i.e., movement sense but less position sense) importantly contributes towards oculomotor and balance control, which is more evident under a neck torsion position in neck pain patients, but is less pronounced in asymptomatic individuals.

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2.2 ADDITIONAL SCIENTIFIC WORKS

2.2.1 Pupillometric parameters of tonic and phasic alertness during unpredictable but not predictable smooth pursuit neck torsion test are altered in patients with neck pain disorders: a cross-sectional study

Majcen Rosker Z., Vodicar M., Kristjansson E. 2022. Pupillometric parameters of tonic and phasic alertness during unpredictable but not predictable smooth pursuit neck torsion test are altered in patients with neck pain disorders: a cross-sectional study. Sent for publication to Disability and Rehabilitation (Current status Under review)

Abstract

Neck pain patients commonly report cognitive disfunctions, but cognitive mechanisms such as increased phasic alertness during unpredictable smooth pursuit neck torsion tasks (SPNTT) have not yet been studied. The aim of this study was to investigate eye movement accuracy and pupillometric responses during predictable and unpredictable SPNTT in neck pain patients and controls. Eye movements and pupillometry indicative of tonic and phasic alertness were measured in twenty-eight neck pain patients and thirty controls using infrared video-oculography during predictable and unpredictable SPNTT. Gain in unpredictable SPNT was lower than in predictable tasks and showed similar levels in neutral and neck torsion positions. This was not the case in the predictable SPNT. Index-of-cognitive-activity (ICA) was lower during neutral position in all tasks in patients but increased during neck torsion positions in unpredictable tasks. Normalized pupil diameters presented with no differences between groups, but differences for average pupil diameter were observed. Higher ICA indicated increased phasic alertness in patients despite no alterations in oculomotor control during SPNTT. This is the first study to confirm cognitive involvement in oculomotor task in neck pain patients. The latter could negatively affect tasks where additional cognitive resources must be involved.

Pupillometric parameters of tonic and phasic alertness during unpredictable but not predictable smooth pursuit neck torsion test are altered in patients with neck pain disorders: a cross-sectional study

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Abstract
Introduction: Neck pain patients commonly report cognitive disfunctions, but cognitive mechanisms such as increased phasic alertness during unpredictable smooth pursuit neck torsion tasks (SPNTT) have not yet been studied. The aim of this study was to investigate eye movement accuracy and pupillometric responses during predictable and unpredictable SPNTT in neck pain patients and controls.
Materials and methods: Eye movements and pupillometry indicative of tonic and phasic alertness were measured in twenty-eight neck pain patients and thirty controls using infrared video-oculography during predictable and unpredictable SPNTT.
Results: Gain in unpredictable SPNT was lower than in predictable tasks and showed similar levels in neutral and neck torsion positions. This was not the case in the predictable SPNT. Index-of-cognitive-activity (ICA) was lower during neutral position in all tasks in patients but increased during neck torsion positions in unpredictable tasks. Normalized pupil diameters presented with no differences between groups, but differences for average pupil diameter were observed.
Conclusion: Higher ICA indicated increased phasic alertness in patients despite no alterations in oculomotor control during SPNTT. This is the first study to confirm cognitive involvement in oculomotor task in neck pain patients. The latter could negatively affect tasks where additional cognitive resources must be involved

Keywords: oculomotor functions; smooth pursuit eye movements; cervical disorders; cognitive disfunction; attention; pupillometry.

Introduction

Patients with neck pain disorders commonly present with disturbances in the oculomotor system [1–4] of which the goal is to maintain visual information carriers' retinal projection on or near the fovea during visual field observation [5,6]. Such disturbances in neck pain patients are reflected in decreased ability to smoothly pursuit a horizontally moving target with their eyes, especially when the neck is in torsioned position (SPNT) [2,7]. The proposed mechanism for deficiencies in eye movement control during neck torsion position is error in proprioceptive drive leading to disturbances in cervico-colic and cervico-ocular reflexes [2,8]. Such adaptations could result in decreased ability to smoothly pursuit a horizontally moving target with their eyes, expressed as ratio between target and eye movement velocity (gain) [7].

Additional mechanism contributing to extraocular muscle control and consequently ocular movements is target projection slippage on the retina or its distance from the fovea [5]. This information supplements central mechanisms of eye movement control integrating preceding knowledge on target movement characteristics resulting in anticipation of target movement trajectory and its temporal characteristics [5]. When the difficulty of following a moving target increases, cognitive resources such as working memory and attention are deemed more involved [9]. According to research, neck pain patients present with alterations in eye movements when observing predictable horizontally moving target [1,3,10], but to our knowledge only one study analysed eye movement control during unpredictable target movements [11]. Their results presented with preserved smooth pursuit eye movements during unpredictable than predictable tasks under neck torsion manoeuvre. Authors speculated that increased performance during unpredictable task might have resulted from altered cognitive involvement, especially level and type of alertness. Cognitive disfunction is commonly described by patients with neck pain disorders [12,13]. Amongst others, altered ability to concentrate to read or focus and difficulty judging distance are commonly reported [14]. Moreover, relationship between above mentioned symptoms and SPNT test has been observed [15]. It is currently unknown whether cognitive deficits such as altered alertness are present during oculomotor tasks such as predictable and unpredictable SPNT. Additionally, it remains unknown to what extent alertness is altered in neck pain patients and whether they can mobilize supplementary cognitive resources when performing predictable and unpredictable SPNT tasks.

An objective and reliable method for assessing alertness during visual tasks is pupillometry [16,17]. Pupillary dilatations are suggested to measure increased activity of locus coeruleus [18–20], which is related to the level of alertness [21]. Furthermore, altered activity of locus coeruleus has been observed in presence of pain [21]. In general, alertness measured via pupillary responses can be divided into the slow adapting pupil dilatations representing tonic alertness (attending to various objects simultaneously) and high frequency pupillary responses representing phasic alertness (attending to a specific object) [22]. Infrared video-oculography has been shown to present a valid and reliable toll for assessing pupillometric responses [23] as well as smooth pursuit eye movements [24,25].

As suggested by Majcen Rosker et al., [1] different mechanisms could be involved when pursuing a target moving at different velocities or amplitudes. Target movement velocity affects interplay between smooth pursuit and saccadic systems [26], while increased eye movement amplitude affects neck muscle activity [27]. As cervical muscle function and sensory drive are altered in neck pain patients, it could be expected, that unpredictably changing target movement amplitude or velocity could present a higher challenge to oculomotor control as compared to predictable target movements.

The aim of this study was to compare the ability to smoothly follow predictable and unpredictable moving targets during SPNT test in chronic neck pain patients and asymptomatic individuals. Additionally, tonic and phasic alertness during different SPNT tasks was studied to better understand cognitive adaptations in neck pain patients.

Methods

Participants

Patients with chronic neck pain and asymptomatic controls were enrolled in this study. Controls were recruited among university staff, doctoral students and their friends. Neck pain patients were referred to the study from orthopaedic outpatient clinics if they experienced pain in the neck from 6 months to 5 years. To be able to perform SPNT test all participants were required to present with minimum of 50° of cervical rotation to each side. All enrolled participants had to be in an age range of 18-55 years. Patients were required to mark pain intensity on 10-cm horizontal line of visual analogue scale [28] presenting with minimum of 4 to be considered for the study. All participants had to be free from previous traumatic injury to the neck or head, shoulders or upper extremities pain, any neurological or vestibular disorders, and were required to take no medication or alcohol for 30-hours prior to the study.

Equipment

A 100-Hz infrared video-oculography (Pro Glasses 2, Tobii, Danderyd, Sweden) was used to measure eye movements during SPNT test and left eye pupillary diameter [29]. All participants were instructed to track a horizontally moving target of a red dot (size 0.5° of visual angle) which was projected with a 100-Hz refresh rate (Optoma ML1050ST LED Projector, Fremont, USA) on a white screen 150 cm away at an eye level [30]. Participants were sitting on a custom-made rotatable chair with upper body fixed to the back support and feet placed flat on the floor. Hip angle was 80° of flexion. All measurements were conducted by the same examiner in a room with constant illumination.

Experiment

Testing protocol consisted of four horizontal SPNT test tasks; (i) tracking a predictable cyclic sinusoidal target movement with 40° of target movement amplitude and 30°s-1 of target movement velocity, (ii) tracking a sinusoidal target movement with changing target movement amplitude ranging from 30° to 50° amplitude at constant velocity of 30°s-1, (iii) tracking a sinusoidal target movement with changing target movement velocity ranging from 20°s-1 to 40°s-1 at a constant target movement amplitude of 30° and (iv) a sinusoidal target movement with changing of amplitude (from 30° to 50° amplitude) and velocity (from 20°s-1 to 40°s-1).

All four tasks were performed at three neck positions: (i) neutral position with the trunk and head facing forward, (ii) torsion of the neck for 45° to the left (rotation of the trunk underneath the stationary head to the right) and (iii) torsion of the neck for 45° to the right (rotation of the trunk underneath the stationary head to the left). The order of neck torsions was pseudo-randomized across subjects.

For each task subjects were required to track 10 cycles of sinusoidal target movements followed by a 60 second rest. All tasks were performed in a random order.

Data analysis

Eye movement data were filtered for blinks, saccades and fixations using Tobii Pro Lab software (Tobii Pro lab 1.145, Tobii, Danderyd, Sweden). Square waves (saccades directed counter to each other and having an interval of relative standstill) were removed from the eye movement data using custom-written software in Matlab (R2017b, MathWorks, Natick, MA, USA). Eye movement data were fitted with a corresponding reference sinusoid. Each fitted sinusoid consisted of 10 cycles with corresponding amplitude (converted from angular degrees to pixels) and frequency matching the profile for each individual condition. Horizontal eye movements were analysed using gain, calculated as the ratio between fitted eye velocity amplitude and visual target velocity amplitude as described by Tjell et al. [7]. Gain torsion R represents the average gain during the right neck torsion and gain torsion L represents the average gain during left neck torsion from the 6th to 9th cycle [10]. In addition, SPNTdiff was calculated as presented in Equation 1 to present differences between neutral and neck torsion positions. The calculation was adapted and is similar to that described by Tjell et al. [7].

*** Equation 1 ***

Pupil size data were analysed using two approaches. The index of cognitive activity (ICA) was derived from the pupil size data using a procedure described in Marshal [19]. This procedure is performed on preprepared data, where short blinks are interpolated to obtain a continuous pupil size data set. Furthermore, Wavelet analysis was used to decompose the pupil signal into high-frequency components which are representative of changes in cognitive activity. Rapid pupil dilatations exceeding a threshold are identified and used to calculate the ICA. The procedure was patented in 2000 (US Patent Number 6.090.051) and the values can be obtained via the Cognitive Workload Module (Cognitive Workload Module 3, EyeWorks, San Diego, USA). The software provides a number of pupil dilatations per second, normalizes and transforms them [19,20]. The ICA was averaged over 6th to 9th cycle of each unpredictable and predictable task. In addition, average pupil size was calculated during 6th to 9th cycle of the unpredictable and predictable tasks. The average pupil diameter at each unpredictable task was further expressed as a ration between the average pupil diameter during unpredictable and predictable SPNT tasks (relative pupil diameter) [31]. Average pupil diameter and relative pupil diameter were used for further analysis.

Statistical analysis

Statistical analysis was performed in SPSS (SPSS 23.0 software, SPSS Inc., Chicago, USA). Shapiro-Wilk test, skewness and kurtosis were calculated to analyse data distribution for each parameter. Median and interquartile range were calculated for both groups in each task and neck position. Due to nonnormality of data distribution in some parameters, Friedman's test was used to analyse differences between the three trunk positions in each SPNT tasks for each group separately and for differences between tasks for each position and group separately. Post-hoc sign rank test was for pairwise comparisons. Differences between groups were analysed using Sign test for each trunk position and each SPNT test task separately. Cohen d was calculated for each post-hoc test. Statistical significance was set at $p < .05$.

Results

Participants

Twenty-eight patients and thirty controls were recruited for the study. Twenty-one women and seven men were included in the patient group and nineteen women and eleven men in the control group. The mean age of the patient's group was 43.1 ± 4.6 years (age range 27 – 51 years) and the mean age of the control group 39.3 ± 5.7 years (age range 23-50 years). The control group was statistically significantly older as compared to the patient group ($p = .046$; $d = 0.203$). In the neck pain group cervical spine magnetic imaging assessment presented disc protrusions or herniations at the levels from C4 to Th1 in 23 patients, 7 patients presented with facet joint osteoarthritis at the levels from C5 to Th1, 6 patients presented with low-grade spondylolisthesis and 7 patients presented with cervical spinal stenosis. Nineteen patients had a combination of at least two types of structural deformity, however in 9 patients only one type of structural deformity was present. Average pain duration in the patient's group was 11.3 ± 6.9 months and average VAS score was 4.8 ± 1.6. Control group presented with no pain.

Neck position and group differences

Table 1 presents the results of the Friedman's test where the differences in Gain between the three neck positions were analysed for each parameter at each SPNT task for both groups separately. Statistically significant differences were present only for the ICA in all three unpredictable tasks in the neck pain patient group.

*** Table 1 ***

Medians, interquartile ranges, and results of the sign post-hoc tests for differences in gain for each group and neck torsion position are presented in Figure 1. Statistically significant differences were observed between both groups in all SPNT tasks. Statistically significant differences between neutral and both neck torsion positions were observed only in the neck pain patient group in the predictable SPNT task.

*** Figure 1 ***

Medians, interquartile ranges, and results of the sign post-hoc tests for differences in the SPNTdiff for group and neck torsion position are presented in Figure 2. Statistically significant differences were observed for SPNTdiff in the predictable but not for the three unpredictable SPNT tasks.

*** Figure 2 ***

Medians, interquartile ranges, and results of the sign post-hoc tests for differences in the ICA for group and neck torsion position are presented in Figure 3. Statistically significant differences between groups were observed for the unpredictable SPNT task and unpredictable task with varying velocity in the neutral neck position. Differences between neutral and some of the neck torsion positions were observed in the unpredictable SPNT task and unpredictable task with varying amplitude in the neck patient group. In the asymptomatic group no statistically significant differences were observed.

*** Figure 3 ***

Medians, interquartile ranges, and results of the sign post-hoc tests for differences in the average pupil diameter for both groups and neck torsion position are presented in Figure 4. Statistically significant differences between both groups were observed for the predictable SPNT task in neutral neck position and for all neck positions in all three unpredictable SPNT tasks. No statistically significant differences between neck positions were observed for either of the groups.

*** Figure 4 ***

Medians, interquartile ranges, and results of the sign post-hoc tests for differences in relative pupil diameter for both groups and neck torsion positions are presented in Figure 5. No statically significant differences were observed between the groups as well as between three neck torsion positions.

*** Figure 5 ***

Discussion

The aim of this study was to compare performance in SPNT test using one predictable and three unpredictable target movement profiles in neck pain patients and asymptomatic individuals. Additionally, tonic and phasic alertness were assessed during all SPNT tasks for both studied groups. Furthermore, differences between the groups were analysed. Neck pain patients presented with decreased ability to follow a moving target in all SPNT tasks as compared to asymptomatic individuals. Moreover, during predictable target movements patients presented with decreased gain (higher SPNTdiff) in neck torsion positions as compared to the neutral position, which was not observed in unpredictable target movement tasks (lower SPNTdiff). Higher ICA on the other hand presented with an increase in alertness under neck torsion manoeuvre as compared to the neutral position in neck pain patients. This was evident for unpredictable but not predictable SPNT tasks. Although similar trend was observed for predictable SPNT task, it could be speculated that this was due to its lesser challenge to the cognitive system. On the contrary, asymptomatic individuals presented with similar alertness in the neutral and neck torsion positions. Comparisons between the two groups presented with statistically significant differences in ICA but only during smooth pursuit task in the neutral position. The tonic alertness presented with statistically significant differences between groups for all observed tasks and neck positions when observing the average pupil diameter, but not for the normalised pupil diameter. Moreover, no differences between neck positions were observed for both parameters of alertness for either of the groups.

Although previous studies investigating predictable eye movement tasks indicate that amplitude and velocity might play an important role in the accuracy of eye movements [1,26,27], this has not been the case when observing unpredictable SPNT tasks. To our knowledge study performed by Janssen et al [11] was the only study investigating SPNT test performance during unpredictably changing velocity of target movements. Our study aimed to determine whether unpredictably changing amplitude, velocity or both would influence the results of SPNT test differently. Results from our study add to current knowledge that unpredictable changes in target movement amplitude, velocity or in both present with no differences in gain in patients with neck pain disorders indicating that target movement amplitude or velocity do not play as significant role in unpredictable SPNT tasks.

