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# Accelerometer-Based Assessment of Head-Trunk Coordination in Subjects with Chronic Neck Pain

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ABSTRACT

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Background: Chronic neck pain is a prevalent condition significantly affecting the quality of life and functional abilities of individuals. The complex interplay between pain and sensorimotor impairments highlights the need for accurate assessment methods to better understand the underlying mechanisms and guide effective interventions.

Objectives: The purpose of this study is to enhance the development of assessment methodologies for individuals afflicted with chronic neck pain. By deepening our understanding of sensorimotor control and its interplay with individual characteristics, the study aspires to improve rehabilitation outcomes and offer targeted interventions. The principal research question addresses the intra- and inter-session reliability of an accelerometer in evaluating head-trunk coordination in patients with chronic neck pain. Secondary questions focus on two main concerns: firstly, the impact of using a mirror for visual feedback on head stability; and secondly, the degree of correlation between head stability and factors such as pain intensity, disability, dizziness or onset of pain.

Methods: This cross-sectional study enrolled 19 participants with chronic neck pain to evaluate the intra- and inter-session reliability of an accelerometer for head-trunk coordination assessment. Participants performed the Head-Trunk Coordination Test (HTCT) facing a wall then facing a mirror. The test was taken twice on the same day, and a third time within a week. A statistical analysis for reliability and exploration of correlations was conducted.

Results: Intra-session reliability was mainly moderate to good, while inter-session reliability was considered reasonable. No significant correlations were observed between accelerometer parameters and Neck Disability Index (NDI), Dizziness Handicap Inventory (DHI), or pain onset. However, the use of visual feedback with a mirror resulted in reduced head movement on one parameter, while three parameters remained unchanged.

Conclusions: This accelerometer-based method is reliable for assessing head-trunk coordination, but inter-session reliability may be influenced by subject variability. The mean of accelerations in absolute values appears to be the most informative parameter. Further investigation is needed to address the variability observed among subjects and to explore ways to document the clinical evolution of neck pain patients.

Keywords: Neck Pain, Sensorimotor, Coordination, IMU, Accelerometer

# FOREWORD

This research project aimed to address a longstanding clinical question regarding the generation of objective indicators for describing the quality of movement, complementing the subjective evaluations commonly used in clinical practice.

This research project has been a significant milestone in my personal development. It marked my first experience presenting a project to an ethics committee, which was a challenge but allowed me to gain valuable insights into the ethical considerations involved in research.

Furthermore, this project played in my discovery of programming. Exploring the field of programming and utilising it for data analysis has been an eye-opening experience. This project has not only improved my technical skills but also broadened my understanding of how technology can be used to support research.

I would like to express my sincere gratitude to the individuals who contributed to the completion of this research project:
Sari Merilampi and Merja Sallinen for their valuable supervision throughout this master thesis,
Markus Ernst for his kind and enlightening guidance,
Julia Trealeven for her precious suggestions,
Thomas Pourchet for our engaging and thought-provoking discussions,
Sandie for her unwavering support and encouragement throughout this journey.

CONTENTS

# LIST OF SYMBOLS AND TERMS

| | |
|---|---|
| BASEC | Business Administration System for Ethics Committees |
| CCMS | Clinical Cervical Movement Sense |
| ClinO | Clinical Trials Ordinance |
| COP | Center Of Pression |
| CSN | Central Nervous System |
| DHI | Dizziness Handicap Inventory |
| eCRF | electronic Case Report Form |
| HRA | Human Research Act |
| HRO | Human Research Ordinance |
| HTCT | Head-Trunk Coordination Test |
| ICC | Intraclass Correlation Coefficient |
| IMU | Inertial Measurement Units |
| NDI | Neck Disability Index |
| NHP | Natural Head Position |
| NRS | Numeric Rating Scale (0-10) |
| SEM | Standard Error of Measurement |
| YLDs | Years Lived with Disability |

# 1 INTRODUCTION

Over the last decades, remarkable advancements have been noted in the field of physiotherapy. A continuous expansion of the assortment of available tools has occurred, and significant adaptations to the profession's guidelines have been made. Indeed, in this dynamic field, lifelong learning is recognized not merely as a marketing slogan but as a genuine necessity (World Physiotherapy, 2021).

However, notable resistance to this rapid evolution is sometimes encountered among professionals. In Switzerland, for instance, limited integration of digital tools is manifest. It appears that factors like the level of education, age, gender, position, or professional experience do not appear to influence this hesitancy. (Keel et al., 2022; Postolache et al., 2017; Rausch et al., 2021.)

To overcome these challenges and promote innovation in healthcare, several conditions are necessary: adequate access to data, alignment with legal frameworks, a clear identification of responsibilities in data management, evidence of safety and efficacy, and trust in both developers and regulators. Beyond specialised education, the fulfilment of these requirements is seen as crucial for the successful integration of digital health tools into healthcare practice. (Fahy et al., 2021; Gordon et al., 2020; Rausch et al., 2021; Vayena et al., 2018.)

In the practice of physiotherapy, the importance of accurate and time-effective assessment methods for making optimal clinical decisions is emphasized (Jones & Rivett, 2019). For conditions like neck pain, a comprehensive evaluation including assessments of range of motion, strength, and coordination is required. On a practical level, existing methodologies for assessing head-trunk coordination tend to be not feasible due to the extended time they require.

Clinical choices, such as the selection of assessment methods, should align with best practices and existing knowledge while also considering the preferences of both patients and healthcare professionals (Sackett et al., 1996). The effective understanding and addressing of the specific needs of physiotherapists, through safe and efficacious methods, are considered crucial.

This master thesis is intended to provide an opportunity for exploring head-trunk coordination and its assessment in individuals with chronic neck pain. The reliability of a new accelerometer-based method will be evaluated, and its correlation with individual characteristics will be understood. By this approach, the development of a user-friendly assessment method that supports clinical reasoning and improves rehabilitation outcomes is aimed to be advanced. Involvement of the end-user in the initial stage of tool development is expected to facilitate greater acceptance among physiotherapists.

After defining the research domain and specific topic, he selection of the most appropriate technology was necessitated. Ethical convictions dictated that the methods should be applicable in private practices and underserved regions with minor investments. Development of a smartphone app was initially considered but was found to be impractical due to reliability concerns across different smartphone models. Then, collaboration with a Swiss start-up specialising in accelerometer-based sensors was explored but was set aside due to significant financial barriers (development costs exceeding 30,000 euros) and lack of aligned objectives. Instead, an open-source external accelerometer was selected for its low cost, proven validity, and ability to utilise raw data.

Insightful guidance throughout this project was provided by Markus Ernst, particularly regarding ethical considerations. Valuable shaping of the research design was achieved through videoconferences with Dr Julia Treleaven and him. This study was carried out solely by the author, from the formulation of the research question to data collection, analysis, and thesis writing.

# 2 THEORETICAL FRAMEWORK

## 2.1 Pain

In 2020, the pain definition was revised as “an unpleasant sensory and emotional experience associated with, or resembling that associated with, actual or potential tissue damage” (Raja et al., 2020). Pain is the most frequent reason for seeing a physician in primary care, accounting for 40% of visits (Mäntyselkä et al., 2001). Chronic pain is characterized by its persistence beyond the normal healing time and the absence of its acute warning function for physiological nociception. Generally, pain that lasts or recurs for more than three months is considered chronic (Geneen et al., 2017; Parikh et al., 2019; Treede et al., 2019). Research indicates that chronic pain has a weighted mean prevalence of 20% among adults (Geneen et al., 2017).

Multiple factors have been identified as risk factors for the development of chronic pain. These factors include being female, having a genetic predisposition, geographical and cultural background, lower socioeconomic status, and advancing age. Additionally, chronic pain has been associated with lifestyle factors such as alcohol consumption, nutrition, obesity, comorbidities, employment status, occupational factors, smoking, and physical activity level. (Malchaire et al., 2001; Smith et al., 2007; van Hecke et al., 2013.)

Chronic pain, in general, carries significant implications, including contributing to disability, depression, anxiety, reduced quality of life, sleep disturbances and increased healthcare costs (Geneen et al., 2017).

## 2.2 Neck pain

The anatomical boundaries of the neck region are illustrated in Figure 1. Neck pain is a widespread condition, affecting a substantial portion of the population (GBD 2019 Diseases and Injuries Collaborators, 2020; Safiri et al., 2020). In

2017, the global age-standardized rate for the point prevalence of neck pain was estimated at 3551.1 per 100’000 individuals. The incidence of neck pain was estimated at 806.6/100’000. There were no significant changes in these estimations between 1990 and 2017. (Safiri et al., 2020.)

Furthermore, the number of years lived with disability (YLDs) due to neck pain is estimated to be 22 million, with a 95% uncertainty interval ranging from 15 to 32 million, according to Cieza et al. (2020). In 2015, neck pain ranked fourth in terms of causing YLDs globally, with low back pain and major depressive disorder ranking highest (Rice et al., 2016). The age-standardized point prevalence of neck pain is 4.9%, with rates of 5.8% in women and 4% in men(Hoy et al., 2014). Various studies support the observation of a higher prevalence of neck pain in women compared to men (Bikbov et al., 2020; Cohen, 2015; Fejer et al., 2006; Hoy et al., 2014; March et al., 2014; Safiri et al., 2020). Blanpied et al. (2017) describe an increased prevalence around the fifth decade of life.

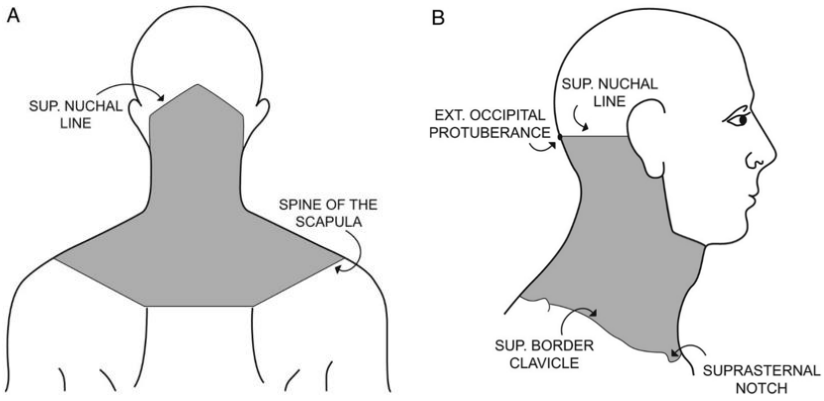



Figure 1. Anatomic region of the neck: posterior (A) and lateral (B) views (Guzman et al., 2008)

Patients with neck pain, particularly those with traumatic pain as opposed to idiopathic pain, experience a decrease in quality of life, pain-related disability, and cognitive deficits (Coppieters et al., 2017; Fejer & Hartvigsen, 2008). Most people with neck pain (50% to 85%) cannot fully resolve this problem (Carroll et al., 2009).

The etiology of chronic neck pain is likely a result of various combinations of pathophysiological mechanisms (Parikh et al., 2019; Sjölander et al., 2008; Waeyaert et al., 2016). As the underlying causes are often unclear, neck pain is commonly referred to as non-specific neck pain (Hush et al., 2011). There is still an important need to better identify and document the factors that influence non-specific neck pain (Werner et al., 2018).

Hodges & Tucker (2011) suggest that pain causes different adaptations, including inter- and intra-muscular reorganization, altered movement and increased stiffness, increased protection from further pain or injury (kinesiophobia), and changes in sensorimotor control, which may lead to short-term benefits but long-term disadvantages.

## 2.3 Sensorimotor control

Sensorimotor control is a complex system which is designed to maintain the postural stability and the ability to perform tasks and movements (Shumway-Cook et al., 2023). Figure 2 illustrates the integration of various afferences and motor commands within the central nervous system to achieve these objectives, including somatosensorial afferences, neck proprioception, vestibular and visual afferences (Kristjansson & Treleaven, 2009).

Somatosensory afferences encompass sensations of touch, pressure, and position, with a specific focus on neck proprioception, which provides information about the position and movement of the neck (Elert et al., 2001; Hülse et al., 1998; Kristjansson & Treleaven, 2009). Vestibular afferences are related to balance and spatial orientation (Highstein et al., 1996), while visual afferences refer to visual input from the environment (Tjell & Rosenhall, 1998).

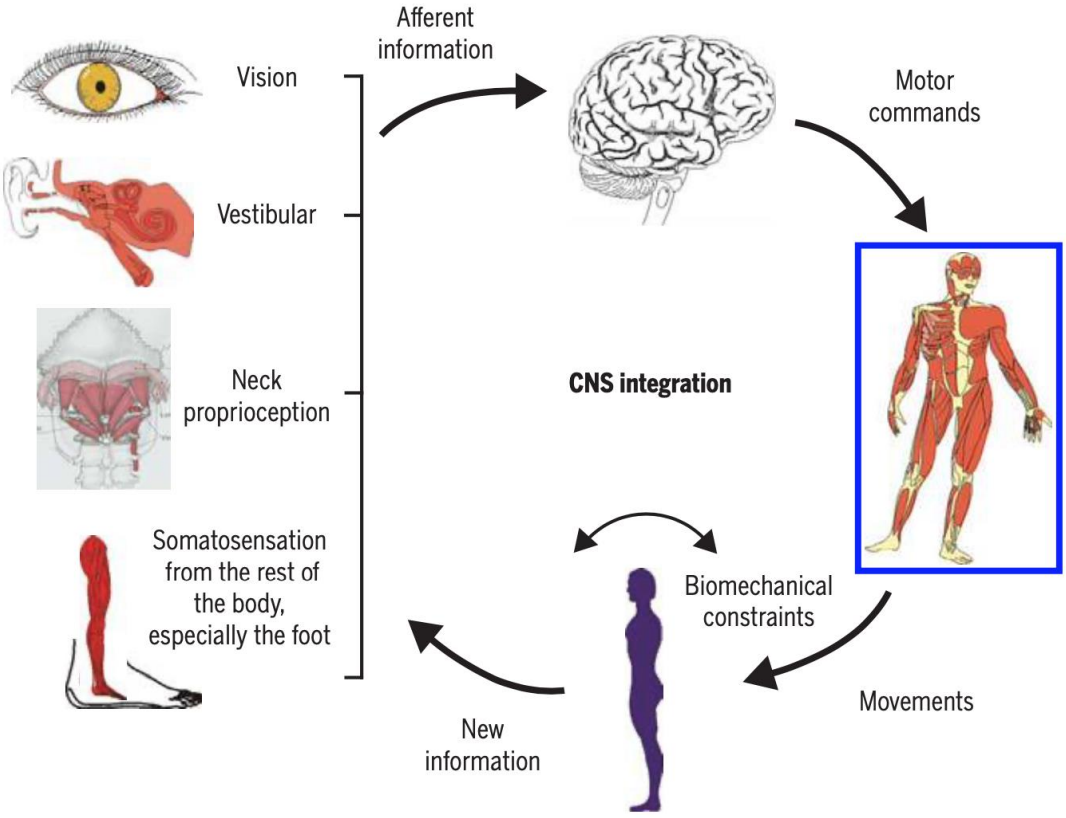



Figure 2. Sensorimotor control and Central Nervous System (CSN) integration (Kristjansson & Treleaven, 2009)

These afferences play a critical role in providing sensory information to the central nervous system, allowing it to monitor the body's position, movement, and relationship to the environment. The central nervous system then utilizes motor commands to execute appropriate motor responses. These motor commands coordinate muscle activation, joint movements, and postural adjustments to maintain stability and achieve desired tasks and movements. The integration of afferences and motor commands enables the central nervous system to adapt and respond to changing environmental conditions and optimize sensorimotor performance. (Kristjansson & Treleaven, 2009; Massion, 1994; Riemann & Lephart, 2002a, 2002b; Stanton et al., 2016; Winter et al., 1990.)

## 2.4 Musculoskeletal pain assessment

Walton and Elliott (2018) introduce a new clinical model based on radar plots, aimed at improving pattern recognition skills in the assessment of musculoskeletal pain. The framework utilizes clinical phenotyping and triangulation techniques to enhance diagnostic accuracy (Figure 3).

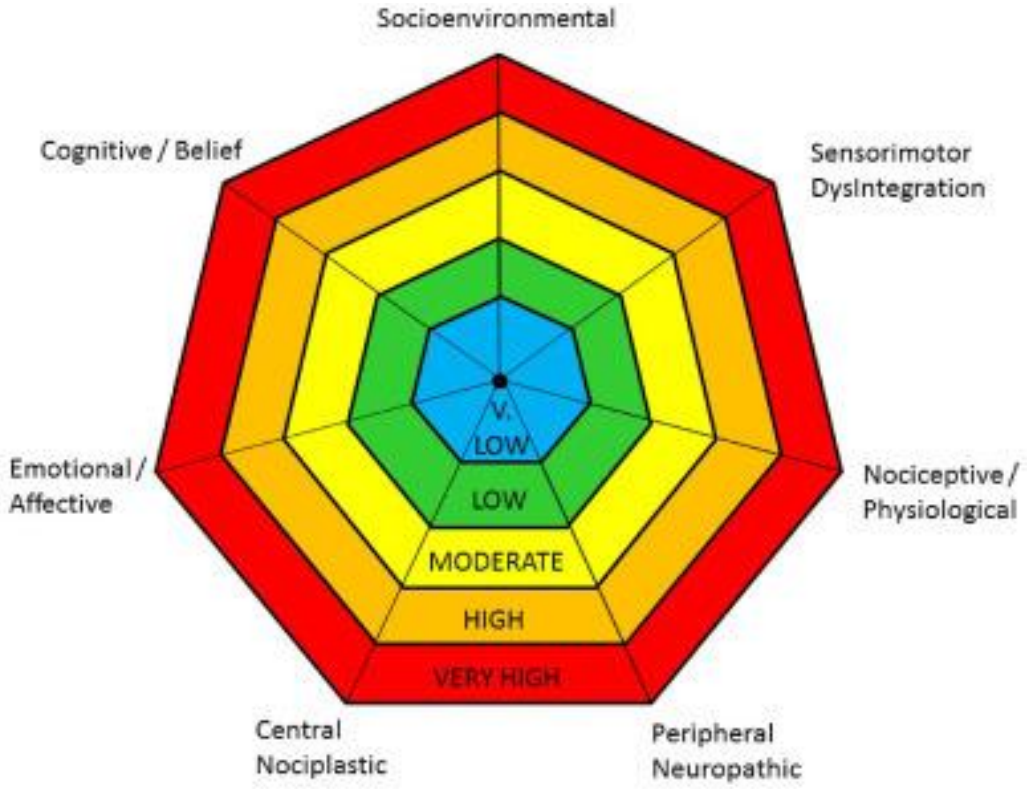



Figure 3. Radar plot of pain experience for clinical evaluation (Walton & Elliott, 2018)

de Vries et al. (2015) reported that there is a higher occurrence of a discrepancy between the perceived self and the actual self in the presence of pain. This mismatch can lead to what is known as sensorimotor disintegration, where the integration of afferences (interoception) is disturbed. Inconsistencies in somatosensory afferents may contribute to this disturbance (Di Lernia et al., 2016). Both Tsao et al. (2011) and Shabrun et al. (2017) have described motor cortical reorganization in individuals suffering from chronic low back pain.

Neck pain has significant implications for sensorimotor control, including balance, gait, and the control of head and eye movements (Treleaven, 2008a, 2008b; Treleaven et al., 2019). Therefore, it is crucial to develop effective methods for identifying and measuring impairments in sensorimotor control. Decline in sensorimotor control can contribute to the development of hypermobility, joint instability, and pain (Comerford & Mottram, 2015; Dankaerts, O'Sullivan, Burnett, et al., 2006; Dankaerts, O'Sullivan, Straker, et al., 2006; Kristjansson & Treleaven, 2009; Sahrmann, 2001; Sahrmann et al., 2017; Stanton et al., 2016).

Head-trunk coordination plays a critical role in sensorimotor control (Treleaven et al., 2019). It involves reflex responses from the neurological system, contributing to the coordination of head and trunk movements (Chen & Treleaven, 2013; Kristjansson & Treleaven, 2009; Mergner & Rosemeier, 1998; Peterson, 2004; Peterson et al., 1985). Maintaining proper coordination between the head and trunk is essential for postural stability, functional movement, and overall sensorimotor performance.