Gain in predictable SPNT task observed in our study was in line with the results reported by other studies [2,3,10], where a decrease in eye movement accuracy was observed in neck torsion position, leading to increase in SPNTdiff. Interestingly gain in unpredictable tasks reported in our study remained unchanged in neck torsion positions. Our results are in line with previous findings presented by Janssen et al. [11] where neck torsion positions showed no alterations in gain. In general, decreased gain under neck torsion position in predictable SPNT tasks is suggested to result from sensory mismatch caused by altered sensory drive from the impaired cervical spine, projecting to superior colliculus and influencing vestibular and visual systems [32,33]. As a consequence of sensory mismatch, cervico-colic and cervico-ocular reflexes are altered, causing decreased accuracy of eye movement control during neck torsion positions [1,7]. The above-described mechanism of eye movement control could be less prevailing during unpredictable SPNT tasks due to involvement of higher order mechanisms governing eye movements [5,6]. Retinal slippage or distance of the retinal target projection from the fovea are supposed to be important sources of information controlling smooth pursuit eye movements [9,34]. During more demanding SPNT tasks (unpredictable target movements) such information on previous target movement influences anticipatory eye movements enabling compensations for delays in sensory feedback loops. These mechanisms are supposed to be governed by higher order processing in the frontal eye fields which demands involvement of cognitive resources such as visual working memory and alertness (attention) [5]. Higher order systems could efficiently compensate for the presence of sensory mismatch caused by the cervical disfunction. This could explain the results from our study as well as results presented by Janssen et. al. [11], where gain during neck torsion remained at the comparable level as during neutral position.

Neck pain patients commonly present with cognitive, more specifically alertness deficits [35,36]. The increased allocation of the cognitive resources to the SPNT task under unpredictable conditions was suggested to be the cause of improved gain during neck torsion positions in neck pain patients [11]. This suggestion was partially confirmed by our study, where ICA, which is supposed to be related to object specific attention allocation (tonic alertness) [22], was increased under neck torsion position. In addition, the ICA was in general decreased in the neutral neck position as compared to healthy controls, which confirms the presence of phasic alertness deficit in patients with neck pain disorders as compared to asymptomatic individuals. The main difference was that in the predictable SPNT task there were no statistically significant differences between the neutral and neck torsion position. This suggests, that during predictable conditions the SPNT task was not cognitively challenging enough which could expose possible effects of proprioceptive deficits on eye movement control. Under neck torsion conditions the difficulty of the task increased, demanding increased alertness in order to focus on the moving target and perceive target movement changes, which could have compensated the oculomotor deficits on the expense of increased involvement of cognitive resources. This observation is important to understand the challenge of everyday tasks in neck pain patients. During more demanding visual tasks, neck pain patients are likely to be better able to compensate for oculomotor deficits, however their cognitive capacity is consequently decreased, making less cognitive resources available for other tasks. Such alterations in cognitive resources could influence other skills where vision is important, such as driving a car, walking in a crowded environment, performing reading tasks where additional cognitive resources are demanded. This could lead to earlier fatigue development and decreased general ability to perform more cognitive demanding work.

Somewhat expected, tonic alertness expressed as a relative pupil diameter, did not show any specific differences between the two groups as well as between neck positions for either of the groups. Tonic alertness is thought to be involved in attending to multiple sources of information simultaneously. In our study during SPNT task only one stimulus (target) was used, with all additional sources of information omitted from the visual field. On the contrary, tonic alertness describes by an average pupil diameter was statistically significantly lower in neck pain patients as compared to asymptomatic individuals in all studied tasks and neck positions. This suggests possible impairments of tonic alertness in neck pain patients as compared to asymptomatic individuals.

Although our results indicate alertness alterations in patients with neck pain disorders, more studies are needed to confirm our observations. An important limitation of our study was that it is unclear to what extent the pupil diameter could have been affected by posturally modulated activity of locus coeruleus. Changes in neck position have been shown to influence the activity of locus coeruleus in animals [37]. The latter is suggested to be related to adaptations in sensory-motor control at the level of brainstem. It is however unknown whether activity of locus coeruleus is modulated by changes in neck position in humans, if these changes are affected by cervical deficits and whether cognitive functions observed via pupil dilatations would be affected.

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Table 1. Results of Friedman's test.

		Neck pain patients	**Healthy controls**
Parameter	**SPNT task**	**χ^2**	**χ^2**
Index of cognitive activity	Predictable	2.286	3.271
	Unpredictable	5.286 *	1.254
	Unpredictable amplitude	5.143 *	1.857
	Unpredictable velocity	6.001 *	4.308
Average pupil diameter	Predictable	0.182	2.462
	Unpredictable	0.149	2.462
	Unpredictable amplitude	1.077	4.429
	Unpredictable velocity	0.247	4.154
Normalized pupil diameter	Predictable	0.371	3.581
	Unpredictable	0.220	3.659
	Unpredictable amplitude	0.176	2.974
	Unpredictable velocity	0.414	3.185

SPNT task – smooth pursuit neck torsion task; χ^2 - chi-square statistic; * - statistical difference > .05

Figure 1. Gain.

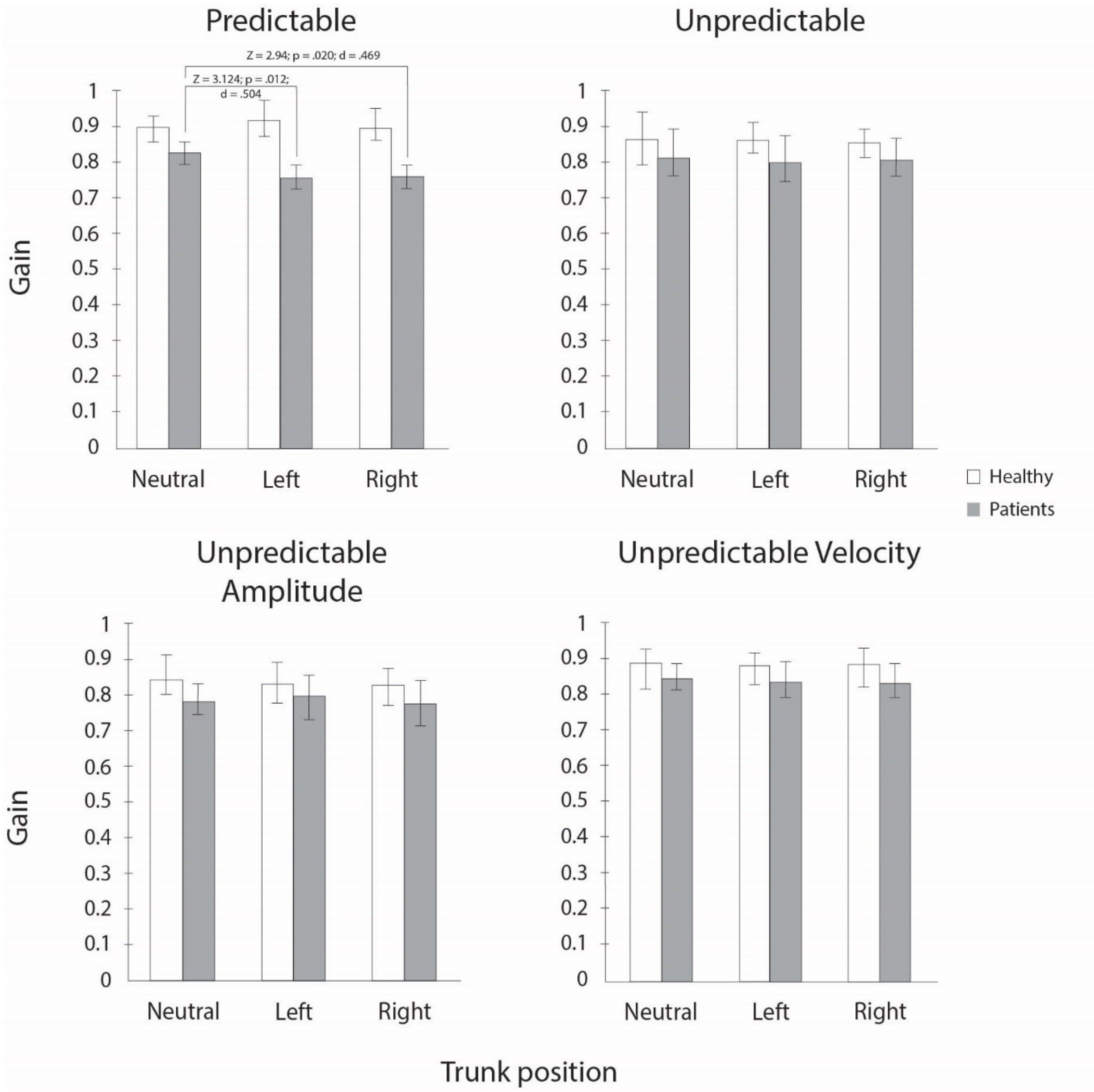
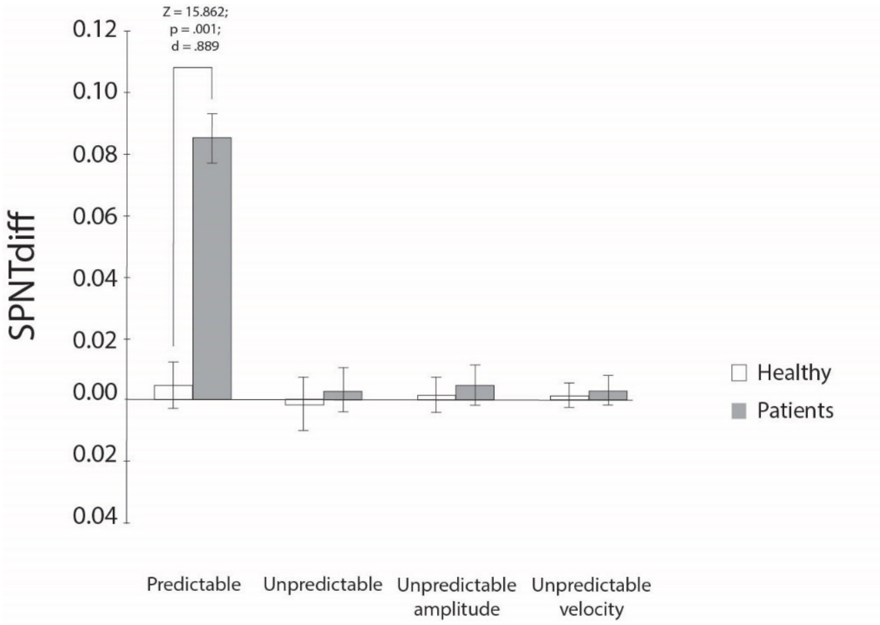
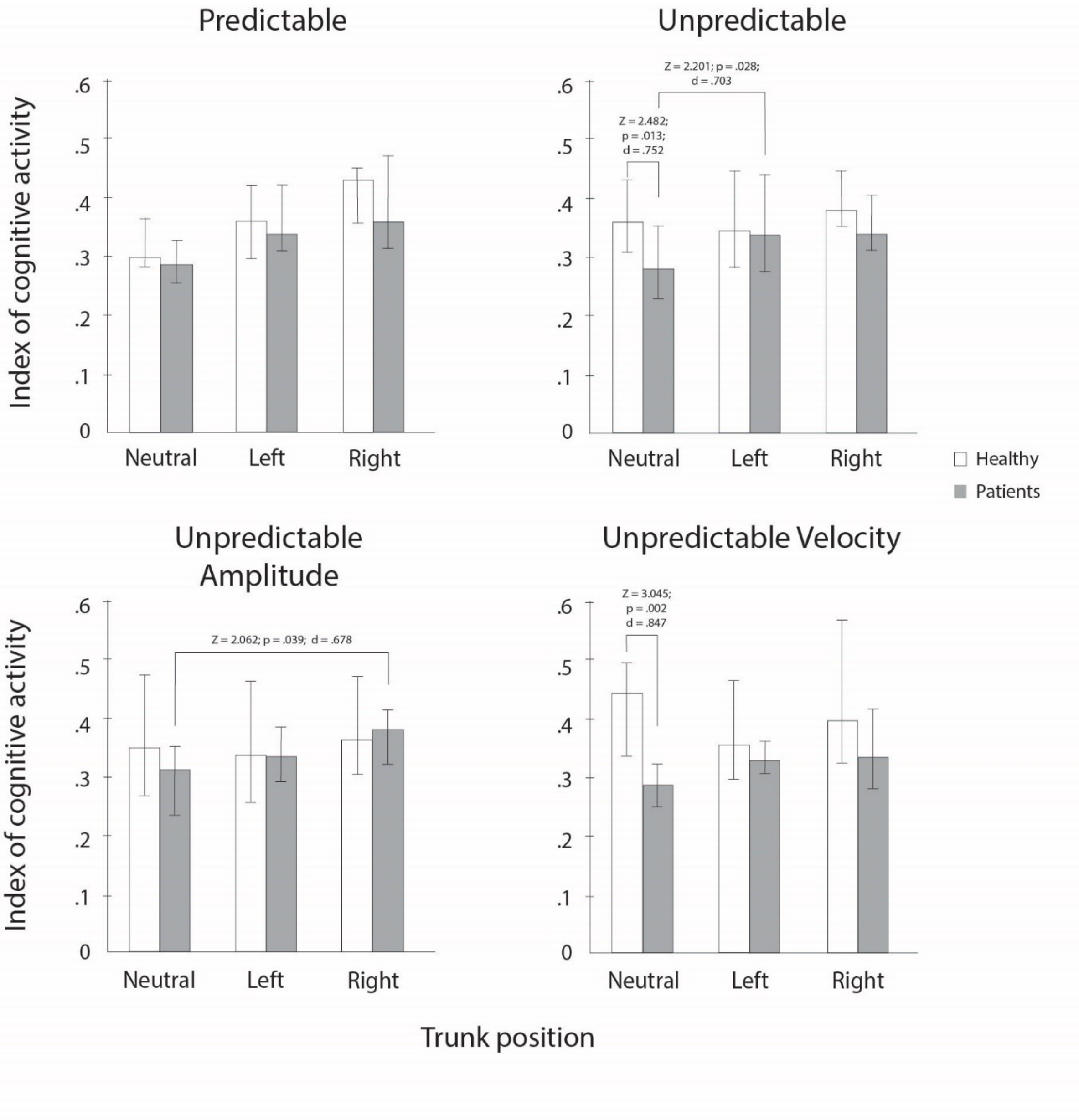


Figure 2. Smooth pursuit neck torsion difference.



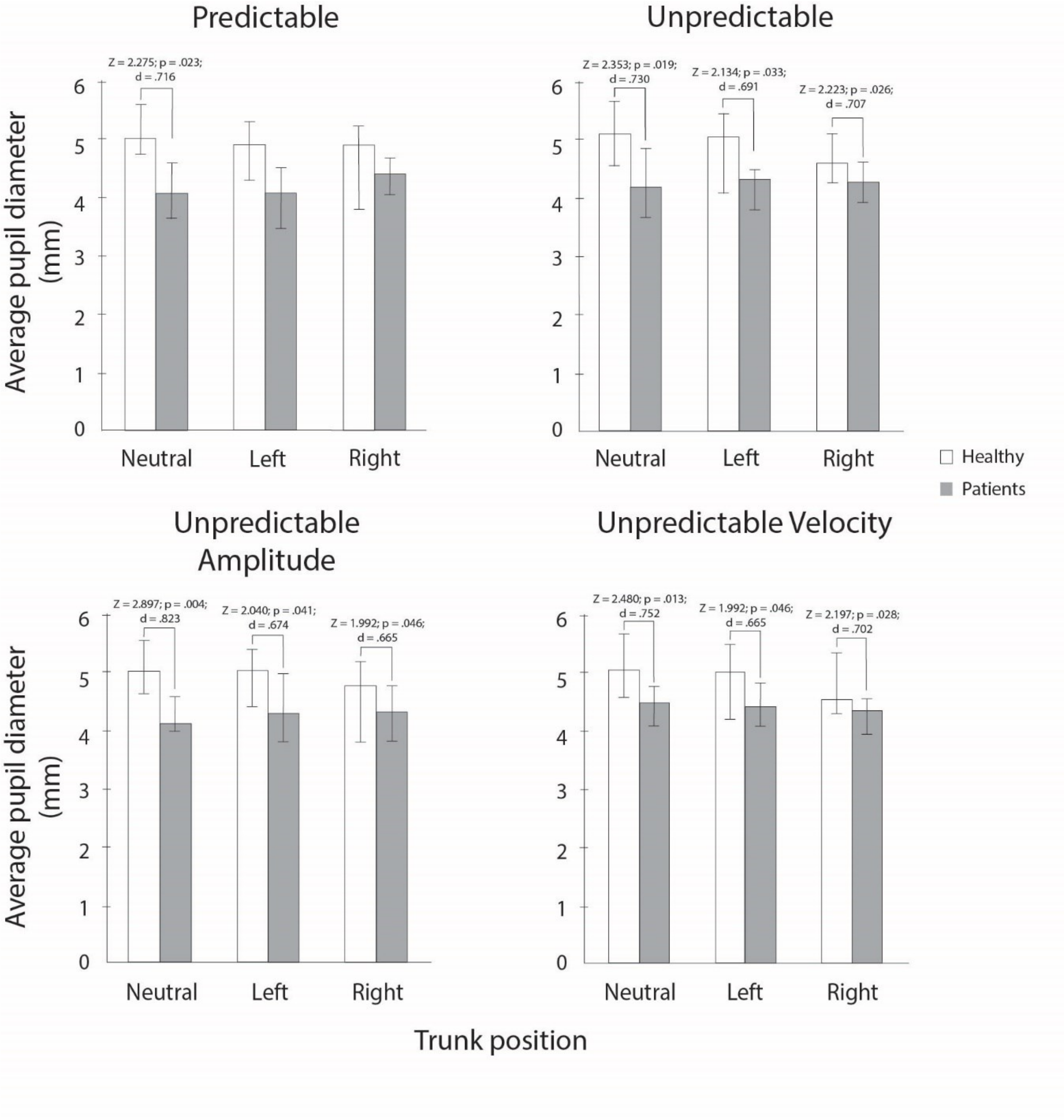
$SPNT_{diff}$ – smooth pursuit neck torsion difference; z – z statistics; p – statistical difference; d – Cohens d

Figure 3. Index of cognitive activity.