Research suggests that neck-specific exercises have demonstrated superior treatment outcomes compared to general physical activity for individuals with neck pain (Ludvigsson et al., 2016). Assessing sensorimotor control can help identifying specific impairments and limitations in an individual's ability to control and coordinate neck movements. This assessment provides valuable information for tailoring exercise programs that target the underlying sensorimotor dysfunctions contributing to neck pain. Studies by O'Leary et al. (2009) and Falla et al. (2012) support the notion that an accurate assessment of sensorimotor control is crucial for selecting appropriate neck-specific exercises that address the specific needs and deficits of each individual, leading to more effective treatment outcomes. Reduced neck sensory input in individuals performing tasks near their maximum neck range, whether they are healthy or have neck pain/injury, is linked to decreased upper limb kinesthetic sense and impaired sensorimotor performance, highlighting the importance of addressing neck-related factors in managing clumsiness and guiding treatment and rehabilitation approaches (Harman et al., 2021).

To assess the sensorimotor control, it is possible to investigate the ability to maintain a position, to dissociate movements, or to follow a given trajectory with the head (movement sense). It is necessary to describe the positions and their time derivatives: the first derivative is the speed, the second the acceleration and the third the jerk (Franov et al., 2022). Most frequently, assessment is conducted by testing the postural sway and the joint position error (de Zoete et al., 2017).

Methods are described to evaluate the capacity to activate and maintain the contraction of the deep cervical flexors, as the Neck Flexor Muscle Endurance Test (Domenech et al., 2011; Edmondston et al., 2008), and to interact with the superficial cervical flexors (Craniocervical Flexion Test) (Jull et al., 2008). Other tests, such as the Cervicocephalic Relocation Test and Joint Position Error, measure the ability to perform movements and return to the initial position (Dugailly et al., 2015; Pinsault et al., 2008).

However, the reliability is sometimes questionable (Jørgensen et al., 2014) and the Joint Position Error has shown no significant difference between healthy individuals and those with neck pain (Meisingset et al., 2015). Nonetheless, according to Lee et al. (2008), the findings suggest that neck proprioception in individuals with subclinical neck pain is more closely related to the frequency of pain rather than its intensity or duration.

Head-trunk coordination is another parameter used to describe cervical sensorimotor control. The ability to dissociate neck and trunk movements has demonstrated differences between healthy subjects and those with neck pain (Treleaven et al., 2019). Reflexes, and in particular the cervicocollic reflex, are deeply involved in head-trunk coordination (Chen & Treleaven, 2013). The cervicocollic reflex is triggered by neck position afferences and provoke adjustments by contractions of neck muscles (Ito et al., 1997).

It is essential to consider other parameters as well, given that sensorimotor control is a complex system. The Clinical Cervical Movement Sense test is considered reliable and feasible in clinical practice for assessing cervical

movement sense (Treleaven et al., 2021; Werner et al., 2018). This test has been shown able to detect differences between healthy individuals and those with neck pain (Ernst et al., 2019).

Various measurement systems are used to assess sensorimotor control, including electromagnetic motion tracking, optical motion capture, virtual reality tracking, inertial motion capture, and head-mounted laser pointers (Franov et al., 2022). While there is a need for reliable sensorimotor control assessments, the studied sensorimotor control variables show limited discriminative validity for the joint position sense and postural stability. Therefore, further exploration of descriptive parameters for sensorimotor control, particularly in individuals with neck pain, is necessary (Franov et al., 2022).

Problematically, existing methods to assess head-trunk coordination are often expensive (Werner et al., 2018) or impractical for clinical use due to their time-consuming nature or the need for specialized training and equipment. In this context, the Head-Trunk Coordination Test (HTCT) emerged as a potential solution, allowing the evaluation of the ability to maintain head stability while rotationally moving the trunk (Treleaven et al., 2020).

The HTCT is an assessment designed to evaluate an individual's ability to maintain head stability while rotating the trunk. It is commonly used to assess head-trunk coordination. During the test, the participant is instructed to rotate their trunk while keeping their head as stable as possible. The HTCT typically involves the use of a visual target, such as a laser pointer or a moving dot, which the participant focuses on while performing the trunk rotations. The goal is to accurately track and maintain the head's position relative to the target throughout the movements. However, the rapid movement of the laser red dot on the target makes it challenging to accurately track and report its trajectory during the clinical practice.

Understanding the complex interactions between afferences and motor commands within the sensorimotor control system is essential in comprehending how disruptions or impairments in these processes can impact head-trunk

coordination and overall sensorimotor function. Therefore, there appears to be an intricate relationship between pain and the impairment of sensorimotor control, suggesting that they can mutually influence each other. By studying these interactions, researchers and clinicians can develop interventions, assessments, and rehabilitation approaches that target specific aspects of sensorimotor control to improve functional outcomes in individuals with conditions such as neck pain. (Peng et al., 2021.)

As the understanding of musculoskeletal pain assessment advances, technological innovations such as wearable Inertial Measurement Units (IMUs) are emerging as valuable tools in capturing precise biomechanical data.

## 2.5 Inertial Measurement Unit

Wearable Inertial Measurement Units typically consist of three sensors: a triaxial accelerometer for linear accelerations, a triaxial gyroscope for angular velocities and a magnetometer for amplitudes and directions of the local magnetic field. Some IMUs are cost-effective, making them an accessible option for studying postural control in various settings. (Ghislieri et al., 2019; Uchitomi et al., 2022.)

Ghislieri et al. (2019) state that the lack of direct comparability between acceleration signals obtained from wearable IMUs and traditional center of pressure (COP) signals from a force platform is not inherently problematic when introducing a new wearable-based measurement. Wearable sensor data can provide additional information that is not available from traditional force platforms, complementing force platform-based posturography and offering a more comprehensive understanding of human postural control.

Emphasizing a high-frequency measurement (>100 Hz) ensures an enhanced assessment of rapid movements and postural shifts. It enables better detection of postural sway and provides detailed information about the dynamics of postural control. A higher frequency also helps reduce noise and errors in the data,

leading to more reliable and accurate results. (Ghislieri et al., 2019; Yang et al., 2016.)

Additionally, in the setup of the sensor, specific choices are often made about which components to activate or prioritize. Depending on the research question and the parameters being investigated, some studies might selectively activate certain sensors over others. For example, Vervaat et al. (2022) demonstrated the reliability of using an IMU focused on accelerometer to assess step time symmetry during stair descent after ACL reconstruction, specifically within a single day.

IMUs require complex signal processing, such as a Kalman filter, to obtain accurate orientation estimations. IMU sensors have inherent flaws like noise and bias that can affect measurement accuracy. The Kalman filter is a mathematical algorithm that compensates for these flaws, but its development and implementation require significant computational resources and expertise. (Seifert & Camacho, 2004; Uchitomi et al., 2022; Yang et al., 2016; Yi et al., 2018.)

# 3 PURPOSE AND RESEARCH QUESTIONS

The purpose of this research is to address the existing gaps in the reliable and user-friendly assessment of head-trunk coordination in individuals with chronic neck pain. Specifically, the study aims to investigate the reliability of a new accelerometer-based assessment method for physiotherapists and its correlation with individual variables such as age, duration of symptoms, and severity of pain.

This thesis places specific emphasis on sensorimotor control due to the bidirectional relationship between neck pain and sensorimotor control. On one hand, neck pain appears to have an impact on sensorimotor control. On the

other hand, compromised sensorimotor control can be a potential contributing factor to the development and persistence of neck pain. By examining and understanding the interplay between neck pain and sensorimotor control, this thesis aims to enhance our knowledge of the underlying mechanisms involved and provide valuable insights for clinical practice.

This master's thesis focuses on investigating the use of a wearable sensor, specifically an Inertial Measurement Unit (IMU), for assessing cervical movement during the HTCT in patients with chronic neck pain. The thesis also examines the influence of visual feedback provided by a mirror during the test.

Using a wearable sensor for assessing head stability during the HTCT offers several advantages over the conventional method of attaching a laser pointer to the participant's head. The use of a wearable sensor allows for precise numeric measurements of head stability, eliminating the need for visual cues from a rapidly moving dot. This overcomes the challenges associated with real-time data collection that arise with the use of a laser pointer.

By incorporating a wearable sensor into the HTCT, this thesis aims to explore whether the test can benefit from the addition of objective measurements provided by the sensor. The objective is to enhance the efficiency and reliability of evaluating head-trunk coordination, which is crucial in understanding and addressing sensorimotor control impairments in individuals with chronic neck pain.

The outcomes of this research can contribute to the development of more effective assessment methods and interventions for individuals with neck pain, ultimately improving their functional outcomes and treatment success.

This thesis explores the reliability of assessing head-trunk coordination in patients with neck pain using the tri-axial accelerometer and additionally investigates the relationships between accelerometer measurements obtained during the HTCT and parameters such as pain, disability, dizziness, and the onset of neck pain (traumatic or idiopathic) (Sterling et al., 2003; Whitney et al.,

2004). It was decided to choose the wall-facing test modality as the reference test for reliability measurements, rather than the mirror-facing test, as it aligns more closely with the protocol described in the literature (Treleaven et al., 2020).

The study will examine how strongly correlated the accelerometer parameters of the head during the HTCT are with measures of pain and disability, operationalized by the scores in the Neck Disability Index (NDI), and dizziness, operationalized by the scores in the Dizziness Handicap Inventory (DHI), in patients with neck pain of traumatic or idiopathic origin. Furthermore, the study will evaluate whether the use of visual feedback provided by a mirror during the test has any influence on head stability, as defined by accelerometer parameters.

Principal research question:

- What is the intra- and inter-session reliability of assessing head-trunk coordination in patients with neck pain using an accelerometer?

The primary focus of this master's thesis is the question of reliability. However, the research within this thesis is not limited strictly to this primary question. Additional questions are included, designed to be exploratory in nature, with the main goal of generating new ideas and questions for future research.

Secondary research questions:

- Does visual feedback by using a mirror during the test has any influence on the head stability defined by accelerometer parameters, and when compared to a no feedback condition, by facing a blank wall?
- How strongly correlated are accelerometer parameters of the head during the HTCT to measures of pain, disability and dizziness (operationalised by the scores in the NDI, and the DHI) in neck pain patients of traumatic or idiopathic origin?