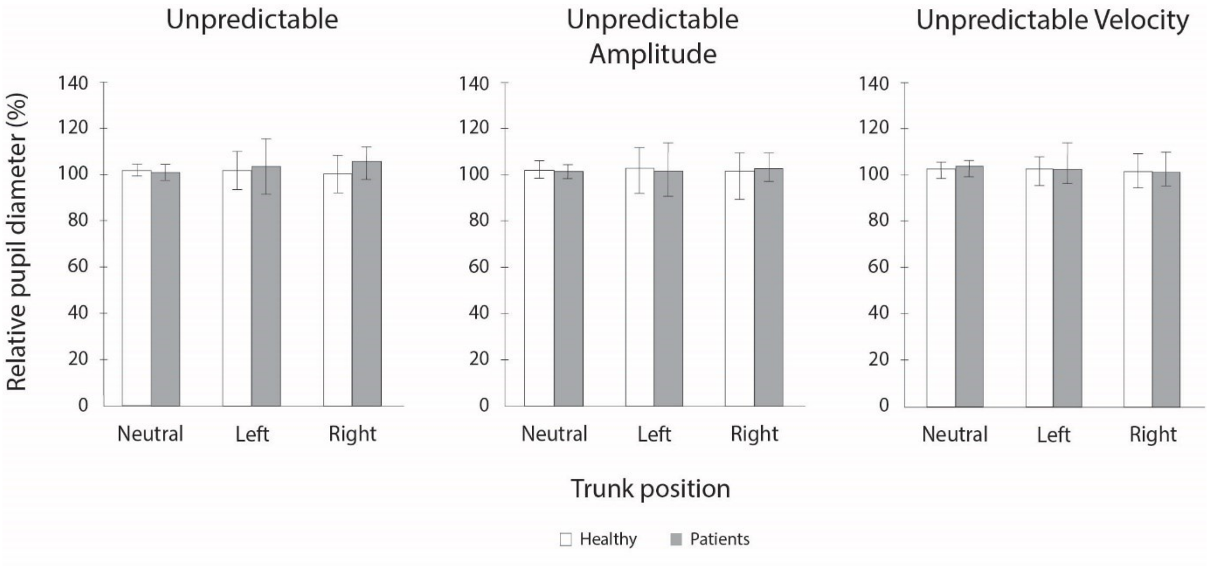
Z represents z statistic; p represents statistical significance; d represents Cohens d.

Figure 4. Average pupil diameters.



Z represents z statistic; p represents statistical significance; d represents Cohens d.

Figure 5. Relative pupil diameter.



2.2.2 How well can we detect cervical driven sensorimotor dysfunction in concussion patients? an observational study comparing patients with idiopathic neck pain, whiplash associated disorders and concussion

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ABSTRACT

Patients with mild traumatic brain injury (mTBI) suffer from sensorimotor impairments. Evidence is emerging that cervical spine plays an important role in mTBI, but it is not known how cervicocephalic kinaesthetic sensibility measured during dynamic unpredictable head movements and measures of position sense, cervical induced postural balance and eye movement control differ between mTBI, whiplash associated disorders (WAD) patients, idiopathic neck pain patients and healthy controls. The aim of this study was to asses, whether sensorimotor disturbances are caused by cervical deficits in mTBI patients and do they differ from disturbances found in traumatic and nontraumatic neck pain patients and healthy controls. Frequency and velocity of centre of pressure movements were measured during parallel stance in the neutral and neck torsion positions, eye movements during smooth pursuit neck torsion test (SPNTT) and cervicocephalic kinaesthesia using Butterfly and head-to-neutral relocation test in 20 asymptomatic controls, 20 idiopathic neck pain patients, 18 WAD and 17 mTBI. Statistically significant differences in postural balance, both tests of cervicocephalic kinaesthesia and SPNTT were observed between healthy controls and all patient groups. No differences were observed between patient groups for SPNTT, Butterfly and head-to-neutral relocation test, but differences were present in postural balance between mTBI and both groups of patients with neck pain disorders. Differences were found in the ML direction for mTBI, but not differences were found for AP direction. Results of our study show that mTBI present with similar impairment in cervical driven sensorimotor deficits as patients with neck pain disorders, but they differ from healthy individuals. Clinical practice would benefit from cervical spine related sensorimotor testing in patients with mTBI.

How well can we detect cervical driven sensorimotor dysfunction in concussion patients? An observational study comparing patients with idiopathic neck pain, whiplash associated disorders and concussion

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ABSTRACT

Background
Patients with mild traumatic brain injury (mTBI) suffer from sensorimotor impairments. Evidence is emerging that cervical spine plays an important role in mTBI, but it is not known how cervicocephalic kinaesthetic sensibility measured during dynamic unpredictable head movements and measures of position sense, cervical induced postural balance and eye movement control differ between mTBI, whiplash associated disorders (WAD) patients, idiopathic neck pain patients and healthy controls.
Research question
Are cervical sensorimotor deficits present in mTBI patients and do they differ from sensorimotor deficits found in traumatic and nontraumatic neck pain patients and whether they differ from healthy controls.
Methods
Twenty idiopathic neck pain patients, 18 WAD, 17 mTBI and 20 healthy controls were enrolled in the study. Frequency and velocity of centre of pressure movements were measured during parallel stance in the neutral and neck torsion positions, gain and smooth pursuit neck torsion difference of eye movements during smooth pursuit neck torsion test (SPNTT) and cervicocephalic kinaesthesia using Butterfly and head-to-neutral relocation test.
Results
Statistically significant differences in postural balance, both tests of cervicocephalic kinaesthesia and SPNTT were observed between healthy controls and all patient groups. No differences were observed between patient groups for SPNTT, Butterfly and head-to-neutral relocation test, but differences were present in postural balance between mTBI and both groups of patients with neck pain disorders. Differences were found in the ML direction for mTBI, but not differences were found for AP direction.
Significance

Results of our study show that mTBI present with similar impairment in cervical driven sensorimotor deficits as patients with neck pain disorders, but they differ from healthy individuals. Clinical practice would benefit from identifying cervical spine related sensorimotor impairments in patients with mTBI. This could enable to design more targeted prevention and rehabilitation programs to minimise cervical spine related disorders in concussion patients.

Key words: Concussion, neck kinaesthesia, body sway, smooth pursuit eye movements, oculomotor control

INTRODUCTION

Mild traumatic brain injury (mTBI) resulting from concussion is a growing public health concern that commonly result in chronicity [1]. There is currently no gold standard diagnostic test for detecting mTBI, therefore its diagnosis is based on clinical reasoning that considers physical signs as well as subjective somatic, cognitive and neurobehavioral symptoms [2,3]. Although these are suggested to resolve within 10 to 14 days, delayed recovery after concussion is frequently observed [4]. It has been suggested that persistent symptoms following concussion do not necessarily reflect brain tissue injury itself [2], whereas some studies suggested the importance of investigating cervical spine function when preventing and treating mTBI [5].

Rising evidence is emerging that cervical spine plays an important role when detecting and treating mTBI. Concussed subjects commonly report myriad of signs and symptoms that are frequently present in neck pain patients [6]. Research indicates that cervical spine injury importantly contributes to persistence of symptoms in mTBI [7], but their mechanism is not fully understood.

There is evidence that imaging remains unreliable to confirm concussion [8] as well as whiplash associated disorders (WAD) [9]. In general concussion is thought to predominantly indicate functional, rather than structural changes [4] with sensorimotor dysfunctions believed to contribute to clinical understanding of concussion. Of these, oculomotor disturbances [10,11] along with postural balance alterations [12] are commonly reported in clinical and research settings. Interestingly, oculomotor dysfunction and altered postural balance are also common in neck pain patients [13]. Moreover, it has been suggested that it is possible to detect cervical spine driven oculomotor [14] and balance dysfunction [15] with neck torsion manoeuvre. Differences between WAD and vestibular pathology were detected in balance under neck torsion manoeuvre and smooth pursuit neck torsion test (SPNTT) [16]. As concussion may present with WAD and vestibular pathology it would be of importance to understand whether they differ from idiopathic neck pain patients and healthy individuals. This is important as WAD might also present with some type of vestibular disfunction, therefore their comparisons to idiopathic neck pain patients and healthy individuals would gather better understanding into cervical driven oculomotor and balance disfunction in those with concussion.

Deficits in cervicocephalic kinaesthesia are specific for neck pain patients. Based on systematic review and meta-analysis performed by Stanton et al. [17] neck pain patients differ from asymptomatic individuals when performing head-to-neutral relocation test. Moreover, the test is suggested to determine cervical kinaesthetic deficits as differences were observed between idiopathic neck pain patients and patients presenting with vestibular pathology [18] but not between WAD and those with vestibular pathology [16]. As vestibular impairments commonly appear after concussion [19,20] and so does after WAD [21] but not in idiopathic neck pain patients, comparing cervicocephalic kinaesthetic sensibility between different groups presenting with cervicogenic deficit could allow better insight into cervical driven proprioceptive deficits.

As head-to-neutral relocation test is thought to measure only one aspect of neck proprioception (i.e. position sense) [22] more complex, unpredictable and slow movement patterns evaluating movement sense should be used [23]. Therefore, the aim of this study was to determine minimal clinically important difference (MCID) between different groups and compare different sensorimotor functions (i.e. postural balance, eye movement control and cervicocephalic kinaesthesia) between the following patients; concussion, WAD and idiopathic neck pain and healthy individuals. We hypothesise that mTBI patients will present with similar sensorimotor disturbances as both neck pain patients group, but will differ from healthy individuals.

MATERIALS AND METHODS

Participants

Three groups of chronic patients were sought for this study: mTBI, WAD and idiopathic neck pain and a group of healthy controls. Inclusion criteria for all participants was age range between 18 and 55 years. All participants had to present with more than 50° of cervical rotation to each side, be free from lower extremity injury or pain, type II diabetes, psychiatric disorders and had to refrain from medication or alcohol 30 hours before the study. All patients had to present with a minimum of 3 months after the onset of symptoms or occurrence of injury.

Concussed subjects were diagnosed with mTBI by a clinician. Patients with mTBI had to present with a Glasgow Coma Scale (GCS) score of 13–15 [24]. WAD patients who had sustained an injury from a motor vehicle collision and experienced neck pain (minimum 4 on VAS) and other symptoms related to WAD were referred to the study. Patients that reported a period of unconsciousness, posttraumatic amnesia or concurrent head injury were excluded from the study. Patients with WAD II according to Quebec Task Force classification [25] were recruited for the study. Idiopathic neck pain patients were referred to the study from orthopaedic outpatient clinics if they presented with minimum of 4 on VAS. Healthy controls were recruited among university staff and their friends.

All participants had to read and sign consent form and were free to withdraw at any time. The study was approved by national medical ethics committee (number: 0120-47/2020/6) and was performed in accordance with the declaration of Helsinki.

Measurement procedures

Participants underwent tests of postural balance, SPNTT, cervicocephalic kinaesthesia (Butterfly test) and position sense (head-to-neutral).
Balance tests in eyes-open conditions were performed while standing on a force plate measuring center of pressure (CoP) movement (9260AA, Kistler Instruments AG, Winterthur, Switzerland) and analysed with Kistler MARS software (MARS 5.0, Kistler Instruments AG, Winterthur, Switzerland). Following balance tasks were assessed in random order; upright quiet stance with feet positioned parallel at the hips` width and hands placed on the hips, parallel stance with neck torsioned to 45° to the left and right. Participants had to stand still for three times 30-seconds with 60-second rest intervals for each position.

SPNTT protocol was described in detail elsewhere [26]. Infrared video-oculography (Pro Glasses 2, Tobii, Danderyd, Sweden) was used to measure eye movements at sampling rate of 100 Hz [27] while tracking a horizontally moving target (moving at 40° amplitude and 30°/s velocity)projected (Optoma ML1050ST LED Projector, Fremont, USA) on white screen 150-cm away at an eye level. SPNTT was performed at three different neck positions: facing forward, neck torsion at 45° right and left. Participants were sitting on a custom-made rotatable chair and were required to track 10-cycles of cyclic sinusoidal target movements with their eyes, followed by 60-second rest interval in a random order. Data were analysed in Tobii Pro Lab (Tobii Pro lab 1.145, Tobii, Danderyd, Sweden).

Cervicocephalic kinaesthesia was tested using Butterfly test. The method was described in detail elsewhere [23,28]. Participants had to track an unpredictable moving target with their head as accurately as possible. Three different movement trajectories of increasing difficulty (easy, medium and difficult) were used. Target movement trajectory and test duration were predefined by the NeckCare software (NeckCare, NeckCare ehf., Reykjavik, Iceland).

Position sense was measured with head-to-neutral relocation test [29]. Head and neck of each participant were positioned in a neutral position, which served as reference. Three slow head movements to both rotations, flexion, or extension and back to neutral position were performed by each participant blindfolded. Both kinaesthetic awareness tests were measured by inertial motion unit (NeckGear, NeckCare ehf, Reykjavik, Iceland) positioned on the participant’s head.

Data Analysis

The following parameters describing CoP movement were calculated; average CoP velocity in medial-lateral (ML) and anterior-posterior (AP) direction and mean frequency of changes in CoP movement direction during ML and AP postural sway.

Neck movements during Butterfly test were analysed and described using the following parameters; mean and standard deviation of the time spent on target during each trial expressed in seconds (time-on-target), time the head and neck spent behind the target expressed as percentage of total time (undershoot) and in front of the target expressed as percentage of total time (overshoot) were calculated. Averages and standard deviations of three trials for all parameters were used for further analysis.

Head-to-neutral relocation accuracy was analysed representing position sense in angular degrees (°). Parameters such as mean of the absolute total deviation from the neutral position over the three trials for each measured direction (absolute error), average magnitude of both under and overestimation of target position (constant error) and variability of three consecutive repetitions expressed as two standard deviations (variable error) were used for further analysis.

The procedure of analysing eye movement data is described in detail elsewhere [26]. Square waves, saccades and blinks were removed from the eye movement data using custom-written software in Matlab (R2017b, MathWorks, Natick, MA, USA). Sixth to ninth cycles were used for further analysis. Horizontal eye movements were analysed using gain (eye velocity amplitude and visual target velocity amplitude ratio) [30] during right (gain R) and left (gain L) neck torsion as well as difference between average gain at neck torsion and neutral position (SPNTdiff).

Statistics

Statistical analysis was performed in SPSS (SPSS 23.0 software, SPSS Inc., Chicago, USA). The normality of data distribution was analysed using skewness and kurtosis. As certain data were not normally distributed, the difference between the four observed groups were analysed using the Kruskal Wallis test and post-hoc analysis of differences between individual groups were analysed using Mann-Whitney U-test. The p values of the Mann-Whitney U-test were corrected for multiple comparisons using Benjamini and Hochberg procedure to decrease Type-1 error. In addition, effect size (r) was calculated for all the pairs of groups presenting with statistically significant differences. MCID was calculated for each pair of groups and for each parameter analysed [31]. Before performing MCID calculations, data were log transformed to achieve normality of data distribution. Statistical significance was set at $p<.05$.