## 3.1 Hypothesis and primary objective

The primary objective of this thesis is to investigate the intra- and inter-session reliability of assessing head-trunk coordination in patients with neck pain using an accelerometer. The hypothesis is that at least one or two accelerometer parameters will exhibit "moderate" intra- and inter-session reliability, as determined by an Intraclass Correlation Coefficient (ICC) with a value of ≥ 0.75 and a lower Confidence Interval (CI) of ≥ 0.5. The null hypothesis assumes that there is no significant relationship between the accelerometer parameters and their reliability in assessing head-trunk coordination in patients with neck pain. This analysis is conducted using a two-way random effects, absolute agreement, single rater/measurement approach. (Koo & Li, 2016; McGraw & Wong, 1996.)

## 3.2 Hypothesis and secondary objectives

The secondary objective of this thesis is to explore new hypotheses related to sensorimotor control, specifically focusing on head-trunk coordination. Firstly, the influence of visual afferents on head-trunk coordination is investigated. Secondly, the relationships between head-trunk coordination and individual parameters such as NDI, DHI, and the onset of pain are examined. The corresponding hypotheses are as follows:

- Providing visual feedback using a mirror during the HTCT leads to a reduction in head movement, as indicated by accelerometer parameters. The null hypothesis is that there is no difference facing a wall or a mirror.
- At least one or two accelerometer parameters exhibit "moderately strong" correlations (correlation coefficient ≥ 0.6) with self-reported measures of pain, disability, or dizziness in neck pain patients, based on previous research findings (Ernst et al., 2015). It is important to note that the interpretation of the correlation coefficient is not standardized in the literature, and categorizing its strength can be somewhat arbitrary (Akoglu, 2018; Chan, 2003). The null hypothesis assumes that there is

no moderately strong correlation (≥ 0.6) between the accelerometer parameters and the self-reported measures in terms of pain, disability, or dizziness in patients with neck pain.

# 4 MATERIAL AND METHODS

## 4.1 Design

The cross-sectional study design is an effective approach for describing various parameters within a specific population at a specific point in time. This design is particularly useful for assessing test-retest reliability and generating hypotheses based on observational data. By collecting data from a diverse population that meets the defined criteria, researchers can gain insights into the relationships between different variables and explore potential hypotheses. However, a major limitation of this design is the risk of erroneously assuming that a correlation implies a causal relationship. (Altman, 1999; Carlson & Morrison, 2009.)

This design was chosen for this study because it allows for the assessment of the reliability of the procedure with the repetition of measurement. It is also valuable in investigating the relationship between accelerometer parameters and individual variables, as well as the influence of visual feedback.

## 4.2 Project population, inclusion and exclusion criteria

Nineteen participants were determined to be necessary to achieve an expected ICC coefficient of ≥0.75 between accelerometer parameters and self-reported variables, considering a two-sided alpha of 0.05, and a beta of 0.8 (Hulley, 2013).

Sex, age, onset (traumatic, idiopathic), and scores on the NDI and DHI needed to be documented (Franov et al., 2022). The NDI is a reliable and valid questionnaire completed by the patients, which report the self-perceived impact of neck pain in their daily life (Castellini et al., 2022; MacDermid et al., 2009; Vernon & Mior, 1991). This questionnaire has been translated and reported to be reliable and valid in French (Wlodyka-Demaille et al., 2002). The DHI assesses the self-perceived handicap related to dizziness and was also translated in French (Jacobson & Newman, 1990; Nyabenda et al., 2004).

The inclusion criteria were:

- neck pain ≥3 months
- NDI >5 points = >10%, expressing at least mild pain and disability
- at least 45 degrees of cervical spine rotation range of motion in standing position to be able to perform the procedure (as 45 degrees trunk rotation is required while keeping the head still)
- given informed consent as documented by signature
- ≥18 years old
- able to communicate in French (verbal and written)

The exclusion criteria were:

- known vestibular disorder
- known inner ear pathology
- known central nervous system pathology
- previous spinal surgery
- psychiatric disorders

### 4.3 Recruitment, screening and informed consent procedure

Participants were recruited at a private physiotherapy practice, "Physio Barillette," in Nyon, Switzerland, during daily clinical practice. Information about the study was also disseminated through flyers and posters displayed in the waiting room.

Interested individuals who expressed their willingness to participate were provided with a study information sheet and a consent form. The information sheet contained detailed information about the study, including its nature, purpose, procedures, expected duration, potential risks and benefits, and any discomfort it may entail.

To ensure that participants could make an informed decision, an interview was conducted by the project leader to provide additional information and address any questions. Participants were informed that their participation was voluntary and that they could withdraw from the study at any time without affecting their subsequent physiotherapeutic assistance and treatment. A minimum of 24 hours was given for participants to decide whether to participate and to ask any questions they had. After this period, participants who still wished to participate underwent a formal eligibility screening conducted by the project leader.

Before any study procedures were carried out, formal consent from each participant was obtained using the approved consent form. The project leader and the participant both signed and dated the consent form simultaneously. A copy of the signed informed consent form was provided to the participant, and the original consent form was retained as part of the study records. The informed consent process was documented in the patient file, and any deviations from the protocol described were explained. The screening process to assess eligibility criteria, including measuring at least 45 degrees of cervical rotation and scoring on the NDI, was conducted after obtaining informed consent.

Participating in this project could directly benefit the patients by identifying any impairment in head-trunk coordination and facilitating the adaptation of individualized physiotherapeutic interventions. However, there was no financial compensation for participating in this study.

## 4.4 Study procedures

In the study procedures, the participants completed the NDI and DHI questionnaires, and the scores were calculated after data collection was complete. The research project was based on the protocol HTCT. Figure 4 shows the procedure being performed, but instead of the laser pointer, an accelerometer was placed on the participant's head (Figure 5) using self-gripping strips. For this master's thesis, the decision was made to use an open-source IMU (Movesense, 2023) and its triaxial accelerometer, while excluding the integration of the gyroscope and magnetometer. Based on the recommendation by Ghislieri et al. (2019) to operate the IMU at a frequency of 100 Hz, the setup was configured to collect data at a frequency of 104 Hz (Figure 6).

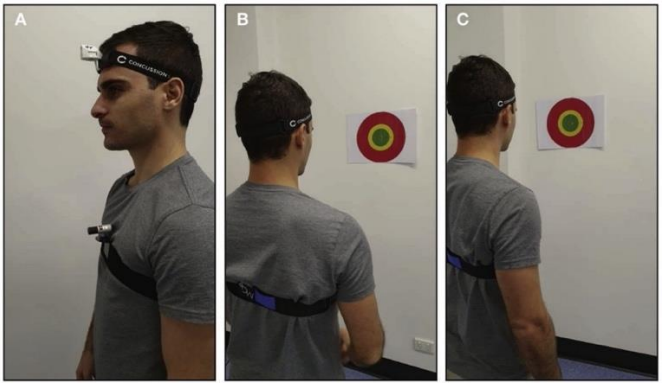



Figure 4. Head Trunk Coordination Test: (A) Starting position standing, (B) Head still, left rotation of the trunk, (C) Head still, right rotation of the trunk. Picture adapted from Treleaven et al. (2020).

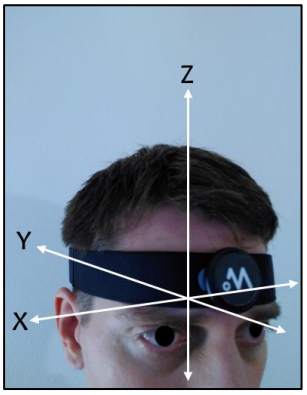



Figure 5. Placement of the accelerometer on the head and representation of measurement axes.

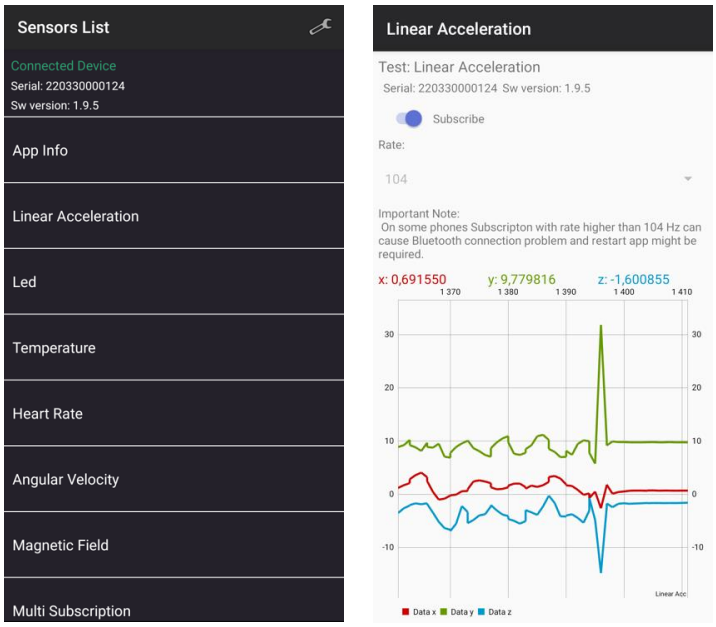



Figure 6. Movesense Showcase App setup (Movesense, 2023).

The test was conducted with participants standing, as previous research found no significant difference between standing and sitting positions and standing allowed for greater trunk mobility in relation to the head. Verbal instructions were given to the participants: "Rotate the chest as far as possible to either the left or right direction and then return to the start position. Keep the head as still as possible" (Treleaven et al., 2020).

The procedure was repeated after a two-minute break, and then again after a period of 1-7 days, as shown in Table 1. This repetition was necessary to establish the intra-and inter-session reliability of the accelerometer.

Conducting a comprehensive study that includes the integration of all three sensors (accelerometer, gyroscope, and magnetometer) would require more time and resources. By narrowing the scope to accelerometer measurement alone, the thesis can delve deeper into the specific aspects of head-trunk coordination using a more focused approach within the available timeframe. Reducing the scope also allows for a more detailed examination of a specific dimension and the ability to test it as such, while acknowledging that it may impact the quality of the measurements.