RESULTS

Sixty-nine subjects of which 20 were asymptomatic controls (37 ± 7.9 years of age), 20 idiopathic neck pain patients (35 ± 8.1 years of age), 18 WAD patients (36 ± 7.2 years of age) and 17 concussion patients (33 ± 8.6 years of age) were enrolled in the study. All subjects were age and gender matched, except for the concussion group that appeared to be younger ($p =.063$, $p = .174$, $p = .081$ respectively).

Cervicocephalic kinaesthesia

Differences between four studied groups in cervical kinaesthesia tests are presented in Table 1. All three patient groups differed statistically significant from healthy controls in time-on-target and undershoot parameters of the Butterfly test, but groups of patients did not differ in any of the Butterfly parameters. Similar trend was observed for differences between groups in head-to-neutral test. No differences between groups were observed for head-to-neutral from the left rotation.

Table 1

MCID is presented in Table 2. Smallest MCID were observed for the Butterfly test when differentiating healthy and all patient groups and higher when differentiating mTBI patients from the two neck pain groups. Higher MCID was observed for head-to-neutral test.

Table 2

Postural balance

Differences between groups in postural balance are presented in Table 3 and MCID in Table 4. The mTBI differed from healthy controls in the neutral stance in ML and AP directions. Additionally, differences in the neutral stance were observed between mTBI and both neck pain patient groups in ML direction. Similar trends were observed in both neck torsion positions. MCID was low for majority of the parameters and groups. It increased under neck torsion positions and was highest between neck patients and mTBI groups and WAD and mTBI groups.

Table 3

Table 4

SPNTT

Differences between groups in SPNTT are presented in Table 5 and MCID in Table 6. Statistically significant differences were observed between all patient groups and healthy controls, but none were observed between three patient groups. MCID proved to be medium between healthy controls and all patient groups and increased to large at neck torsion positions. Between the three patient groups MCID remained low at all positions.

Table 5

Table 6

DISCUSSION

Our study aimed to compare sensorimotor tests of postural balance, smooth pursuit eye movements both in the neutral and neck torsion positions as well as cervicocephalic kinaesthesia between the following groups of patients; mTBI, WAD, idiopathic neck pain and healthy controls. Based on the results from our study body sway differed between healthy controls and all patient groups. Moreover, differences were found between mTBI group and both neck pain disorders groups in ML direction but not in AP direction. Eye movement control during the neutral and neck torsion positions differed between healthy controls and all patient groups, but no differences were found between all three groups of patients. Similarly, cervicocephalic kinaesthesia presented with statistically significant differences between healthy and all studied patient groups. This was evident for both cervicocephalic kinaesthetic tests. However, no differences in both test of neck kinaesthesia were observed between patient groups.

Postural balance was previously compared between subjects with WAD and those with vestibular pathology associated with acoustic neuroma [16]. Based on the results from their study balance in eyes opened conditions differed between those with cervical disorders in AP direction and those with vestibular pathology in ML direction. Their results indicated differences in the ability to maintain postural balance between different pathologies. Results from our study showed that patients with mTBI differed from healthy in the frequency of CoP movement in AP direction as well as frequency and velocity of CoP movement in ML direction. However, mTBI only presented with differences between both groups of neck pain disorders in frequency and velocity of CoP movement in ML direction. It has been well researched that neck pain patients present with alterations in AP direction when maintaining postural balance [32]. Our study showed that mTBI and both groups of patients with neck pain disorders presented with postural deficits in AP direction which was evident by no statistically significant differences between groups observed in the neutral and neck torsion positions. This suggests the presence of concurrent cervical pathology in those with mTBI. This is not surprising as concomitant injury to the neck resembling whiplash may occur as a result of the acceleration–deceleration forces sustained in concussive trauma [33]. Therefore, comorbid vestibular involvement along with cervical contribution to balance deficits might be present in mTBI.

Oculomotor dysfunctions are commonly present in mTBI and patients with neck pain disorders. Tjell and Rosenhall [34] were the first to introduce SPNTT with the goal to investigate differences in eye movements between WAD, a group of central vertigo and Meniere disease group. Their results were able to identify differences between WAD and other observed groups in the difference between neutral and neck torsion positions (SPNTdiff) suggesting neck torsion position being specific for cervical driven oculomotor disfunction. Our study found differences in both gain and SPNTdiff between healthy and all three groups of patients but no differences between mTBI and both groups of patients with neck pain disorders. There results are likely due to the specificity of the SPNTT for detecting cervical driven oculomotor disturbances as opposed to balance tests, where vestibular pathology could lead to specific deficits in mTBI patients.

Based on the results of our study no differences were reported on both kinaesthetic tests between idiopathic neck pain patients and patients with WAD. This is in line with the results of other studies where no differences between neck pain patients with traumatic and nontraumatic origin were found in neck kinaesthesia [35]. Interestingly, our study found no differences between mTBI and WAD or mTBI and idiopathic neck pain patients. This also suggests cervical driven pathology is present in mTBI subjects. This is in line with studies suggesting that cervical spine plays an important role in concussion subjects [2,36], but to our knowledge our study was the first to investigate alterations in complex cervicocephalic kinaesthesia in mTBI and compared them to patients with neck pain disorders of traumatic and nontraumatic originf as well as healthy controls. Based on the results of our study, no statistically significant differences in both; the Butterfly and head-to-neutral relocation test were found between all patient groups, but they all differed between healthy controls.

The importance of cervicocephalic kinaesthetic sensibility when treating mTBI patients has been stressed out previously. In the study by Hammerle et al. [37] two rehabilitation protocols were compared when treating dizziness as a consequence of mTBI in military personnel. Their results suggest that proprioceptive training was thirty times more efficient in alleviating dizziness as one of the most common symptoms of mTBI than vestibular rehabilitation therapy. In addition, another study reported significant improvements of individuals with mTBI who were treated with cervical spine physiotherapy and vestibular rehabilitation and were medically cleared to return to sport within 8 weeks of initiating treatment [38]. In general, upper cervical spine would sustain high forces during WAD or blows to the head during concussion that would overstretch the upper cervical spine ligaments and mainly suboccipital muscles as well as craniocervical flexors [39]. This consequently causes injury to the embedded mechanoreceptors and alters their function. Proprioceptors found in the cervical spine are muscle spindles, Golgi tendon organs and joint receptors [40,41]. Suboccipital muscles possess substantially high amount of muscle spindles but lack Golgi tendon organs, which indicates that suboccipital muscles are functionally concerned with precise movement control of the craniovertebral region [41]. This could indicate the importance of kinaesthetic senses in head and neck movement control. It has previously been suggested that kinaesthetic awareness of the neck is related to eye movement control and postural balance [42,43] therefore great amount of sensorimotor disfunction in mTBI patients could be related to cervical deficits.

Important limitation is that mTBI subjects appeared to be younger and most were physically active (sports) than other participants. This could potentially influence the results of our study. Additionally, as idiopathic neck pain patients are heterogeneous, future studies should subgroup them based on their level, location of pain and structural impairments. Another limitation of our study was that WAD patients were not screened for possible vertebrobasilar insufficiency or concomitant vestibular pathology that could affect the results of our study.

CONCLUSION

Our study managed to find cervical driven sensorimotor deficits in concussion patients (balance deficits in ML direction and oculomotor control impairments) that were comparable to WAD and idiopathic neck pain patients, but they all differ from healthy controls. Clinical practice would benefit from sensorimotor testing related to cervical spine dysfunction in concussion patients. Recognising them in early stages after concussion could help towards faster recovery by incorporating more targeted rehabilitation programmes focusing on eliminating cervical spine sensorimotor deficits. Therefore, more articles should be conducted in the future to better understand involvement of cervical spine in concussion injuries. Future studies should investigate relationship between the amount of sensorimotor dysfunction related to cervical spine and presence of symptoms.

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Table 1: Differences between the four observed groups in cervical kinaesthetic tests

		Kruskal-Wallis test		Mann-Whitney U test																	
				Healthy - WAD			Healthy - Neck pain			Healthy- mTBI			Neck pain - WAD			Neck pain - mTBI			WAD – mTBI		
		H	p	U	p	r	U	p	r	U	p	r	U	p	r	U	P	R	U	P	r
Butterfly test	ToT	5.189	**	4.811	*	0.432	7.327	**	0.526	6.090	**	0.696	1.274		0.233	1.345		0.087	0.848		0.224
	Un	2.952	**	5.623	*	0.667	8.610	**	0.561	7.277	*	0.508	0.992		0.025	0.879		0.065	0.726		0.129
HN-Right	Ae	4.196	**	8.108	*	0.692	9.110	**	0.485	8.674	*	0.301	0.639		0.292	1.224		0.108	0.756		0.187
	Ce	3.939	**	1.087		0.258	10.274	**	0.579	7.957	*	0.125	1.978		0.271	0.897		0.457	1.998		0.469
HN-Flex	Ae	4.455	*	0.811		0.162	9.521	*	0.494	7.733	*	0.447	0.887		0.162	1.002		0.074	0.505		0.175
	Ve	9.325	*	1.050		0.261	1.520		0.405	8.682	*	0.195	0.527		0.365	0.498		0.137	0.493		0.216
HN-Ext	Ce	8.095	*	5.406	*	0.544	0.8240		0.276	9.483		0.564	0.781		0.244	0.873		0.022	0.274		0.099

*WAD – whiplash associated disorders patients; mTBI – mild traumatic brain injury group; H – H statistic; U – u statistic, p – statistical significance; r – effect size; ToT – time-on-target; Un – undershoot; HN-Right – head-to neutral relocation from right head rotation; HN-Flex – head-to neutral relocation from head flexion; HN- Ext – head-to neutral relocation from head extension; Ae – absolute error; Ce – constant error; Ve – variable error; * – p < .05; ** – p < .001).*

Table 2: Minimal clinically important difference for cervical kinaesthetic tests

		Butterfly test		Head-to-neutral				
	Groups	ToT	Undershot	Ae_r	Ce_r	Ae_f	Ve_f	Ce_e
MCID	Healthy_WAD	1.893	1.763	1.943	0.064	0.587	0.729	1.075
	Healthy_NP	2.205	1.870	1.988	1.685	2.165	0.725	0.568
	Healthy_mTBI	2.547	1.749	2.807	2.126	2.789	1.208	1.110
	WAD_NP	0.165	0.058	0.016	0.764	0.924	0.004	0.608
	NP_mTBI	0.186	0.075	0.286	0.202	0.165	0.272	0.373
	WAD_mTBI	0.345	0.007	0.303	0.956	1.290	0.453	0.041

ToT – Time on target; Ae_r – Absolute error at heat-to-neutral test from right head rotation; Ce_r – Constant error at heat-to-neutral test from right head rotation; Ae_r – Absolute error at heat-to-neutral test from head flexion; Ve_f – Variable error at heat-to-neutral test from head flexion; Ce_e – Constant error at heat-to-neutral test from head extension; WAD – whiplash associated disorders patients; NP – neck pain patients; mTBI – mild traumatic brain injury group; MCID – minimal clinically important difference.

Table 3: Differences between the four observed groups in postural balance

		Kruskall- wallis test		Mann-Whitney U test																	
				Healthy_Neck pain			Healthy_mTBI			Healthy_WAD			Neck pain_mTBI			Neck pain_WAD			mTBI_WAD		
		H	p	U	P	r	U	P	r	U	p	r	U	P	r	U	p	r	U	p	r
Neutral position	Vml	7.230	*	0.984		0.301	18.948	*	0.556	0,795		0.298	6.551	*	0.676	0.673		0.117	8.519	*	0.427
	Fap	6.837	*	1.553		0.356	23.654	*	0.474	0,997		0.254	0.749		0.246	0.618		0.142	1.361		0.215
	Fml	7.720	*	2.542		0.108	10.943	*	0.635	0,674		0.103	7.612	*	0.428	0.664		0.079	6.819	*	0.381
Left torsion	Vml	6.951	*	1.584		0.258	4.549	*	0.674	1.037		0.267	9.711	*	0.518	0.573		0.097	8.443	*	0.472
	Fap	6.895	*	8.500	*	0.319	5.317	*	0.421	9.438	*	0.487	0.812		0.279	0.715		0.174	1.517		0.251
	Fml	6.700	*	0.615		0.149	6.484	*	0.695	1.207		0.108	8.305	*	0.539	0.947		0.163	10.514	*	0.537
Right torsion	Vml	9.266	.*	4.848		0.382	8.488	*	0.850	1.599		0.284	5.714	*	0.284	0.765		0.097	12.647	*	0.608
	Fap	7.494	*	0.798		0.107	6.348	.*	0.797	.795		0.193	2.794	*	0.193	0.992		0.245	8.626	*	0.427
	Fml	9.156	*	0.315		0.257	9.517	**	0.835	.814		0.301	8.142	*	0.301	0.642		0.241	10.334	*	0.591

*WAD – whiplash associated disorders; mTBI – mild traumatic brain injury group; Left torsion – parallel stance with head and neck rotated to the left; Right torsion – parallel stance with head and neck rotated to the right; U – U statistic; p – statistical significance; r – effect size; Vml - average velocity of centre of pressure movement in medial-lateral direction; Fap - mean frequency of changes in centre of pressure movement direction in anterior-posterior direction; Fml - mean frequency of changes in centre of pressure movement direction in medial-lateral direction; * – p < .05; ** – p < .001).*

Table 4: Minimal clinically important difference for postural balance

		Neutral position				Left torsion				Right torsion			
		Vap	Vml	Fap	Fml	Vap	Vml	Fap	Fml	Vap	Vml	Fap	Fml
MCID	Healthy_WAD	0.156	0.263	0.620	0.004	0.375	0.332	0.740	0.435	0.336	0.760	0.597	0.024
	Healthy_NP	0.095	0.185	0.494	0.001	0.543	0.111	0.541	0.229	0.195	0.471	0.244	0.105
	Healthy_mTBI	0.254	0.261	0.758	0.620	0.290	0.215	0.653	0.860	0.058	0.117	0.887	0.976
	WAD_NP	0.056	0.073	0.095	0.002	0.109	0.084	0.202	0.424	0.091	0.114	0.289	0.054
	NP_mTBI	2.161	1.388	0.936	1.609	0.978	2.288	0.884	2.664	12.242	3.249	1.561	1.941
	WAD_mTBI	2.015	1.557	0.900	1.678	0.984	1.890	0.840	1.599	11.226	3.705	1.195	1.998

Vap - average velocity of centre of pressure movement in anterior-posterior direction; Vml - average velocity of centre of pressure movement in medial-lateral direction; Fap - mean frequency of changes in centre of pressure movement direction in anterior-posterior direction; Fml - mean frequency of changes in centre of pressure movement direction in medial-lateral direction; WAD – whiplash associated disorders patients; NP – neck pain patients; mTBI – mild traumatic brain injury group; MCID – minimal clinically important difference.

Table 5: Differences between the four observed groups in smooth pursuit neck torsion test

	Kruskall- wallis test		Mann-Whitney U test																	
			Healthy_Neck pain			Healthy_mTBI			Healthy_WAD			Neck pain_mTBI			Neck pain_WAD			mTBI_WAD		
	H	p	U	p	r	U	P	r	U	p	r	U	p	r	U	p	r	U	p	r
Gn	1.682	.*	3.594		0.172	2.951		0.274	3.051		0.167	1.873		0.095	0.389		0.048	2.645		0.118
Gl	7.816	.*	15.648	*	0.428	11.382	*	0.315	14.978	*	0.543	2.084		0.176	0.978		0.130	1.880		0.265
Gr	8.172	*	18.327	**	0.497	14.372	*	0.452	15.388	*	0.544	1.846		0.207	1.208		0.201	1.121		0.076
$SPNT_{diff}$	5.228	*	10.002	*	0.336	12.842	*	0.398	9.372	*	0.309	0.867		0.154	1.097		0.249	0.899		0.148

*WAD – whiplash associated disorders patients; mTBI – mild traumatic brain injury group; H – H statistic; U – u statistic, p – statistical significance; r – effect size; Gn – gain during smooth pursuit neck torsion test at neutral head and neck position; Gl - gain during smooth pursuit neck torsion test at head and neck torsion position to the left; Gr - gain during smooth pursuit neck torsion test at head and neck torsion position to the right; SPNTdiff – smooth pursuit neck torsion difference; * – p < .05; ** – p < .001).*

Table 6: Minimal clinically important difference for smooth pursuit neck torsion test

		Butterfly test			
	Groups	**Gain_Neutral**	**Gain_Left**	**Gain_Right**	***$SPNT_{diff}$***
MCID	**Healthy_WAD**	0.755	1.345	1.920	1.114
	Healthy_NP	0.694	1.384	2.294	1.059
	Healthy_mTBI	0.709	1.427	1.397	0.959
	WAD_NP	0.101	0.138	0.078	0.107
	NP_mTBI	0.097	0.122	0.057	0.146
	WAD_mTBI	0.127	0.174	0.146	0.161

WAD – whiplash associated disorders; mTBI – mild traumatic brain injury group; Gain-Neutral – gain during neutral head and neck position; Gain-Left – gain during head and neck torsion position to the left; Gain-Right – gain during head and neck torsion position to the right; $SPNT_{diff}$ – smooth pursuit neck torsion difference.

3 DISCUSSION AND CONCLUSION

3.1 DISCUSSION

The aim of this PhD thesis was to analyse metric characteristics of SPNT test using different target movement amplitudes, velocities and neck torsion positions in idiopathic neck pain patients and healthy individuals. In addition, relationship between SPNT test and frequency as well as intensity of visual symptoms was studied in idiopathic neck pain patients. Furthermore, smooth pursuit eye movements during predictable and unpredictable target movement profiles were analysed in idiopathic neck pain patients and healthy individuals as well as possible attentional alterations. As idiopathic neck pain patients commonly present with sensorimotor disturbances, relationships between cervicocephalic kinaesthetic sensibility and smooth pursuit eye movements or postural balance were analysed. Moreover, sensorimotor disturbances are also present in concussion patients, with current research suggesting that they can additionally present with cervicogenic deficits. Therefore, additional aim of this PhD thesis was to study possible differences in cervical driven sensorimotor deficits in concussion patients suffering from mTBI, WAD patients, idiopathic neck pain patients and healthy controls.

Based on the results of underlying studies present in this PhD thesis, gain during SPNT test presented with moderate to good inter-visit reliability in patients with neck pain disorders and moderate to excellent inter-visit reliability in asymptomatic controls. Additionally, $SPNT_{diff}$ presented with moderate to good inter-visit reliability for both studied groups. Based on these results it is possible to partially confirm hypothesis 1.1 where healthy individuals presented with higher inter-visit reliability for gain, but not for $SPNT_{diff}$ than idiopathic neck pain patients. Our study aimed to analyse inter-visit reliability at different target movement amplitudes and velocities. Based on the results, inter-visit reliability was greater in lower target movement velocities for both analysed groups and larger target movement amplitudes. This was observed for both studied groups. The latter can be partially explained by the functional connections between extraocular and cervical muscle activity. Moreover, Bexander and Hodges (2019) report of greater activity of obliquus capitis inferior with increase in eye movement amplitude. This can cause higher bilateral co-contraction of obliquus capitis inferior, leading to increase in head and neck stiffness and sensory feedback consequently having a positive effect on reliability. In addition, velocity of moving target showed the highest inter-visit reliability at 30°/s. This is in line with the previous findings presented by Ettinger et al. (2003) however our study upgraded their knowledge by presenting similar results in idiopathic neck pain patients as in healthy individuals.

No target movement velocity and amplitude specific trends for inter-visit reliability were observed for $SPNT_{diff}$. These results can partially confirm hypothesis 1.2 and 1.3 with anticipated trends observed for gain, but not for $SPNT_{diff}$. Based on the results from our study $SPNT_{diff}$ presented with lower inter-visit reliability as gain. These results are somehow expected as $SPNT_{diff}$ is calculated form average gain in the neutral and in the neck torsioned positions. Consequently, the cumulative error of three different parameters (i.e. gain at neutral, neck torsion to the right and neck torsion to the left) could potentially weaken inter-visit reliability.

Based on the results of study one, it is possible to partially confirm hypothesis 1.4 as inter-visit reliability of gain in the neutral position presents with a trend of slightly higher reliability as gain under neck torsion positions. This has not been studies previously but it is somehow expected that reliability is worsen in neck torsion position. As neck pain patients present with alterations in cervico-colic and cervico-ocular reflexes when their neck is torsioned, these alterations could lead to less consistent eye movement control and possibly effect inter-visit reliability.

Intra-trial reliability for gain and $SPNT_{diff}$ proved to be similar for both idiopathic neck pain patients as well as healthy individuals confirming hypothesis 2.1. Moreover, a trend of higher reliability at lower and medium movement velocities was observed in both groups which confirms hypothesis 2.2. Intra-trial reliability of gain and $SPNT_{diff}$ presented with no observable differences between different target movement amplitudes, consequently leading us to reject hypothesis 2.3. Based on the results of the present study patients with idiopathic neck pain presented with statistically significant differences in the average gain at target movement velocities of 30°/s in neck torsion positions. Therefore hypothesis 2.4 can be partially confirmed. Patients form our study presented with comparable results of intra-trial reliability as healthy controls. This could be explained by the lack of movement variability commonly seen in patients with neck pain disorders (Alsultan et al., 2019) that could lead to more stereotypical head positioning and consequently decreased information flow for adjusting eye movements relative to head oscillations. These adjustments could lead to more repeatable eye movements on trial-to-trial basis in patients with neck pain disorders that finally present with similar gain as in healthy control that could present with more efficient eye movement control. Such differences in mechanisms governing eye movement control should be studied in the future in order to confirm our suggestions on possible reasons of comparable reliability between idiopathic neck pain patients and healthy controls.

In the third study, medium level of agreement in gain and $SPNT_{diff}$ was observed between the 30° and 45° neck torsion angles in idiopathic neck pain patients but higher in healthy individuals. A possible reason for moderate agreement in idiopathic neck pain patients could be explained by different pathological mechanisms affecting afferent sensory drive that my arrive from stimulation of different cervical spine structures during the two neck torsion angles (Janssen et al., 2015; Liu et al., 2021). These pathological alterations could alter eye movement control based on the amount of neck torsion. Therefore, larger neck torsion amplitudes should be used if tolerated by individual neck pain patients.

In addition, larger target movement amplitudes and lower target movement velocities positively affected agreement between the two analysed angles. Based on these results both hypothesis 3.1 and 3.2 can be rejected. Eye movement amplitude and neck muscle activity could alter proprioceptive information available for eye movement control (Velay et al., 1994). Therefore, there findings must be considered when smaller or different neck torsion positions are used in studies in order to decrease possible negative effect of different neck torsion angles on studies results.

In the fourth study, the sensitivity of the SPNT test was analysed. The results presented with highest sensitivity for gain at 40° or 30° target movement amplitude and 30°/s target movement velocity and lower reliability for $SPNT_{diff}$ (highest sensitivity was observed at 30° target movement amplitude and 30°/s target movement velocity). Therefore, hypothesis 4.1. was rejected. In addition, higher classification accuracy was achieved when two target movement profiles were used simultaneously as classifiers, allowing us to confirm hypothesis 4.2. The results of classification analysis presented with higher classification accuracy for gain than $SPNT_{diff}$ rejecting hypothesis 4.3.

The aforementioned studies have looked at metric characteristics of the SPNT test and found good to moderate inter-visit reliability, excellent inter-trial reliability, moderate agreement between 30° and 45° neck torsion angles and high classification accuracy. The most reliable and sensitive target movement profile that was chosen for further studies used 40° of target movement amplitude and 30°/s of target movement velocity and was performed at 45° of neck torsion. These results suggest that the velocity, amplitude and neck torsion position affect smooth pursuit eye movements. Majority of previous studies applied target movement profiles of 40° target movement amplitude and 20°/s target movement velocity with interchanging neck torsion positions (Prushansky et al., 2004; Tjell et al., 2002; Treleaven, Jull, and LowChoy, 2005). As observed in our studies these parameters when tracking horizontally moving target possess inferior reliability and sensitivity and could have affected the results reported in other studies. Therefore, it is of importance for future studies conducted on neck pain patients to apply sensitive and reliable target movement profiles in order to provide highest validity of the SPNT test. It should however be stressed out that sensitivity of SPNT test should be studied in relation to other pathologies where smooth pursuit eye movements are affected, especially under neck torsion position. In addition, our studies presented important differences between the two most commonly applied neck torsion positions (30° and 45°). Although researchers usually apply different neck torsion positions interchangeably, our results suggest that 45° of neck torsion should be applied when possible.

Another possible reason for inconsistencies in the results across the studies when evaluating smooth pursuit eye movements could be the use of chin rest (Bargary et al., 2017; Kongsted

et al., 2007; Tjell and Rosenhall, 1998; Treleaven, Jull, and LowChoy, 2005; Treleaven et al., 2011) not applied in our study. Application of chin rest is desirable when investigating patients with neurological and psychological pathologies (Franco et al., 2014; Pierrot-Deseilligny and Gaymard, 1992) with the focus on excluding all external factors that could affect the results (i.e. the effect of cervical kinaeshtesia). These settings may not be so desirable when evaluating smooth pursuit eye movements in patients with neck pain disorders. As sensory mismatch is a common driver for their deficits in eye movement control, SPNT test should incorporate active maintenance of their head and neck stability.
Results of our fifth study showed, that intensity, but less frequency of visual symptoms can be partially classified using gain and $SPNT_{diff}$ in idiopathic neck pain patients, therefore hypothesis 5.1 was confirmed. Moreover, visual symptoms that are related to focal vision disorders proved to present with highest relations with SPNT test. Augmented focal vision oscillations could decrease steady-state gaze accompanied by increased number of saccades. Consequently, patients may report blurred vision, which would demand higher concentration while reading or keeping the gaze on a moving target. Some other commonly reported symptoms such as “words moving on page” can be a consequence of upper cervical spine instability or of impaired vestibulo-ocular reflex (Tilikete and Vighetto, 2011) common in neck pain patients (Johnston et al., 2017). Another visual symptom commonly reported in neck pain patients is “difficulty judging distance”, which could be a consequence of decreased ability to control eye vergence due to cervical spine imapirements (Sánchez-González et al., 2019). Based on the results from study, relationships between these visual symptom and gain were found in neck torsion position. Generally, our study confirmed the relationship between cervical driven oculomotor deficits measured during the SPNT and some of the commonly reported visual complaints in neck pain patients. Intensity of visual symptoms should be considered in clinical practice as it might show a more pronounced relationship to oculomotor control deficits measured during neck torsion positions. Although some relations between visual symptoms and cervical driven eye movement disturbances were suggested, other potential causes should be considered.

Our sixth study aimed to compare SPNT results during predictable and unpredictable target movements between neck pain patients and healthy individuals. Furthermore, tonic and phasic alertness during SPNT tasks were assessed in both groups. Neck pain patients have been shown to present with cognitive deficits in other studies (Thompson et al., 2010). Moreover, our study proved cognitive impairments in neck pain patients during unpredictable visual tasks, as ICA was higher in neck torsion positions and lower in the neutral position during SPNT test, which was accompanied by maintenance of gain in neck torsion position at the comparable level as during neutral position. In the neutral position the ICA proved to be statistically significantly different from ICA in healthy individuals but not under neck torsion position. On the contrary, no such differences were observed in the relative pupil diameter. Indicators of decreased tonic attention were statistically significant differences in average pupil diameter between the groups. Therefore, hypothesis 6.1 can be partially confirmed. Moreover, no statistically significant differences in the following parameters: ICA, relative pupil diameter and average pupil diameter were observed between the predictable and unpredictable target movements in both groups. Therefore, hypothesis 6.2 was rejected. The final hypothesis was aimed at studying differences in tonic and phasic alertness between the neutral and neck torsion position in both experimental tasks. Such differences were observed only for the ICA in the neck pain patient group, therefore hypothesis 6.3 was confirmed.

Findings from our sixth study are in line with suggestions presented by Janssen et al. (2015), where unpredictable target movements presented increased demand of attention allocation in neck pain patients. We hypothesised that unpredictable target movements present more demanding tasks that demands involvement of higher order processes governing eye movement control. These enable compensation of negative effects caused by cervical spine derived sensory mismatch on eye movements via involvement of higher nervous centres such as frontal eye fields. Consequently, cognitive resources are additionally occupied by simple eye movement tasks, possibly resulting in smaller amount of cognitive capacity being available for other tasks that are usually present in daily activities such as driving a car (Takasaki et al., 2013) or reading (Treleaven and Takasaki, 2014). Additional important finding of our study was absence of above-described compensations in eye movement control during predictable target movements in SPNT test. These findings suggest that predictable target movements present less demanding smooth pursuit eye movement task, where higher order cognitive processes are not additionally involved, exposing impairments at lower level of oculomotor control in neck pain patients. Therefore, SPNT test in neck pain patients should use predictable target movement profiles in order to be able to screen for deficits caused by functional impairments of the cervical spine.

Tonic alertness on the other hand proved no differences between the groups when observing relative pupil diameter. However, relativisation of pupil diameter to a specific task disguises the actual deficits in alertness as suggested by the average pupil diameter in our study. As statistically significant differences were observed, it could be suggested that tonic attention is impaired as well. However, our study design presented a task, where tonic attention was not demanded, therefore it is difficult to make a final conclusion in this regard. Our first six studies enabled a better understanding of how target movement profile characteristics affect the oculomotor controlling mechanisms as well as alertness allocation during SPNT tasks.

Neck pain patients commonly present with sensorimotor disfunction of which in addition to eye movement control, cervicocephalic kinaesthesia and postural balance are commonly investigated. Moreover, cervicocephalic kinaesthetic deficits are suggested to contribute towards poorer cervical driven oculomotor dysfunction and postural balance. The aim of study seven was to investigate the relationship between different aspects of cervical kinaesthesia (i.e. position sense and movement sense) as suggested by Kristjansson and

Treleaven (2009), SPNT test and balance under neck torsion manoeuvre. Our results presented with medium relations between some of the parameters of the Butterfly test and gain and less with $SPNT_{diff}$ in neck pain patients but not with the head-to-neutral relocation test. In addition, we have studied relationship between postural balance and cervicocephalic kinaesthesia. Based on the results of our study, relationship was present for both; Butterfly test and head-to-neutral relocation test. These finding partially confirm hypothesis 7.1. As these relations were stronger in idiopathic neck pain patients than healthy controls, hypothesis 7.2 was confirmed. An important finding of our study was a more pronounced relationship between cervicocephalic kinaesthesia and postural sway when measured during neck torsion manoeuvre. This upgraded previous research (Ruhe et al., 2011; Treleaven, Jull, and Lowchoy, 2005) where only relations in the neutral position during balance tasks were studied. These results gathered during neck torsion position suggest that neck torsion causes increased proprioceptive mismatch that has an important effect on postural control especially in idiopathic neck pain patients. Moreover, body sway in the anterior-posterior direction presented with stronger relationship to cervicocephalic kinaesthesia as medial-lateral body sway. These findings are in line with previous research on postural and locomotor control in neck pain patients (Falla et al., 2017; Jiménez-Grande et al., 2021), suggesting specific effects of cervical impairment on postural control.

In addition, we have studied relations between cervicocephalic kinaesthesia and SPNT test. Results of the study suggest that gain measured during neck torsion manoeuvre is an important parameter indicting cervical impairment in oculomotor control that should be used in addition to commonly used parameter of relative difference between the neutral and neck torsion position. Our study presented with relations between the Butterfly test and gain in neck torsion position, especially between the undershoot parameter and gain. It could be argued that undershoot parameter from the Butterfly test could be related to increased stiffness of the cervical spine, which makes accurate and on time corrections of head and neck movements more difficult. As such stiffness could be related to cervical muscle co-contraction, which can produce asymmetric proprioceptive drive (Kristjansson and Treleaven, 2009; Liu et al., 2021) it can be suggested, that this represents a common mechanism which also influences eye movement control during neck torsion position.

In our final study (study eight), differences in cervicocephalic kinaesthesia, postural balance and SPNT test between three groups of patients (i.e. patients with mTBI injury, WAD and idiopathic neck pain patients) and healthy controls were investigated. No differences between patients' groups were observed in cervicocephalic kinaesthesia and SPNT test confirming hypothesis 8.1 and 8.1. In postural balance differences between all three patient groups were observed in medial-lateral balance, suggesting specific changes in body sway controlling mechanisms in patients with mTBI. Therefore hypothesis 8.3 could be only partially confirmed. When comparing all patient groups with healthy controls, statistically significant differences were observed in all tests, confirming hypothesis 8.4.

Absence of differences in cervicocephalic kinaesthesia between the three observed groups suggest similar alterations in cervical proprioception. Cervical deficits in patients with mTBI have been suggested in the literature (Kennedy et al., 2019), however this was the first study to present with comparable cervical sensorimotor driven deficits in groups of mTBI, and neck pain patients of traumatic and non-traumatic origin, but they all differed from healthy individuals. These comparable deficits could result from high forces acting on the upper cervical spine during the concussion resulting in overstretching of the upper cervical spine ligaments and suboccipital muscles as well as craniocervical flexors (Dowdell et al., 2018). This can lead to injury of the proprioceptors such as muscle spindles, Golgi tendon organs and joint receptors (Kulkarni et al., 2001; Proske and Gandevia, 2012). As these proprioceptors are highly involved in sensation of movement their disfunction can lead to kinaesthetic alterations consequently influencing postural balance and eye movement control.