Table 1. Summary listing procedures and timelines

| Schedule in days | Duration in minutes | Intervention |
|---|---|---|
| >-1 | 30-60 | Oral and written patient information |
| 0 | 30 | Written consent<br>Screening:<br>Inclusion-/exclusion criteria<br>Participant eligibility confirmation |
| | | DHI questionnaire<br>General information (sex, age)<br>Pain Numeric Rating Scale 0-10 (NRS) 1<br>Dizziness NRS 1 |
| | | HTCT 1 (with and without mirror) |
| | | Pain NRS 2<br>Dizziness NRS 2 |
| | | Rest 2 minutes |
| | | HTCT 2 (with and without mirror, same order) |
| | | Pain NRS 3<br>Dizziness NRS 3 |
| +1-7 | 20 | Pain NRS 4<br>Dizziness NRS 4 |
| | | HTCT 3 (with and without mirror, same order) |
| | | Pain NRS 5<br>Dizziness NRS 5 |

By focusing the analysis on the X axis, this study aims to capture and understand the specific dynamics of the horizontal accelerations of the head to the left and right that occur during the HTCT task. The choice to focus on the X axis is driven by its correspondence to the horizontal rotational movement observed during the HTCT task. By analysing the data from the X axis, it enables a comparison between the linear accelerations measured in this study and the rotational movements reported in existing published studies. Additionally, the X axis serves as a parameter which can be cautiously related to the lateral deviation of the laser projection on the target.

Participants performed the test once with a mirror placed one meter away in front of them and once without the mirror. The order of testing conditions, with or without the mirror, was determined by tossing a coin. The sensor was connected to a smartphone via Bluetooth, and the Movesense Showcase application was used. The accelerometer data was exported after each participant

using a wire connection to a dedicated secure computer and saved in a secured file.

The specific accelerometer parameters that were derived from the raw data include mean accelerations, mean of accelerations in absolute value, sum of accelerations, variance.

The entire procedure was conducted at the Physio Barillette premises, a private physiotherapy practice, at route des Tattes d'Oie 99, 1260 Nyon, Switzerland.

## 4.5 Withdrawal and discontinuation

If the test procedure encountered an unexpected adverse event, such as significant pain or dizziness, the procedure would be discontinued immediately, and the event would thoroughly documented. However, based on previous studies and the nature of the procedure, it was regarded as very unlikely for adverse or serious adverse events to occur.

In the event that a participant decided to withdraw prematurely or withdrew their informed consent, the data that had already been obtained were still used for analysis, unless the participant explicitly requested the complete deletion of all their data from the study.

## 4.6 Statistical analysis plan

The sample size for the study was calculated based on a two-tailed significance level (α) of 0.05 and a power (1-β) of 0.8. These values are commonly used in research studies to achieve a balance between precision and the number of participants required (Hulley, 2013). The calculation was performed twice: once for assessing reliability using an expected Intraclass Correlation Coefficient (ICC) of 0.75 (Sharma et al., 2019), and once for examining

correlation with an expected correlation coefficient of 0.6 (Akoglu, 2018; Chan, 2003).

The figure 7 illustrates the use of the pwr package in R, which was employed to calculate the required sample size (Kabacoff, 2015). The calculation was performed to determine the appropriate sample size needed, and it resulted in a sample size of 19 participants.

```
> library(pwr)
> pwr.r.test(r=0.75,sig.level = 0.05, power = 0.8,alternative = "two.sided")

     approximate correlation power calculation (arctangh transformation)

               n = 10.72495
               r = 0.75
       sig.level = 0.05
           power = 0.8
     alternative = two.sided

> pwr.r.test(r=0.6,sig.level = 0.05, power = 0.8,alternative = "two.sided")

     approximate correlation power calculation (arctangh transformation)

               n = 18.63858
               r = 0.6
       sig.level = 0.05
           power = 0.8
     alternative = two.sided
```

Figure 7. Sample size calculation for reliability and for correlation analysis.

Standard Error of Measurement (SEM) was calculated with a reliability coefficient of 0.8 to assess the level of error in individual measurements. The formula is as follows: SEM <- sqrt(var_scores * (1 - reliability)). These measures provide a comprehensive assessment of reliability. (Altman, 1999; Koo & Li, 2016; Stratford & Goldsmith, 1997.)

For assessing correlations, different tests were employed depending on the variables being analysed. Non-parametric tests, including the Wilcoxon test and the Spearman correlation, were selected. The assumption of a normal distribution in the data was not required or expected, eliminating the need to assess the normality of the distribution. (Altman, 1999.)

The Wilcoxon signed rank sum test was used to compare continuous variables between two conditions, such as NDI and DHI subgroups, or the onset of pain. It provides a p-value, which indicates the probability of observing the reported difference in the outcomes by chance. A p-value below the predetermined significance level (in this case, 0.05) suggests a significant difference between the two conditions. Additionally, a 95% CI was calculated for the mean difference, providing a range of values within which the true mean difference is likely to fall. If the CI does not include zero, it suggests a significant difference between the conditions. By analysing the p-value and CI, the statistical significance of the condition on the outcomes is determined. For other parameters, the Spearman correlation coefficient was calculated, to assess the strength and direction of the relationship between two ordinal or continuous variables. (Akoglu, 2018; Altman, 1999; Chan, 2003.)

All statistical analyses and graphs were conducted using RStudio version 2023.03.0 (RStudio Team, 2023), an integrated development environment for R version 4.2.3 (R Core Team, 2023).

## 4.7 Handling of missing data

The experimentation involved two sessions, and great emphasis was placed on the importance of adhering to the timeline during the information interview to minimize the risk of dropouts. If dropouts had occurred, the reasons would have been thoroughly documented. Additional participants would have been recruited in the event of dropouts or invalid data to ensure a total of 19 participants with complete data. (Shih, 2002.)

## 4.8 Regulatory aspects and safety

This research project was conducted in accordance with the protocol, the Declaration of Helsinki, the principles of Good Clinical Practice, the Human Research Act (HRA, 2011) and the Human Research Ordinance (HRO, 2013) as

well as other locally relevant regulations. The Project Leader acknowledged his responsibilities as both the Project Leader and the Sponsor.

There were no risks regarding the procedures, as these tests are frequently used during physiotherapy care of neck pain patients. Therefore, the risk category of the study was considered as “A” according to Clinical Trials Ordinance, Art. 61 (ClinO, 2013).

If, during the research project, circumstances had arisen which could jeopardise the safety or health of the participants or lead to a disproportionate relationship between the risks and burdens and the benefits, all the measures required to ensure protection would have been taken without delay. The Ethics Committee would have been notified via BASEC of these measures and of the circumstances necessitating them within 7 days.

If a serious event occurs, the research project would have been interrupted and the Ethics Committee notified on the circumstances via BASEC within 7 days according to HRO Art. 21 (2013). All study data are archived for 10 years after study termination.

In the event of project-related damage or injuries, Physio Barillette Sarl would have been liable, except for damages that are only slight and temporary, and for which the extent of the damage was no greater than would be expected in the current state of scientific knowledge (Art. 12 HRO, 2013). No additional insurance package was needed for a project from risk category “A”, accordingly any damages of participants are covered by the insurance of Physio Barillette Sarl. However, an extension of the professional liability insurance was obtained specifically for the study.

## 4.9 Ethical considerations

This study contributes to a better understanding of a problem (head-trunk coordination in case of chronic neck pain). The study procedures were not

restrictive for the participants and the benefit of better identifying a potential coordination deficit is relevant. Participation in the study was voluntary and the right of withdrawal guaranteed.

Participants incurred no risks by the study procedures beyond, there was a minimal risk of the procedure reproducing pain or dizziness. When defining this research protocol, the risk of these symptoms lasting more than a few seconds or minutes was considered very low. Pain and dizziness were monitored throughout the procedure to identify potential issues. Participants could obtain information which could potentially help guiding further treatments. On a broader scale, neck pain is a major challenge that needs to be better understood in order to limit its financial and societal cost.

Ethical clearance was granted by Swissethics (Commission cantonale vaudoise d'éthique de la recherche sur l'être humain), reference number CER-VD 2022-01205 (Appendix 1).

### 4.10 Quality control

The experimentation was carried out following rigorous training to ensure the highest possible quality. For quality assurance the Ethics Committee may have visited the research site. Direct access to the source data and all project related files and documents would have been granted on such occasions.

### 4.11 Data management

Study data was recorded using an electronic Case Report Form (eCRF). Data was always available to the authorities of the ethics committee. For each participant an eCRF was maintained. eCRFs did not identify participants by their name or birth date but provided appropriate coded identification.

To ensure participant confidentiality, a coding system was implemented. This coding system replaced all identifying information (such as names and birth

dates) with a unique code. After the information session, a period of 24 hours and the signing of the consent form, a specific coding key was determined for each potential participant. The coding format used for participants was "MTXX," where "MT" represents "Master Thesis," and the numbers XX were assigned based on the order of participant screening. For example, the first participant screened would be assigned the code MT01, and so on.

A register of codes and information identifying participants was created on the protected and encrypted server of Physio Barillette Sarl, hosted in Switzerland. Access to this register was restricted by a password, which was known only to the project leader responsible for participant communication. Without the code, it was not possible to link the data to one person, which remains within the institution until the end of the study (submission and approval of the thesis) and is destroyed afterwards. Only the project leader could consult the data in an uncoded form, and this, exclusively to be able to carry out tasks necessary for the conduct of the study, bound by professional secrecy. Participants have the right to consult their own data.

A smartphone, locked with a PIN code, was used to run an application which exports acceleration data to a .csv file, that is named according to each participant's code, repetition (Head-trunk coordination test 1 to 6) and date. No name or personal information is kept in the .csv file, just accelerometer data (timestamp and values) in the file and the exact time and nature of test in the title (MTXXTest0X_Date.csv). The exact time of each measurement, as well as identification number of each participant, was recorded in the eCRF.

Source data:

- eCRF (including NDI, DHI, NRS scores for pain and dizziness)
- Csv files (report of accelerometer data)

Csv files were transferred to a computer for analysis via wire. These reports of accelerometer data were added to the eCRF. The data is stored on a secure and encrypted computer belonging to Physio Barillette Sarl. Regular printouts of the eCRF table were made, which were dated and signed and kept

according to the deadlines indicated in the protocol. The printouts were stored in the Physio Barillette Sarl premises, in a secure locker, locked and accessible only to the project leader.