As described above, cervical proprioceptive mismatch can affect oculomotor control. SPNT test has been previously shown to be able to differentiate subjects with neurological disorders and vestibular disorder from neck pain patients (Tjell and Rosenhall, 1998). This is especially important for understanding the involved mechanisms of sensorimotor impairments in mTBI. As mild traumatic brain injury can be accompanied by vestibular disorder it is not clear whether it also plays an important role in functional deficit in mTBI patients. As presented in our study, no differences were observed between mTBI and idiopathic neck pain patients, suggesting, that alterations observed in our study were primarily due to cervical impairments.

Additional presentation of cervical involvement in patients with mTBI came from body sway test. Previous research presented statistically significant differences in body sway between patients with WAD and patients with acoustic neuroma (Treleaven et al., 2008). Patients in their study suffering from WAD presented primarily with deficits in body sway in anterior-posterior direction and those with acoustic neuroma in medial-lateral direction. Similarly, all patient groups in our study presented with deficits in anterior-posterior body sway, but mTBI additionally presented with deficits in medial-lateral direction. Therefore, it can be concluded that patients with mTBI present with cervical spine driven sensorimotor deficits that are similar to patients suffering from traumatic and non-traumatic neck injury.

An important limitation of our study was that all patient groups had to present with a minimum of 50° cervical spine ROM. As decreased ROM is a common functional impairment in neck pain patients, it is unclear how this would affect oculomotor control as well as other sensorimotor functions (i.e. cervicocephalic kinaesthesia and postural balance under neck torsion manoeuvre), therefore future studies should also assess those with decreased ROM. Our thesis investigated relationship between visual symptoms and oculomotor functions. As neck pain patients also present with other common complaints (i.e. dizziness, headaches, and others) relationship between other commonly reported symptoms and cervical driven sensorimotor functions should be studied in future research. Additional limitations of our studies were age difference between studied groups. The first part of the thesis (metric characteristics of SPNT test) presented with large number of repetitions that participants had to perform, although not specifically indicated this could influence the results. Idiopathic neck pain is defined as a term that generally describes heterogeneous origin of problems and structural impairments that could result in higher variability of results. Future studies should minimise this with classifying neck pain patients based on their imaging results, level and location of pain and outcome of manual examination to gather more in-depth insight into the underlying mechanisms influencing sensorimotor functions. Another limitation of our study was that the amount of time patients and healthy individuals spent behind the computer every day was not recorded. As computer vision syndrome could co-exist in those with neck pain and could influence eye movement control and cervical kinaesthesia, future studies should include more in-depth information about their everyday life. All neck pain patients recruited for our studies were referred from orthopaedic outpatient clinics. However, across other studies different patient recruitment techniques were used, such as advertising in local newspapers, social media, local physiotherapy clinics (Daly et al., 2018; de Zoete et al., 2020). These could have resulted in enrolling different cohorts of neck pain patients with larger variability in their functional impairments with altered ability to summarise results between different studies. Another important limitation of our study was that only chronic neck pain patients were included. Future studies should investigate existence of possible differences.

3.2 CONCLUSIONS

This PhD thesis presents with important findings which help towards improving screening and diagnosing functional impairments related to neck pain patients. The latter could provide better baseline and help design more accurate rehabilitation programs. As sensorimotor functions are likely to influence the long-term outcome and remission, these should be recognised and targeted in early stages after the occurrence of injury and the onset of symptoms. This is important as functional problems that result in chronicity involve more complex mechanisms that would require multimodal treatment approaches.

4 SUMMARY (POVZETEK)

4.1 SUMMARY

Patients with neck pain disorders commonly present with oculomotor dysfunction, of which deficiencies in smooth pursuit eye movements are frequently observed. However, results about the nature and extend of dysfunction are inconclusive due to methodological inconsistencies in the literature. These include applying different angles of neck torsion, using different target movement profiles that include variety of target movement amplitudes and velocities. In addition, to date reliability and sensitivity of smooth pursuit neck torsion (SPNT) test have not yet been studied. Therefore, the aim of this PhD thesis was to study metric characteristics of SPNT test in idiopathic neck pain patients and asymptomatic individuals. As neck pain patients commonly report vision related symptoms such as needing to concentrate to read, sore eyes, words moving on page, eye strain, heavy eyes, difficulty judging distance, blurred vision, and red eyes the relationship to objectively measured oculomotor functions that are altered in patients with neck pain disorders should be studied. In addition, as patients with neck pain disorders report cognitive dysfunction, the aim of this PhD was to study the presence of cognitive involvement with pupillometry during SPNT test including predictable and unpredictable target movements. Another aim of this study was to investigate the relationship between different sensorimotor functions (kinaesthetic awareness, postural balance and eye movement control) commonly altered in idiopathic neck pain patients and healthy controls. Furthermore, relationship between aforementioned sensorimotor functions in healthy individuals and different patient groups (mild traumatic brain injury (mTBI), whiplash associated disorders (WAD) and idiopathic neck pain patients) should be studied.

Infrared video-oculography was used to measure eye movement control during SPNT test in 30° and 45° of neck torsion applying different target movement velocities (20°/s, 30°/s and 40°/s). Parameters of gain (precision of eye movements) and smooth pursuit neck torsion difference (SPNTdiff – difference between gain in neutral and neck torsion positions) were used for further calculations to determine accuracy of eye movements. Intra-trial reliability and sensitivity of gain and SPNTdiff measured at different target movement profiles and at two neck torsion angles were analysed. In addition, agreement between the two beck torsion positions was analysed. Further, ability to classify frequency and intensity of proforma of subjective visual symptoms using gain and SPNTdiff was studied in idiopatic neck pain patients. Differences in phasic and tonic alertness were measured with pupillometry during predictable and unpredictable target movements during SPNT test for healthy subjects and idiopathic neck pain patients. In the last two studies, Butterfly test (measuring movement sense) and head-to-neutral relocation test were used to measure cervicocephalic kinaesthetic sensibility and force plate to assess postural balance during quiet stances in the neutral and neck torsioned position where velocity and frequency of

centre of pressure during anterior-posterior and medial-lateral direction were assessed. First, we were interested in relations between the previously listed tests of sensorimotor functions in neck pain patients and healthy controls. And second, we analysed differences in these sensorimotor functions between healthy controls, idiopathic neck pain patients and WAD and mTBI patients.

Results from our studies showed that SPNT test presented with good to moderate intra-trial reliability for neck pain patients and good to excellent for healthy controls when SPNT test is performed at 40° or 50° target movement amplitude, 20°/s or 30°/s of target movement velocity all performed under 45° of neck torsion. Reliability of SPNTdiff presented with moderate to good reliability in both groups. Inter-trial reliability proved to be good to excellent in both groups for neutral and neck torsion positions. Although no differences were observed between 2nd to 5th and 6th to 9th set of cycles a trend of decreased gain in the 6th to 9th set of cycles was observed for neck pain patients. Lower inter-trial reliability was observed for SPNTdiff, bit no trend of differences between the two sets of cycles. The Bland-Altman analysis revealed moderate level of agreement between the two most commonly used neck torsion positions for both gain and SPNTdiff (30° and 45° of neck torsion). Target movement profiles using larger target movement amplitudes and lower target movement velocities presented with higher agreement. In general, agreement was lower in patient group as compared to healthy group.

The sensitivity study presented with highest classification accuracy when target movement profiles using 30° or 40° of target movement amplitude and velocity of 30°/s. In general neck torsion angle of 45° presented with superior sensitivity as compared to 30° of neck torsion. The SPNTdiff presented with inferior classification accuracy as compared to gain.
Next, we analysed relations between SPNT test and visual symptoms reported in neck pain patients. Interestingly, intensity of visual symptoms could be classified with higher accuracy using gain as frequency of visual symptoms. Moreover, gain under neck torsion position proved to have higher ability to classify the intensity of visual symptoms as neutral position. Highest classification accuracy based on gain was observed for the following visual symptoms; need to concentrate to read, sore eyes, words moving on page, eye strain, heavy eyes, difficulty judging distance, blurred vision, and red eyes. Similar trends were observed for SPNTdiff, but fewer symptoms presented with at least low classification accuracy.

The comparisons between predictable and unpredictable target movement profiles presented with differences in gain, especially in neck torsion position, where no decrease in gain was observed under neck torsion position in neck pain patients. On the contrary, index of cognitive activity (phasic alertness) increased under neck torsion in unpredictable target movement profile in neck pain patients. No such trends were observed in healthy subjects. Average pupil diameter presenting tonic alertness presented with no differences between neck positions. However, absolute pupil diameter indicated decreased tonic alertness in neck pain patients.

Finally, relationship between cervicocephalic kinaesthetic awareness and postural balance or gain in SPNT test were observed in neck pain patients but less in healthy individuals. The cervicocephalic kinaesthesia presented relations primarily with body sway movement in anterior-posterior direction and gain.

The final study upgraded these results by observing differences in cervicocephalic kinaesthesia tests, postural balance and SPNT between healthy controls and three patients' groups (idiopathic neck pain patients, patients with whiplash associated disorders and mild traumatic brain injury patients). However, no differences were observed between the three patient groups, except in postural balance when observing medial-lateral direction, where mild traumatic brain injury differed statistically significantly as compared to the traumatic and nontraumatic neck pain patients.

Results of our studies confirmed the influence of target movement amplitude and velocity in SPNT test on reliability and sensitivity of the test and identified the most appropriate target movement profiles (30° or 40° of target movement amplitude with 30°/s of target movement velocity at 45° of neck torsion). Higher reliability of the SPNT test when using larger target movement amplitudes can be related to neurophysiological connections between extraocular muscles and upper cervical spine muscles, especially obliquus capitis inferior. This muscle increases its activity under larger eye movement amplitude, which could lead to increased sensory feedback when using larger target movement amplitudes in SPNT test. In addition, bilateral activation of obliquus capitis inferior could lead to improved mechanical stability of the head having a positive effect on precision of eye movements.
Velocity of target movement also presented wit important affect on reliability and sensitivity. The eye movement velocity directly affects interplay between smooth pursuit and saccadic eye movement systems, which in turn affects eye movement precision. Consequently, SPNT test should use velocities where healthy subjects don't use saccadic eye movements, however, patients could start implementing them.

The third identified factor affecting reliability and sensitivity of SPNT test was neck torsion position. The metric characteristics proved superior when using 45° as compared to 30° of neck torsion. Therefore, future studies should use 45° of neck torsion if the neck patient's status enables them to do so.

In addition, we were able to present a week to moderate relation between gain and intensity of some of the visual symptoms reported by neck pain patients. The highest relations were observed between visual symptoms related to focal vision disorders, which was expected as SPNT test is designed to assess focal vision movement control.

In this PhD thesis deficits in phasic and tonic alertness were presented for the first time using pupillometric measures. Based on the observations of increased phasic alertness and decreased tonic alertness in neck pain patients when performing SPNT with unpredictable target movement it can be concluded, that oculomotor deficits can be partially compensated using higher level cognitive processes involved in eye movement control. However, this comes at an expense of decreased capacity of cognitive resources available for other cognitive tasks such as driving a car or reading. In addition, it can be concluded, that unpredictable SPNT tasks are less sensitive as eye movement precision is effectively compensated and are therefore less suitable for assessing neck pain patients.

Our research work also confirmed relation between cervicocephalic kinaesthetic deficits and oculomotor functions, which has been suggested in previous research. Interestingly these relations were more pronounced in neck pain patients as compared to healthy controls, as cervical deficits present a disturbance at lower levels of oculomotor control. Moreover, the last study confirmed cervical deficits in three groups of patients (mild traumatic brain injury and traumatic or nontraumatic neck injury). These deficits were observed in all three sensorimotor tests (postural balance, SPNT and cervicocephalic kinaesthesia). The only test, that presented with a difference between the three observed patients groups was postural balance in medial-lateral direction which could be therefore related to mild traumatic brain injury and not cervical impairments.

Our work presented with important limitations such as: including patients with cervical range of motion higher than 50°, not considering other symptoms and pain regions, smaller differences between patients and healthy groups, high number of SPNT test repetitions in first five studies, recruitment techniques that could lead to involvement of specific neck pain patients, not including the data on the amount of time spend behind the computer or smart phones and the fact that only chronic neck pain patients were included. These factors could have influenced our findings therefore transfer of our findings to neck pain patients' populations should be performed causally.

4.2 POVZETEK

Mišično skeletna obolenja pomembno znižujejo kvaliteto življenja posameznikov in pogosto vodijo v razvoj kroničnih obolenj, ki predstavljajo veliko breme za zdravstvene sisteme. Napredki na področjih rehabilitacije, razumevanja mehanizmov nastanka bolečine, sprememb v gibalnih vzorcih in senzorično-motoričnem upravljanju nakazujejo, da proces rehabilitacije zahteva celosten in kompleksen pristop. Na področju rehabilitacije hrbteničnih patologij se je v zadnjem desetletju pozornost usmerjala predvsem na ocenjevanje velikosti bolečine in stopnje prizadetosti, ne pa na razumevanje ostalih prisotnih živčno-mišičnih mehanizmov, ki lahko vodijo v razvoj kroničnosti in remisij.

Ravno razvoj kroničnosti in remisij naj bi bil glavni razlog za povečano nezmožnost in posledično povečano finančno breme zdravstvenih sistemov. Bolečina v vratu sodi med deset najvišje uvrščenih bolezni po letih prisotnosti simptomov. Prevalenca bolečine v vratu narašča vse do 74 leta starosti in doseže svoj vrh pri starostni skupini med 45 in 54 letom, tako pri moških kot pri ženskah. Kar je še posebej izstopajoče, je nespremenjena prevalenca, incidenca ter leta preživeta s simptomi v zadnjih 28 letih. Pojavnost obolenj hrbtenice narašča kljub naraščajočemu številu raziskav na tem področju. Prevalenca bolečine v križu, ki traja dlje kot tri mesece, se je med leti 2005 in 2015 povečala za 17,3 %, medtem ko se je prevalenca ljudi z bolečino v vratu povečala za 21,4 %. Med leti 1990 in 2017 se je pojavnost bolečine v vratu povečala za 75,7 %.

Naraščanje pojavnosti bolečine v vratu, njene kroničnosti in remisij nakazuje, da uporabljeni raziskovalni pristopi ne omogočajo dobrega razumevanja vplivov različnih rehabilitacijskih pristopov. Razlog lahko med drugim iščemo v slabem kliničnem razumevanju mehanizmov nastanka težav in nerazumevanju številnih spremljajočih znakov in simptomov, kot so radikulopatije, glavoboli, disfunkcije spoznavnih sposobnosti, vrtoglavice, in redkeje preiskovane vendar pogosto prisotne motnje v vidnem zaznavanju.

Pacienti z bolečinami v vratu poročajo o številnih simptomih povezanih z vidom, kot so potreba po večji zbranosti med branjem, utrujene oči, boleče oči, premikanje besed med branjem, težke oči, težave z globinskim vidom, meglen vid in rdeče oči. V literaturi ni mogoče zaslediti poročil o povezanosti naštetih simptomov z objektivno izmerjenimi okulomotoričnimi funkcijami, kot so sledilni pogled pri pacientih z idiopatsko bolečino v vratu. Za spremembe v sledilnem pogledu naj bi bil odgovor spremenjen ter nasprotujoč si senzorični dotok iz vratne hrbtenice, vestibularnega ter vidnega sistema. Ta pomembno vpliva na delovanje cerviko-količnega ter cerviko-okularnega refleksa, kar se izraziteje odraža med sledilnim pogledom izvedenim med torzijskim položajem vratu (SPTV).

Kljub pogosti uporabi testa SPTV pri ljudeh z idiopatsko bolečino v vratu, prihaja do pomembnih razlik v izsledkih študij. Med pomembnejše razloge sodijo metodološke razlike v izvedbi testa. Med te sodijo uporaba različnih amplitud in hitrosti gibanja sledene tarče med testom SPTV ter različnih torzijskih položajev glave in vratu. V literaturi ni mogoče zaslediti podatkov o tem kakšen vpliv imajo različne hitrosti in amplitude gibanja tarče med testom SPTV ter dva najpogosteje uporabljena položaje torzije vratu (30° in 45°) na natančnost sledilnega pogleda. Posledično je težko sklepati o najbolj veljavni izvedenki test SPTV ter primernosti izbire določenega kota torzije vratu in glave. Dodatno ni mogoče zaslediti pomena izbranih ciklov testa SPTV na znotraj-obiskovno ponovljivost, saj si tudi v tem pogledu študije niso enotne.

V študijah SPTV pri pacientih z bolečino v vratu se najpogosteje uporablja predvidljivo gibanje tarče. Redke študije, kjer so preverjali sposobnost SPTV nakazujejo na upad sposobnosti sledilnega pogleda med predvidljivim gibanjem tarče ter odsotnost tovrstnih deficitov med sledenjem nepredvidljivo premikajoče se tarče. Med predlagane vendar nepreverjene dejavnike naj bi sodile ravno spremembe v upravljanju pozornosti pri ljudeh z bolečinami v vratu.

Pomembno naj bi k kroničnosti in remisijam bolečin v vratu prispevale spremembe v senzorično-motoričnih funkcijah. Med pomembnejše sodi upad sposobnosti ohranjanja ravnotežja ter spremembe v cervikocefaličnih kinestetičnih funkcijah. Vendar v literaturi ni mogoče zaslediti podrobnejših podatkov o povezanosti tovrstni senzorično-motoričnih deficitov, predvsem z upadom kinestetičnih funkcije vratu pri pacientih z idiopatsko bolečino v vratu.

Med pomembnejša še neodgovorjena vprašanja sodi tudi obstoj patologij vratne hrbtenice pri ljudeh, ki so utrpeli blažjo travmatsko poškodbo možganov (BTPM). Med njenim nastankom naj bi prišlo do povečanih mehanskih obremenitvah možganovine ter na vratno hrbtnico, kar predstavlja podoben mehanizem kot je značilen za nastanek nihajne poškodbe vratu. Primerjanje senzorično- motoričnih deficitov vratne hrbtenice med skupinami pacientov z BPM, nihajno poškodbo vratu ter idiopatsko bolečino v vratu lahko omogoči boljši vpogled v prisotnost deficitov v funkcijah vratu ter njihovi povezanosti z ostalimi senzorično-motoričnimi funkcijami, kot so upad natančnosti sledilnega pogleda in ravnotežja.

Predstavljen doktorski projekt lahko razdelimo v dva glavna dela. V prvem želimo poiskati najbolj veljavno obliko izvedbe testa SPTV, preveriti povezanost simptomov v vidnem zaznavanju s sposobnostjo SPTV in proučiti sposobnost usmerjanja pozornosti med nalogo SPTV. V drugem delu želimo preveriti povezanost upada kinestetičnih funkcij vratu pri pacientih z idiopatsko bolečino v vratu s upadom v sposobnosti SPTV ter sposobnostjo ohranjanja ravnotežja. Dodatno želimo preveriti ali v omenjenih senzorično-motoričnih funkcijah prihaja do razlik med pacientih z BTPM, nihajno poškodbo vratu in idiopatsko bolečino v vratu ter zdravimi posamezniki. S tem bi lahko prispevali k razumevanju pomena deficitov v vratni hrbtenici pri ljudeh z blažjo travmatsko poškodbo možganov.

V okviru doktorske naloge smo si zastavili osem raziskovalnih vprašanj, na katere smo odgovor iskali v osmih študijah. Raziskovalna vprašanja so bila naslednja:

1. Kakšna je med-obiskovna ponovljivost različnih izvedenk testa SPTV pri pacientih z idiopatsko bolečino v vratu in zdravih posameznikih?
2. Kakšna je znotraj-obiskovna ponovljivost različnih izvedenk testa SPTV pri pacientih z idiopatsko bolečino v vratu in zdravih posameznikih?
3. Kakšna je skladnost spremenljivk testa SPTV med dvema najpogosteje uporabljenima kotoma torzije vratu pri različnih izvedenkah testa pri pacientih z idiopatsko bolečino v vratu in zdravih posameznikih?

4. Kakšna je občutljivost različnih izvedenk testa SPTV za klasifikacijo pacientov z idiopatsko bolečino v vratu in kateri profili gibanja tarče izvedenih med dvema najpogosteje uporabljenima kotoma torzije vratu so najuspešnejši klasifikatorji?
5. Kako uspešno lahko klasificiramo intenzivnost in pogostost pojavljanja vidnih simptomov pri pacentih z idiopatsko bolečino v vratu s pomočjo spremenljivk testa SPTV?
6. Ali prihaja do sprememb v pupilometričnih spremenljivkah tonične in fazične pozornosti med izvajanjem nepredvidljivih in predvidljivih nalog SPTV pri pacientih z idiopatsko bolečino v vratu ter zdravih posameznikih?
7. Kakšna je povezanost dveh cervikocefaličnih kinestetičnih testov s testom SPTV ali sposobnostjo ohranjanja ravnotežja pri pacientih z idiopatsko bolečino v vratu in zdravih posameznikih?
8. Kakšne so razlike v dveh testih cervikocefalične kinestezije, ravnotežja ter SPTV med skupinami pacientov z idiopatsko bolečino v vratu, nihajno poškodbo vratu, BTPM ter zdravih posameznikih?

V prvih štirih študijam so sodelovali pacienti z idiopatsko bolečino v vratu (32 pacientov v prvi in drugi, 34 v tretji ter 38 pacientov v četrti študiji) in ne-simptomatski zdravi posamezniki (32 zdravih v prvi, drugi in tretji študiji, 40 zdravih v četrti študiji). V peti študiji je sodelovalo 43 pacientov z idiopatsko bolečino v vratu. V šesti študiji je sodelovalo 28 pacientov z idiopatsko bolečino v vratu in 30 zdravih ne-simptomatskih posameznikov. V sedmi študiji je sodelovalo 43 bolnikov z idiopatsko bolečino v vratu ter 42 zdravih posameznikov. V zadnji osmi študiji je sodelovalo 20 zdravih posameznikov, 20 pacientov z idiopatsko bolečino v vratu, 18 pacientov z nihajno poškodbo vratu ter 17 pacientov z BTPM. V vseh študijah smo vključili preizkušance v starosti od 18 do 55 let starosti brez dodatnih obolenj in poškodb gibalnega aparata, vestibularnih motenj (izjema je bila zadnja osma študija) in ostalih nevroloških obolenj. Vse študije je odobrila komisija za medicinsko etiko Republike Slovenije (številka: 0120-47/2020/6) in so bile izvedene skladno z Helsinško deklaracijo in Ovidsko konvencijo in njunimi kasnejšimi dopolnitvami.

V vseh študijah je bil uporabljen test sledilnega pogleda med torzijo vratu kot pokazatelj okulomotorične funkcije, med katerim smo gibanje oči merili s infrardeče video-okulografijea. V prvih štirih študijah smo preverjali merske lastnosti predvidljivega sinusnega gibanja sledene tarče. Preverjali smo uporabo različnih hitrosti (20°/s, 30°/s in 40°/s) in amplitud (30°, 40° in 50°) v nevtralnem in torzijskem položaju glave v obe smeri (30° in 45°). Za potrebe preverjanja med-obiskovne ponovljivosti so vsi preiskovanci opravili test sledilnega pogleda med torzijo vratu z vsemi profili gibanja tarče na dveh ločenih obiskih. Prvi obisk te študije smo uporabili tudi za analizo znotraj-obiskovne ponovljivosti ter preverjanje razlik med zaporednimi cikli. Dodatno smo podatke iz teh meritev uporabili za preverjanje skladnosti natančnosti sledilnega pogleda (pridobitek) in torzijske razlike v pridobitku med 30° in 45° torzije glave (zasuk trupa pod stacionarno glavo). Skladno z rezultati prvih štirih študij smo v vseh nadaljnjih študijah uporabili najbolj ponovljiv in občutljiv profil gibanja sledene tarče (hitrost 30°/s, amplituda 40° ter 45° torzije vratu).

Za potrebe šeste študije smo uporabili tri spreminjajoče se profile sinusnega gibanje sledene tarče (spreminjajoča se amplituda, spreminjajoča se hitrost in spreminjajoča se amplituda ter hitrost hkrati). V vseh študijah smo preračunali pridobitek kot razmerje med tekočim sledilnim pogledom in gibanjem tarče (delež trajanje sledilnega pogleda brez sakadičnih preskokov) ter torzijsko razliko v pribitku sledilnega pogleda (razlika med pribitkom v nevtralnem in torzijskem položaju). Dodatno smo v šesti študiji s pomočjo sledilca pogleda merili tudi konstrikcijske in dilatacijske odzive zenice, ki odražajo pozornost posameznika med izvedbo testa sledilnega pogleda. Iz zeničnih odzivov smo preračunali indeks kognitivne obremenitve (pokazatelj velikosti fazične pozornosti) ter relativno in povprečno širino zenice (pokazatelja velikosti tonične pozornosti).

V peti študiji so preiskovanci ob testu SPTV odgovorili še na šestnajst-delni vprašalnik za oceno intenzivnosti in pogostosti pojavljanja simptomov vidnega zaznavanja.

V sedmi in osmi študiji so preizkušanci ob testu sledilnega pogleda med torzijo vratu opravili še meritve ravnotežja v tihi paralelni stoji z glavo in vratom v nevtralnem položaju ter ob torziji glave in vratu za 45° v vsako stran. Vsi preiskovanci so opravili še metuljni test na treh težavnostnih stopnjah za oceno cervikocefaličnega kinestetičnega občutka za gibanje (metuljni test) tar repozicijski test (vračanje glave v nevtralni položaj) za oceno občutka za položaj. Slednjega so preizkušanci izvedli z uporabo štirih različnih gibanj glave (rotacijo glave v obe smeri, prehodom v upogib in izteg glave).

Za preverjanje med-obiskovne ponovljivost testa sledilnega pogleda med torzijo vratu smo uporabili dvosmerni mešani koeficient intraklasne korelacije z absolutnim ujemanjem ter dodatno izračunali koeficient variabilnosti, standardno napako ter najmanjšo zaznano napako. Za potrebe druge študije (preverjanje znotraj-obiskovne ponovljivosti) smo najprej napravili transformacijo podatkov za doseganje normalnosti porazdelitve podatkov. Na to smo uporabili enake statistične metode, kot v primeru preverjanja med-obiskovne ponovljivosti. Dodatno smo v tej študiji preverili še razlike med povprečnim pridobitkom med drugim in petim ciklom ter povprečnim pridobitkom med šestim in devetim ciklom s pomočjo več-faktorske analize variance ter s pomočjo post-hoc T-testov. Za preprečevanje napake tipa 1 smo napravili še korekcije za multiple primerjave s pomočjo Benjamini in Hochbergovega postopka. V tretji študiji smo skladnost med dvema kotoma torzije vratu preverjali s pomočjo Bland-Altmanove analize. Sprva smo preračunali povezanost med kotoma s pomočjo Spearmanovega korelacijskega koeficienta, ter statistično značilnost korigirali za multiple primerjave s pomočjo Benjamini-Hochbergovega postopka. Sledila je priprava Bland Altmanovih prikazov ter preračun pristranskosti merjenja. Zaradi nenormalnosti porazdelitve smo intervale zaupanja za posamezen profil gibanja tarče preračunali s pomočjo kvartilne regresije. V četrti študiji smo preverjali sposobnost klasifikacije pacientov z idiopatsko bolečino v vratu s pomočjo pridobitka ali torzijske razlike v pribitku sledilnega pogleda različnih izvedenk testa sledilnega pogleda s pomočjo Naive Baies modela strojnega učenja. Najprej smo klasifikacije izvedli za vsak profil gibanja tarče posebej ter uspešnost klasifikacije opisali s površino pod odnosom resničnostno pozitivnega deleža in lažno pozitivnega deleža klasifikatorja ter velikostjo resnično pozitivnih klasifikacij in lažno pozitivnih klasifikacij. V nadaljevanju smo s pomočjo Naive Baies modela strojnega učenja ter nomograma klasificirali posamezne profile gibanja tarče glede na njihovo uspešnost ter združili dva najvišje uvrščena profila. Ta par klasifikatorjev smo na to ponovno hkrati uvrstili v Naive Baies model strojnega učenja ter ponovili analizo. Dodatno, smo preračunali minimalno klinično pomembno razliko med skupinama.

Sledil je sklop analiz v peti študiji, kjer smo preverjali sposobnost klasificirati velikost intenzivnosti in pogostost pojavljanja simptomov v vidnem zaznavanju s pomočjo dveh vrst klasifikatorjev (pridobitka ali torzijske razlike v pridobitku sledilnega pogleda) pridobljenih med uporabo najbolj ponovljivega ter občutljivega profila gibanja sledene tarče. Tudi v ta namen smo uporabili Naive Baies model strojnega učenja, kot je bilo opisano zgoraj v primeru četrte študije.

V šesti študiji smo razlike v pribitku, torzijski razliki v pridobitku sledilnega pogleda, indeksu kognitivnega napora ter povprečni širini zenice med tremi različnimi položaji glave in vratu ali štirimi različnimi nalogami sledilnega pogleda preverjali s Friedmanovim testom. Za parne primerjave smo uporabili post-hoc test predznaka. Test predznaka smo uporabili tudi za preverjanje razlik med skupinama zdravih preizkušancev ter pacientov z idiopatsko bolečino v vratu.

V sedmi študiji smo preverjali povezanost med spremenljivkami metuljnega testa ali testa repozicije vratu in glave s spremenljivkami nihanja skupne točke pritiska telesa na podlago ter testa sledilnega pogleda. Uporabljen je bil model multiple regresije z modelom najboljšega ujemanja, v katerega smo kot napovedne spremenljivke vključili rezultate metuljnega testa ali testa repozicije vratu.

V osmi študiji smo preverjali razlike v spremenljivkah metuljenega testa, testa repozicije vratu in glave, naloge ohranjanja ravnotežja v paralelni stoji z glavo v nevtralnem in torzijskem položaju ter testa sledilnega pogleda med štirimi skupinami preizkušancev (zdravi posamezniki, pacienti z idiopatsko bolečino v vratu, pacienti z nihajno poškodbo vratu ter pacienti z BTPM). V ta namen smo uporabili Kruskal-Wallisov test, za posamezne parne primerjave pa Mann-Whitney U-test. Za zmanjševanje napake tipa I smo uporabili Benjamini-Hochbergov postopek. Dodatno smo za posamezne pare preračunali minimalno klinično pomembno razliko med skupinama.

Rezultati prve študije so pokazali srednje visoko do dobro ponovljivost pridobitka pri skupini pacientov z idiopatsko bolečino v vratu, kadar sta bili uporabljeni 40° in 50° amplitudi ter 20°/s in 30°/s hitrosti gibanja tarče. Pri zdravih preiskovancih je bila med-obiskovna ponovljivost pribitka višja in sicer dobra do visoka. Ponovljivost torzijske razlike v pridobitku sledilnega pogleda je bila srednje visoka do dobra v obeh skupinah preiskovancev. V obeh skupinah je bil nakazan trend višje med-obiskovne ponovljivosti v nevtralnem položaju vratu, čeprav večjih razlik ni bilo opaziti.

Znotraj-obiskovna ponovljivost spremenljivk sledilnega pogleda, ki smo jo preverjali v drugi študiji se je izkazala za dobro do visoko v obeh opazovanih skupinah (pacientih z idiopatsko bolečino v vratu ter zdravih preiskovancih) neglede na amplitudo in hitrost gibanja tarče. V skupini pacientov je bil nakazan trend nižjega pridobitka med šestim in devetim ciklom, ki je prag statistične značilnosti dosegel zgolj pri hitrosti 30°/s.

Skladnost v pridobitku in torzijski razliki v pridobitku sledilnega pogleda med dvema različnima kotoma, ki smo jo preverjali v tretji študiji, je bila srednje visoka pri pacientih z idiopatsko bolečino v vratu in nekoliko višja pri zdravih preiskovancih. Na skladnost pridobitka je vplivala amplituda (večja pri večjih amplitudah) ter hitrost (višja pri nižjih hitrostih) gibanja sledene tarče. Takšnega trenda nismo opazili za torzijsko razliko v pridobitku sledilnega pogleda.

V četrti študiji smo prepoznali največjo občutljivost pridobitka kot klasifikatorja za klasificiranje pacientov z idiopatsko bolečino v vratu kadar sta bila uporabljena dva profila gibanja sledene tarče hkrati (pri hitrosti 30°/s in amplitudah 30° in 40°) in nekoliko nižjo kadar sta bila ta dva profila uporabljena posamezno. Podobno se je izkazalo tudi za torzijsko razliko v pridobitku sledilnega pogleda, ki je imela najvišjo občutljivost pri hitrosti 30°/s in amplitudi 30°, vendar je dosegla nekoliko nižjo občutljivost kot pridobitek. Tako pri pridobitku kot torzijski razliki v pridobitku sledilnega pogleda je bila veliko višja občutljivost dosežena kadar je bila uporabljena 45° torzija vratu kot v primeru kadar je bila uporabljena 30° torzija vratu.

Na podlagi rezultatov prvih štirih študij je mogoče zaključiti, da je največjo veljavnost testa sledilnega pogleda izvedenega v torziji vratu mogoče doseči z uporabo profila gibanja tarče s hitrostjo 30°/s ter amplitudama 30° ali 40°. Dodatno je priporočljivo uporabiti 45° torzije vratu, kadar to omogoča prisotna patologija.