### 4.12 Confidentiality and coding

Project data were handled with uttermost discretion and were only accessible to authorized personnel who required the data to fulfil their duties within the scope of the research project. On the eCRFs and other project specific documents, participants were only identified by a unique participant number. The project leader, who is a physiotherapist at Physio Barillette Sarl, was responsible for the screening and measurements. He is the only person who have access to the register of identification codes on a dedicated computer also protected with a code. The access to the register is also protected by code, known only to the project leader. The computer is saved on an encrypted server, belonging to Physio Barillette Sarl, located in Switzerland.

### 4.13 Retention and destruction of study data

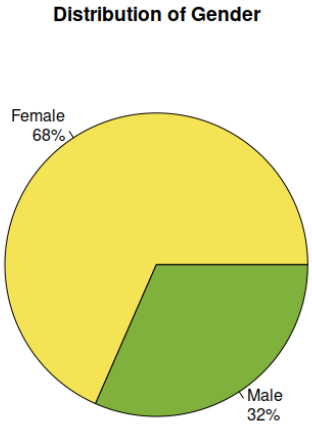
All study data are archived for 10 years after study termination or premature termination of the study. There will be no further use of the study data. When the data collection was sufficient (19 complete datasets), recruitment was terminated. The project leader contacted the participants to know if they want their own data.

## 5 RESULTS

The data collection was conducted between December 6, 2022, and February 3, 2023. No dropouts were reported during the study. The table 2 displays the demographic and clinical characteristics of the participants and the proportion of recruited men and women whose data were analysed is illustrated.

Table 2. Demographics

| Clinical characteristics (subjects n=19) | Mean | SD |
|---|---|---|
| Age (years) | 52.95 | 17.76 |
| Sex (% males) | 31.58 | NA |
| Onset (% traumatic) | 42.11 | NA |
| NDI (%) | 23.16 | 11.08 |
| DHI (%) | 15.84 | 15.35 |




Figures 8 to 12 depict the composition of the recruited subjects. Most of the subjects experience mild pain and mild dizziness (table 2 and 3).

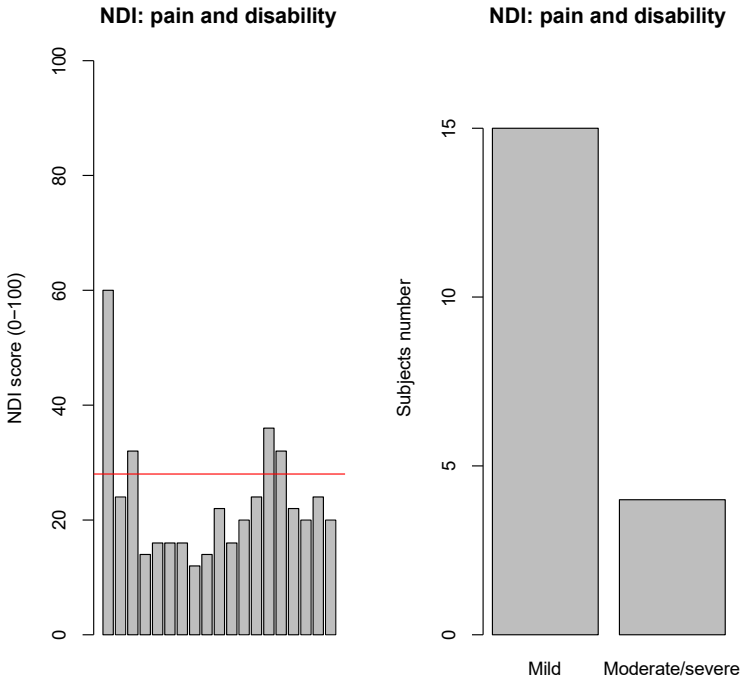



Figure 8. Subject-specific NDI scores and subgroups repartition.

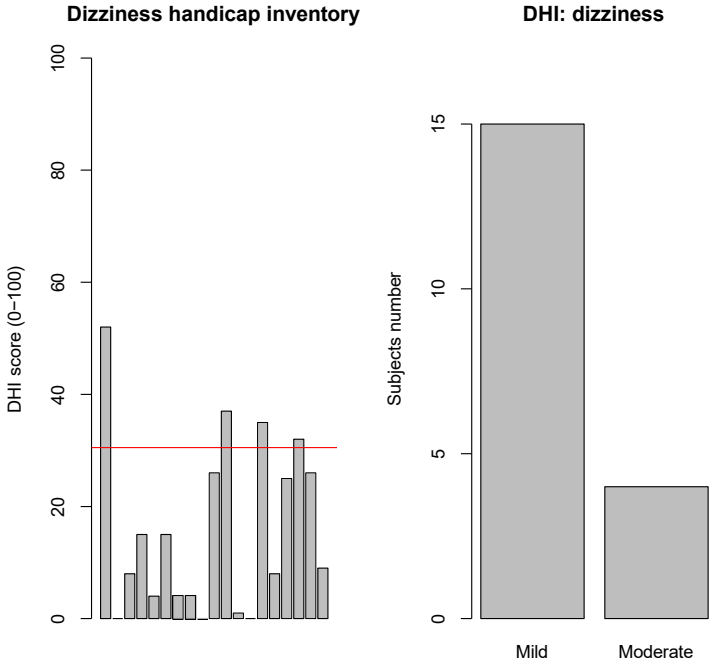



Figure 9. Subject-specific DHI scores and subgroups repartition.

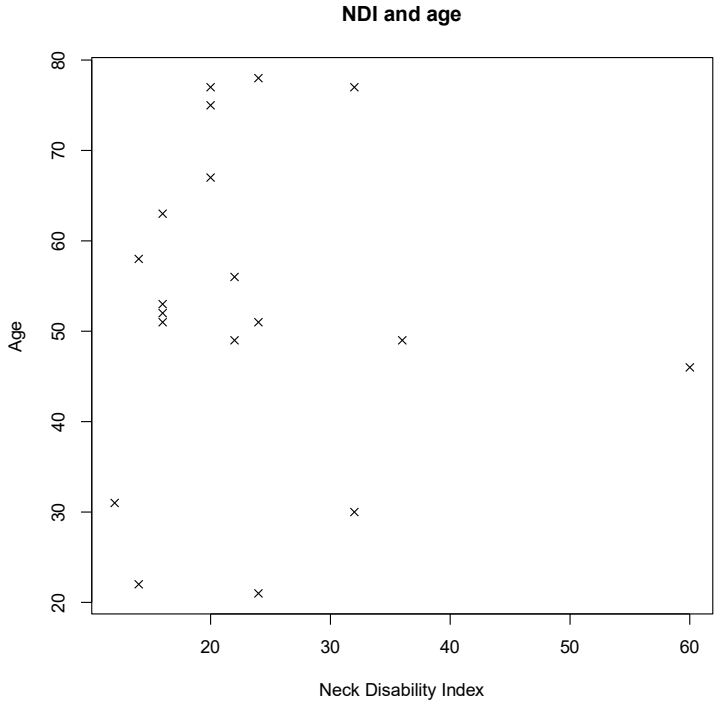



Figure 10. Relationship between subjects' age and NDI score.

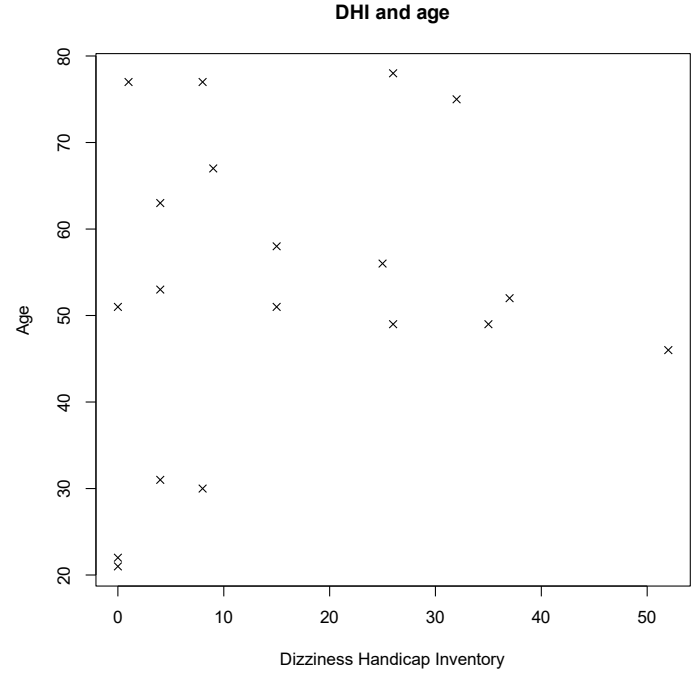



Figure 11. Relationship between subjects' age and DHI score.

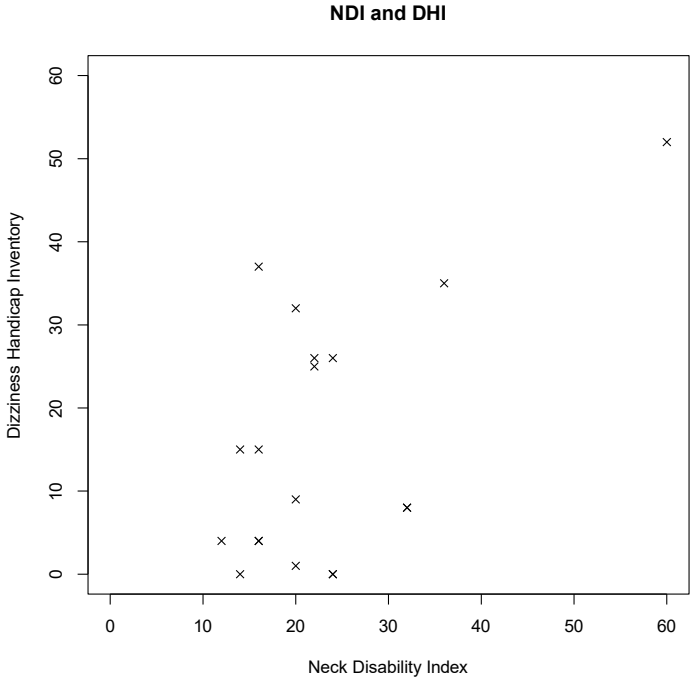



Figure 12. Relationship between NDI and DHI scores.