Nadalje smo v peti študiji ugotovili, da lahko zmerno dobro klasificiramo intenzivnost in nekoliko manj pogostost pojavljanja posameznih simptomov v vidnem zaznavanju s pomočjo spremenljivk testa SPTV pri pacientih z idiopatsko bolečino v vratu. Med simptome, katerih intenzivnost lahko v največji meri napovemo s pridobitkom sodijo motnje v fokalnem vidu, ki jih tudi sicer povezujemo s simptomom računalniškega vida. Torzijska razlika v pridobitku sledilnega pogleda je bila manj učinkovit klasifikator intenzivnosti in pogostosti simptomov v vidnem zaznavanju kot pridobitek.

V šesti študiji smo ugotovili, da med nalogami sledilnega pogleda z uporabo nepredvidljivo spreminjajočega se gibanja sledene tarče prihaja do nižjega indeksa kognitivne aktivnosti v nevtralnem položaju pri pacientih z idiopatsko bolečino v vratu kot pri zdravih posameznikih, vendar ta razlika izgine pri izvajanju testa v torziji vratu. Dodatno smo opazili, da pri nalogah nepredvidljivega gibanja sledene tarče prihaja do statistično pomembnih razlik med nevtralnim in torzijskimi položaji pri pacientih z idiopatsko bolečino v vratu ne pa tudi pri zdravih posameznikih. Povprečen relativen presek zenice ne kaže razlik med pacienti in nalogami sledilnega pogleda, medtem ko absoluten presek zenice nakazuje na nižjo tonično pozornosti pri pacientih z idiopatsko bolečino v vratu. Primerjava predvidljive naloge in treh nepredvidljivih nalog sledilnega pogleda ne kaže statistično značilnih razlik v spremenljivkah zeničnih odzivov.

V sedmi študiji smo ugotovili, da je gibanje skupne točka gibanja sile reakcije podlage med nalogami mirne stoje (predvsem v anteriorno-posteriorni smeri) povezano z metuljnimi testom in manj z relokacijskim cervikocefaličnim kinestetičnim testom. Dodatno je bila prisotna srednje velika povezanost med metuljnim testom in pridobitkom med sledilnim pogledom in manj s torzijsko razliko v pridobitku sledilnega pogleda. Omenjene povezave so bile večje pri pacientih z idiopatsko bolečino v vratu.

V osmi študiji nismo dokazali statistično značilnih razlik v ravnotežju, metuljnem testu, repozicijskem cervikocefaličnem kinestetičnem testu ter sledilnem pogledu med pacienti z BTPM in skupinama s travmatsko in ne-travmatsko patologijo vratne hrbtenice. Vse omenjene skupine so se statistično značilno razlikovale v vseh naštetih testih od skupine zdravih preiskovancev. Statistično značilna razlika med skupinama pacientov z BTPM ter skupinama z ne-travmatsko in travmatsko patologijo vratne hrbtenice se je pokazala zgolj v velikosti nihanja skupne točke sile reakcije podlage v medialno-lateralni smeri med ohranjanjem mirne stoje.

Namen doktorske disertacije je bil v sklopu prvih štirih študij preveriti merske lastnosti (med-obiskovno in znotraj-obiskovno ponovljivost, občutljivost ter skladnost) testa SPTV ter določiti najbolj veljaven profil gibanja sledene tarče za vrednotenje natančnosti sledilnega pogleda pri pacientih z idiopatsko bolečino v vratu. V peti študiji smo želeli preveriti prisotnost povezave med testom SPTV in intenzivnostjo ter pogostostjo pojava simptomov povezanih z vidnim zaznavanjem. V šesti študiji smo želeli preveriti tudi spremembe v tonični ter fazični pozornosti pacientov z idiopatsko bolečino v vratu med izvajanjem predvidljivega in nepredvidljivega gibanja tarče v testu SPTV. V sedmi študiji smo preverjali prisotnost povezav med testi cervikocefalične kinestezije, testom SPTV ali sposobnostjo ohranjanja ravnotežja pri pacientih z idiopatsko bolečino v vratu. V zadnji, osmi študiji smo preverjali ali obstajajo razlike v testih cervikocefalične kinestezije, testom SPTV in sposobnostjo ohranjanja ravnotežja med tremi skupinami pacientov (pacienti z idiopatsko bolečino v vratu, nihajno poškodbo vratu ter pacienti z BTPM). V sklopu prvih štirih raziskav smo določili profil gibanja tarče z največjo veljavnostjo (amplituda gibanja 40° ali 30° in hitrost gibanja 30°/s pri predvidljivem cikličnem gibanju tarče med nevtralnim položajem in 45° torziji vratu). Pridobitek med najobčutljivejšim profilom gibanja tarče med testom SPTV je lahko deloma napovedal intenzivnost, ne pa tudi pogostosti pojavljanja simptomov v vidnem zaznavanju. Dodatno smo ugotovili upad fazične in deloma tonične pozornosti med nalogami sledilnega pogleda pri pacientih z idiopatsko bolečino v vratu. V sedmi študiji smo ugotovili povezanost med cervikocefaličnimi kinestetičnimi testi ter pridobitkom v testu SPTV ter cervikocefalično kinestezijo ter sposobnostjo ohranjanja ravnotežja pri pacientih z idiopatsko bolečilno v vratu. V zadnji študiji smo preverjali razlike med zgoraj navedenimi testi cervikocefalične kinestezije, SPTV in ravnotežja med ohranjanjem mirne stoje z torzijo vratu in glave.

Rezultati prvih štirih raziskav potrjujejo naše predvidevanje, da na pridobitek in torzijsko razliko v pridobitku testa SPTV vplivajo amplituda in hitrost gibanja sledene tarče ter torzijski kot vratu. Izkazalo se je, da je ponovljivost testa SPTV večja, kadar uporabljamo večjo amplitudo gibanja tarče. Višjo ponovljivost v večjih amplitudah lahko pripišemo nevrofiziološkim povezavam med očesnimi in vratnimi mišicami, predvsem obliquus captitis inferior. Slednje izdatneje povečajo svojo aktivnost med večjo amplitudo gibanja oči. Posledično se lahko poveča število povratnih senzoričnih informacij iz mišičnih vreten vratnih mišic, kar lahko vpliva na upravljanje gibanja oči. Dodatno se lahko zaradi povečane bilateralne aktivnosti mišic vratu poveča mehanska stabilnost zgornjega vratnega predela, kar vodi v stabilnejše ohranjanje položaja glave in posledično učinkovitejše upravljanje gibanja oči.

Na ponovljivost in občutljivost je pomembno vplivala tudi hitrost gibanja sledene tarče. Znano je, da hitrost sledilnega pogleda vpliva na medsebojno prepletanje sledilnega pogleda ter sakadičnih preskokov pogleda. Število slednjih se poveča kadar je gibanje sledene tarče hitrejše. Ker je pridobitek med SPTV mera natančnosti gibanja osrednjega vida, ki je v veliki meri odvisna ravno od prisotnosti sakadičnih preskokov, lahko sklepamo, da je potrebno za večjo občutljivost uporabiti nekoliko višje hitrosti gibanja oči. Slednja predstavlja zahtevnost test SPTV kjer se nakazuje poslabšana okulomotorična funkcija pri pacientih z idiopatsko bolečino v vratu ne pa tudi pri zdravih nesimptomatskih posameznikih.

Med pomembnimi dejavniki, ki so vplivali na veljavnost testa sodi tudi velikost torzije vratu in glave. Tako ponovljivost kot občutljivost testa SPTV sta bili višji med 45° torzijskim položajem. Dodatno smo v naši tretji študiji zaznali srednjo skladnost med 30° in 45° torzijskim položajem. Iz teh ugotovitev lahko zaključimo, da je v prihodnje smiselno uporabljati 45° torzijski položaj v kolikor to dopušča gibljivost vratnega predela ter pojavnost bolečine. V primerih, kadar zaradi omejitev pri pacientih ni mogoče uporabljati kota 45° je smiselno uporabiti večje amplitude ter nižje hitrosti gibanja tarče, s čimer lahko izboljšamo skladnost spremenljivk testa SPTV.

Med pomembnejše izsledke naše pete študije sodi ugotovitev, da lahko spremenljivke testa SPTV uporabimo za klasifikacijo intenzivnosti simptomov povezanih z vidnim zaznavanjem, ne pa tudi za klasifikacijo njihove pogostosti. Med simptome, ki smo jih lahko klasificirali v največji meri sodijo tisti, ki so povezani z upravljanjem osrednjega vida. Ta ugotovitev je pričakovana, saj je potrebno v testu SPTV natančno upravljati osrednji vid in je v tem oziru v mehanizmih upravljanja gibanja oči sorodna opisanim simptomom.

V šesti študiji smo ugotovili prisotnost deficitov v upravljanju fazične in deloma tonične pozornosti. Upad fazične pozornosti pri pacientih z idiopatsko bolečino v vratu se je pokazal predvsem med nepredvidljivim gibanjem tarče med testom SPTV izvedenim v nevtralnem položaju ne pa tudi med torzijo vratu. Takšni trendi niso bili prisotni pri zdravih posameznikih. Zaključimo lahko, da med nepredvidljivim gibanjem tarče med testom SPTV pri pacientih z idiopatsko bolečino v vratu prihaja do povečane fazične pozornosti kar omogoči ohranjanje natančnosti sledilnega pogleda. Zaradi omejene kapacitete vidno delovnega spomina ter hitrosti procesiranja informacij lahko sklepamo, da je posledično pri pacientih z idiopatsko bolečino slednja zmanjšana za potrebe opravljanja sekundarnih nalog kot je vožnja avtomobila ali branje. Dodatno lahko iz predstavljenih ugotovitev zaključimo, da predstavljajo naloge sledilnega pogleda z nepredvidljivim gibanjem tarče zahtevnejšo nalogo, v kateri poslabšano okulomotorično funkcijo deloma uravnovesi povečana aktivnost višjih centrov za nadzor gibanja oči. Posledično se nepredvidljivi obliki testa SPTV zmanjša občutljivost in je neprimeren za nadaljnje študije namenjene proučevanju sprememb v vidnem zaznavanju pri pacientih z idiopatsko bolečino v vratu.

V sedmi študiji smo proučevali povezanost spremenljivk cervikocefaličnih testov s spremenljivkami testa SPTV ter sposobnostjo ohranjanja ravnotežja med nalogami mirne stoje. Metuljni test je bil povezan z pridobitkov sledilnega pogleda med torzijo vratu, kar potrjuje pomen vratne kinestezije za upravljanje gibanja oči. Prisotne so bile tudi povezave med cervikocefalično kinestezijo ter gibanjem skupne točke sile reakcije podlage v anteriorno-posteriorni smeri, ne pa tudi v medialno-lateralni smeri.

V zadnji študiji smo nadgradili sedmo študijo ter potrdili prisotnost cervikogenih deficitov pri pacientih z BTPM, ki se v testih cervikocefalične kinestezije in SPTV niso razlikovali od pacientov s travmatsko in ne-travmatsko poškodbo vratu. Podobno je bilo tudi v testih ravnotežja, vendar je bila pri slednjem prisotna razlika med pacienti v medialno-lateralni smeri. Zaključimo lahko, da BTPM povzroči specifične spremembe v sposobnosti ohranjanja ravnotežja, ki so povezane z deficiti v cervikalni funkciji (poslabšana sposobnost ohranjanja ravnotežja v anteriorno-posteriorni smeri) in mehanizmi, ki so povezani s poškodbo možganov (poslabšana sposobnost ohranjanja ravnotežja v medialno-lateralni smeri).

Naše študije so imele tudi pomembne omejitve, med pomembnejše sodijo: vključevanje zgolj pacientov z gibljivostjo vratne hbtenice večje od 50°, neupoštevanje ostalih spremljajočih simptomov ter področja bolečine, razlike v starosti nekaterih proučevanih skupin, veliko število ponovitev testa SPTV v prvih petih študijah, način rekrutacije pacientov, ne-upoštevanje vsakodnevnih navad kot je čas preživet za računalnikom ali telefonom, ter osredotočenost na kronična obolenja vratne hrbtenice. Našteti omejitveni dejavniki bi lahko pomembno spremenili rezultate naše študije, kar omejuje prenos naših ugotovitev na širšo populacijo pacientov.

Rezultati doktorske naloge predstavljajo pomemben doprinos k izboljšanju vrednotenja in razumevanja deficitov v vidnem zaznavanju pri pacientih z idiopatsko bolečino v vratu. Z učinkovitejšimi pristopi lahko omogočimo zgodnejšo prepoznavanje tovrstnih težav ter pripravo učinkovitejših rehabilitacijskih programov. Posledično lahko naše ugotovitve pozitivno doprinesejo k zmanjševanju možnosti pojava kroničnosti in remisij pri pacientih z bolečinami v vratu.

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ANNEXES

Anex 1 – Licence agreement: The influence of neck torsion and sequence of cycles on intra-trial reliability of smooth pursuit eye movment test in patients with neck pain disorders

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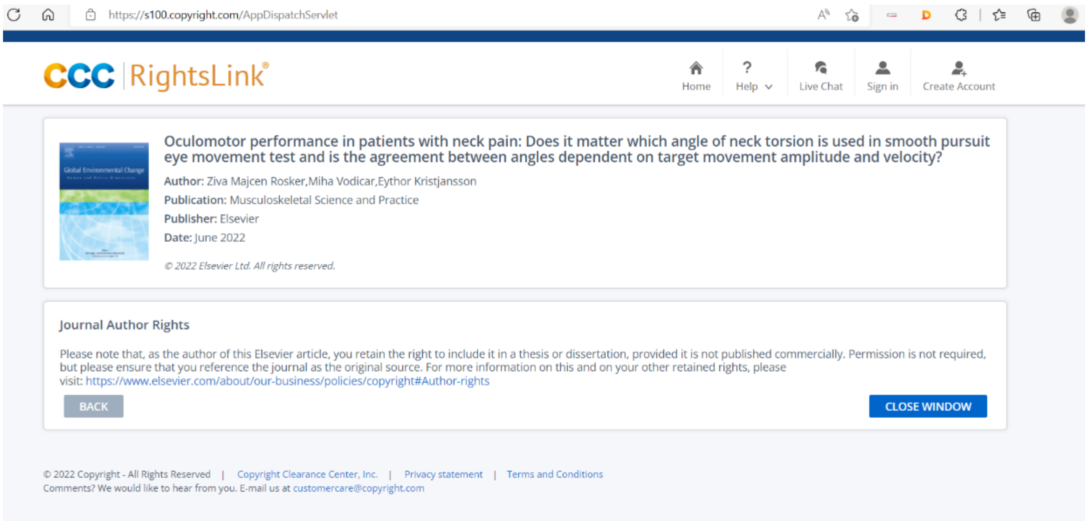

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Oculomotor performance in patients with neck pain: Does it matter which angle of neck torsion is used in smooth pursuit eye movement test and is the agreement between angles dependent on target movement amplitude and velocity?

Author: Ziva Majcen Rosker,Miha Vodicar,Eythor Kristjansson

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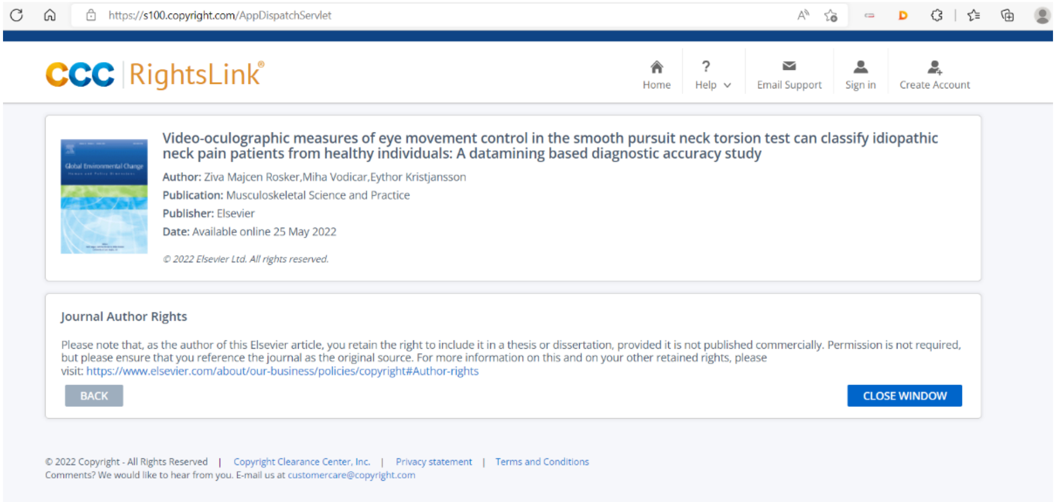

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