Table 3. Subjects subgroups (Sterling et al., 2003; Whitney et al., 2004)

| | Subgroups | | |
|---|---|---|---|
| Onset of pain | Traumatic | Idiopathic | |
| NDI | 10-28 pts<br>mild pain and disability | >30 pts<br>moderate/severe pain and disability | |
| DHI | 0-30 pts<br>mild | 31-60 pts<br>moderate | 61-100 pts<br>severe |

The perceived intensity of pain or dizziness throughout the testing protocol is depicted in figures 13 and 14. p1 was completed before the first test, p2 between the first and the second, and p3 at the end. p4 and p5 were completed on the second test day, within a week, before and after the test. The same principle applies to the measurements of dizziness (d1-5).

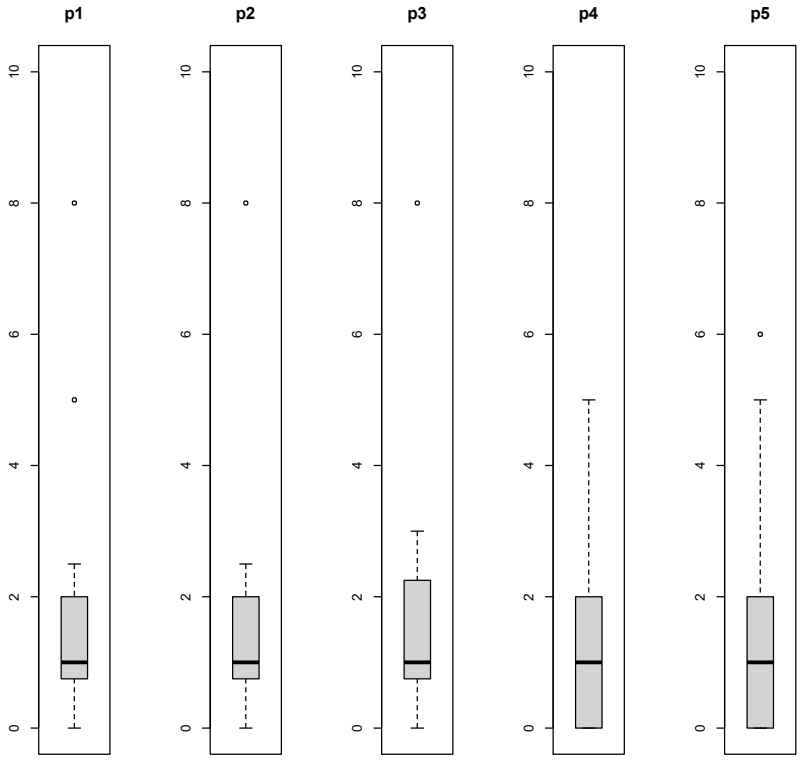



Figure 13. Described pain intensity (NRS): p1-3 (Day 1), p4-5 (Day 2).

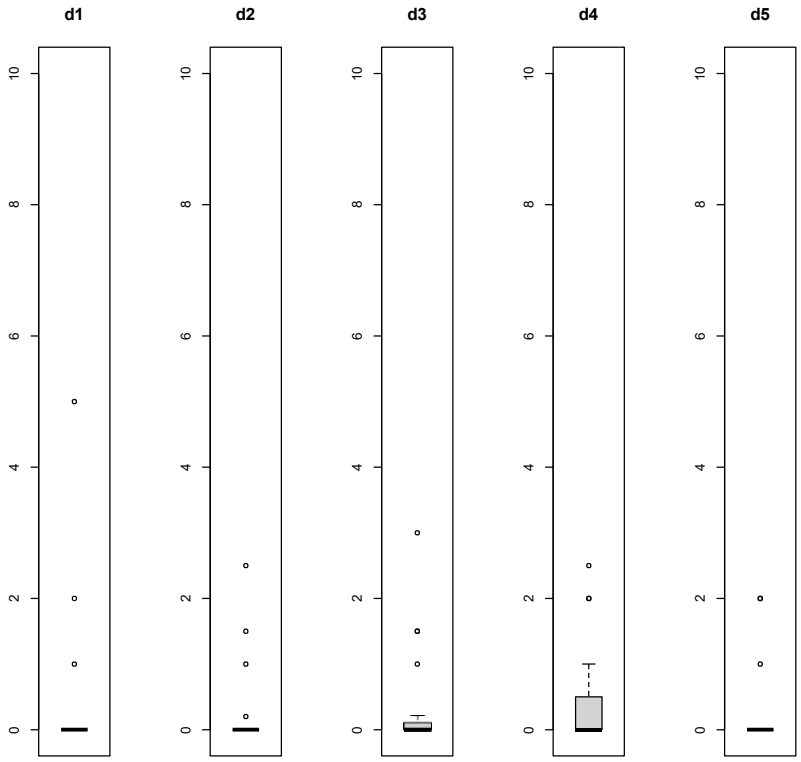



Figure 14. Described dizziness intensity (NRS): d1-3 (Day 1), d4-5 (Day 2).

## 5.1 Accelerometer parameters

Tables 4 and 5 display the mean and Standard Deviation (SD) of the HTCT outcomes when performed facing the wall and facing the mirror. The tables provide a summary of the results for the two conditions, allowing for a comparison of the mean values and variability between the wall and mirror conditions in the HTCT.

The X mean refers to the average of accelerations measured on the X axis, which corresponds to the frontal plane (left and right movements). There is a risk that positive and negative accelerations cancel each other out, affecting the mean and decreasing the interest of this indicator. To address this issue, the mean of the absolute values of the X axis is also considered.

The X sum represents the total sum of accelerations. The advantage of this measure is its ability to identify “hidden” coordination problems. Various

strategies can be employed to perform the HTCT. For example, a subject may choose to take more time and move slower, potentially resulting in reduced head movements and better results (Treleaven et al., 2019). By summing the accelerations, it becomes possible to highlight lower accelerations that occur over a longer period of time.

The X variance reflects the variability of accelerations and may be associated with chaotic sensorimotor control. It can be considered somewhat comparable to the jerk index (Sjölander et al., 2008).

Table 4. Accelerometer parameters while facing the wall.

| Variable | HTCT1 mean | HTCT1 SD | HTCT2 mean | HTCT2 SD | HTCT3 mean | HTCT3 SD |
|---|---|---|---|---|---|---|
| X mean | -0.470 | 0.471 | -0.444 | 0.432 | -0.587 | 0.388 |
| X abs mean | 0.653 | 0.316 | 0.638 | 0.313 | 0.663 | 0.323 |
| X sum | 62.018 | 34.159 | 64.508 | 45.981 | 62.968 | 38.846 |
| X variance | 0.201 | 0.217 | 0.297 | 0.270 | 0.246 | 0.213 |

Table 5. Accelerometer parameters while facing the mirror.

| Variable | HTCT1 mean | HTCT1 SD | HTCT2 mean | HTCT2 SD | HTCT3 mean | HTCT3 SD |
|---|---|---|---|---|---|---|
| X mean | -0.472 | 0.396 | -0.470 | 0.396 | -0.530 | 0.337 |
| X abs mean | 0.584 | 0.304 | 0.631 | 0.307 | 0.613 | 0.292 |
| X sum | 58.053 | 39.289 | 62.647 | 43.845 | 60.759 | 43.148 |
| X variance | 0.203 | 0.173 | 0.323 | 0.311 | 0.258 | 0.275 |

## 5.2 Intra- and inter-session reliability

To assess the reliability of the measurements, both intra-session and inter-session reliability analyses are conducted. Table 6 presents the intra-session reliability for all the measured parameters. These results give insights into the consistency of measurements within the same testing session.

Table 6. Intra-session reliability.

| Intra-session W1-W2 | ICC (95%-CI) | SEm (rel=0.8) |
|---|---|---|
| X mean | 0.84 ( 0.63 - 0.93 ) | 0.03 |
| X (absolute values) mean | 0.9 ( 0.76 - 0.96 ) | 0.01 |
| X sum | 0.87 ( 0.69 - 0.95 ) | 2.11 |
| X variance | 0.63 ( 0.25 - 0.84 ) | 0.03 |

For a longer-term perspective on measurement stability, inter-session reliability is also analysed. This gives an overview of how consistent the measurements are over different testing days within a week. The standard error of measurement is also presented to provide an idea of the precision of the measurements. These details are depicted in table 7.

Table 7. Inter-session reliability and standard error of measurement

| Inter-session W1-W3 | ICC (95%-CI) | SEm (rel=0.8) |
|---|---|---|
| X mean | 0.65 ( 0.3 - 0.85 ) | 0.06 |
| X (absolute values) mean | 0.62 ( 0.24 - 0.84 ) | 0.05 |
| X sum | 0.73 ( 0.43 - 0.89 ) | 4.26 |
| X variance | 0.49 ( 0.06 - 0.77 ) | 0.04 |

## 5.3 Pain and dizziness correlations

The relationship between the variables and the NDI or DHI, is explored through correlation tables. Table 8 presents the correlation coefficients between the variables and NDI, while table 9 details the same with DHI.

Table 8. Correlation of accelerometer parameters with NDI.

| Correlation with NDI | Spearman's rank rho | p-value |
|---|---|---|
| X mean | 0.136 | 0.578 |
| X (absolute values) mean | 0.113 | 0.644 |
| X sum | -0.092 | 0.708 |
| X variance | 0.465 | 0.045 |

Table 9. Correlation of accelerometer parameters with DHI.

| Correlation with DHI | Spearman's rank rho | p-value |
|---|---|---|
| X mean | 0.457 | 0.049 |
| X (absolute values) mean | -0.243 | 0.316 |
| X sum | -0.301 | 0.211 |
| X variance | 0.455 | 0.05 |

According to table 10, there are no significant differences observed between patients with traumatic neck pain and those with idiopathic neck pain.

Table 10. Correlation with onset of pain (traumatic/idiopathic)

| Correlation with onset of pain | Wilcoxon non paired test p-value |
|---|---|
| X mean | 0.545 |
| X (absolute values) mean | 0.272 |
| X sum | 0.968 |
| X variance | 0.968 |

The results suggest also that there is no strong evidence of a relationship between the mean pain score (mean of the five self-reported pain evaluations) or p1 (the pain before the first test) and the accelerometer parameters in this study (tables 11 and 12).

Table 11. Correlation of accelerometer parameters with mean pain.

| Correlation with mean pain | Spearman's rank rho | p-value |
|---|---|---|
| X mean | 0.055 | 0.825 |
| X (absolute values) mean | -0.113 | 0.644 |
| X sum | 0.015 | 0.952 |
| X variance | 0.076 | 0.758 |

Table 12. Correlation of accelerometer parameters with p1.

| Correlation with p1 | Spearman's rank rho | p-value |
|---|---|---|
| X mean | -0.267 | 0.269 |
| X (absolute values) mean | 0.142 | 0.562 |
| X sum | 0.121 | 0.621 |
| X variance | -0.017 | 0.945 |

## 5.4 Visual feedback influence

The hypothesis stated that providing visual feedback using a mirror during the HTCT would lead to a reduction in head movement, as indicated by accelerometer parameters. Table 13 provides valuable information regarding the observed differences between the wall and mirror conditions. For X mean, the non-significant p-value of 0.86 suggests that there is no substantial difference between the wall and mirror conditions. This is further supported by the 95% confidence interval, which includes zero.

Regarding X sum, the p-value of 0.049 indicates a significant difference between the wall and mirror conditions. However, it is important to note that the 95% CI includes zero. The SEM of 2.11 (table 6) reflects moderate precision in estimating the mean difference, indicating a level of variability in the measurements. For X variance, the non-significant p-value of 0.953 suggests that there is no meaningful difference between the wall and mirror conditions. This is supported by the 95% confidence interval, which includes zero.

Table 13. Comparison of the results based on visual feedback.

| Variable | Wall | Mirror | Wilcoxon paired test p-value | 95% CI for mean difference |
|---|---|---|---|---|
| X mean | -0.470 | -0.472 | 0.860 | -0.074 - 0.079 |
| X abs mean | 0.653 | 0.584 | 0.020 | 0.001 - 0.137 |
| X sum | 62.018 | 58.053 | 0.049 | -2.869 - 10.8 |
| X variance | 0.201 | 0.203 | 0.953 | -0.103 - 0.1 |

In contrast, for X abs mean, the significant p-value of 0.02 indicates a significant difference between the wall and mirror conditions. The 95% CI suggests that the mirror condition tends to have a lower absolute mean compared to the

wall condition. The small SEM of 0.01 enhances the precision of this mean difference estimation (table 6).

# 6 DISCUSSION

## 6.1 Demographics

According to the cross-sectional design, participants do not need to be matched. This observation of a higher proportion of women in the study sample could potentially be associated with the higher prevalence of the condition among women, as reported by Hoy et al. (2014) with a prevalence of 5.8% in women and 4% in men. However, it is important to acknowledge that other factors related to the recruitment process may have also contributed to this gender imbalance and should not be overlooked. It is important to note that this imbalance was not intentional or manipulated.

## 6.2 Clinical observations

It can be observed that age and NDI and DHI scores do not appear to be related. The analysis was not further explored as it was not the focus of this study.

The findings suggest that there was no substantial aggravation in the perceived intensity of pain or dizziness following the testing protocol (figures 13 and 14). Although there is observed variation in the distribution of pretest values on day 2 (p4 and d4), with a wider interquartile range, the overall median values did not show significant changes. These findings indicate that the testing protocol did not lead to a notable increase in pain or dizziness intensity among the participants.

These results are consistent with expectations, as the testing protocol is a commonly used procedure and does not appear to pose any significant risks to the patients. It is important to highlight that there were no dropouts or adverse events reported during the data collection phase, emphasizing the overall safety of the protocol. Moreover, the lack of significant changes in pain and dizziness intensity supports these findings and suggests that the protocol was well-tolerated by the participants.

### 6.3 Intra- and inter-session reliability

The intra-session reliability demonstrates at least a moderate to good level, except for the variance of X (table 6). According to the criteria outlined in the statistical analysis plan, the ICC was expected to meet or exceed a threshold of 0.75. Additionally, the lower limit of the confidence interval associated with the ICC was required to have values greater than 0.5. This criterion ensures a sufficiently high level of confidence in the reliability estimate, indicating that the ICC is significantly different from zero and that the observed agreement is unlikely to be due to chance alone. Meeting these criteria provides evidence of strong agreement or reliability among the measurements or ratings being evaluated. It suggests that the observed variability can be attributed to true differences between the objects or individuals being measured, rather than measurement error or random fluctuations. (Koo & Li, 2016.)

The SEMs should be interpreted in conjunction with the corresponding mean values (tables 4 and 5). It is logical to observe a greater SEM for X sum, but it is important to consider the overall pattern and not draw conclusions based solely on SEM values.

The inter-session reliability is lower than the intra-session reliability but still reasonable (table 7), with the X sum approaching the defined criteria. The lower inter-session reliability may be attributed to the variability in subjects' positions and movements over time. It is observed that individuals with idiopathic neck pain exhibit greater variability in vertical perception, a component

of cervical proprioception, compared to healthy individuals (Treleaven & Takasaki, 2015). Furthermore, individuals with neck pain have shown higher variability in cervical force generation (Li et al., 2019). These factors could contribute to the lower inter-session reliability observed in the study.

This leads to the hypothesis that testing the reproducibility of the same movement among patients with sensorimotor deficits could provide valuable insights into the variability of their movement patterns. By conducting repeated tests and assessing the consistency of movement, clinicians could gain information about the stability and control of sensorimotor function. This approach may serve as an indicator of underlying deficits and help guide interventions for patients with movement-related disorders. Further research is needed to explore the relationship between movement reproducibility and sensorimotor deficits in different patient populations.

It is possible that controlling the starting posture could improve reliability. The Neck Holding Position (NHP) is typically assessed while a patient stands in front of a mirror, commonly referred to as the mirror-guided head position (Billiaert et al., 2021). In a study conducted by Al-Yassary et al. (2022) involving young healthy individuals, the reliability of self-balanced head position was found good to excellent, with correlation coefficients ranging from 0.78 to 0.96. However, the reliability of mirror-guided head position varied from poor to excellent, with correlation coefficients ranging from 0.49 to 0.92, depending on the axis (the horizontal rotation showing the lowest reliability).

Billiaert et al. (2021) also reported no significant relationship in NHP between two sessions in the horizontal rotation (Pearson correlation $r$ = .08, $p$=.78). It is important to note that positions on rotational axes cannot be directly compared to linear accelerations. Nevertheless, these studies indicate that the inter-session reliability of head position is not consistent, even among young healthy people.

Furthermore, the researchers observed that natural head posture exhibited variations over a five-minute period, but these variations were reduced when

participants self-corrected using a mirror (Al-Yassary et al., 2022). It appears that individuals with neck pain may exhibit greater movement variability and less adaptability to a given task compared to healthy subjects due to impaired sensorimotor control (Hage et al., 2021). The poor ability to reproduce a movement in the short or long term may contribute to the lower reliability observed in the study.

These findings suggest that the modified HTCT can be used with caution to document a patient's evolution. Its purpose is not to serve as a diagnostic test. The lower inter-session reliability underscores the need for careful interpretation when using them to track changes in a patient's condition over time. However, these results also highlight the potential significance of the patient's variability itself as a clinical sign. Higher variability in the measurements may indicate reduced stability or control in sensorimotor function, potentially associated with irrelevant movements patterns. Further investigation is necessary to fully understand the implications and clinical significance of this variability and its relationship to other parameters.

### 6.4 Pain and dizziness correlations

The correlation analysis did not demonstrate any significant relationship between the NDI or the DHI score and the accelerometer parameters (tables 8 and 9). While the overall correlation was weaker than hypothesized (rho expected value of 0.6), it is interesting that the x-variance for NDI was found to be below 0.05. This suggests that there might be a statistically significant relationship, even if the correlation strength did not meet the predefined criteria. Further research with a larger sample size or more refined methodology could potentially find a stronger correlation.

### 6.5 Visual feedback influence

For parameters like X mean and X variance, the non-significant p-values (0.86 and 0.953, respectively) coupled with a 95% confidence interval that includes

zero, suggest that the presence of the mirror did not have a meaningful impact on head movements. This counterintuitive result could possibly be due to various factors such as individual differences in interpreting and utilizing visual feedback or perhaps the parameters measured were not sensitive enough to detect subtle differences induced by visual feedback.

However, the significant p-value for X abs mean (0.02) and a narrow Standard Error of Measurement (SEM) of 0.01 does support the hypothesis. It indicates that this particular parameter was sensitive enough to detect a significant improvement in accuracy when subjects performed the task with the mirror compared to the wall condition (table 15). This suggests with caution that visual feedback provided by the mirror does have an influence on an accelerometer parameter, leading to a reduction in head movements during the task. These results support the hypothesis that the addition of a mirror can enhance head stability and coordination.

Interestingly, while X sum has a borderline significant p-value (0.049), its 95% confidence interval included zero, making it less clear if the difference is practically significant. The moderate SEM of 2.11 indicates a level of variability in the measurements that should be considered when interpreting these findings.

In summary, the influence of visual feedback on head-trunk coordination appears to be parameter-specific. It is possible that the wall was not the best choice for eliminating visual feedback, and that subjects may have been able to orient themselves using the wall's texture, for example. For future research, it would be valuable to explore the effect of removing visual feedback altogether by using a mask or blindfold over the eyes in addition to reproducing the experiment to confirm the findings. This approach could provide valuable insights into the role of visual feedback in sensorimotor control and potentially uncover any additional factors influencing performance.

## 6.6 Limitations

It is important to acknowledge some limitations of the study.

Firstly, the decision to prioritize the analysis of the X axis in assessing the accelerometer parameters may be seen as arbitrary, and considering other axes could have provided a more comprehensive understanding of the results.

Secondly, conducting multiple tests and statistical analyses increases the likelihood of obtaining significant findings by chance (type I error). To mitigate this risk, it is crucial to stay focused on the research questions and clearly state that certain analyses are exploratory in nature, such as the correlation analysis with NDI or DHI groups, average pain, or initial pain description.

Thirdly, it should be noted that the findings are specific to the population that was included in this research. Therefore, the generalizability of these results to other groups, such as asymptomatic individuals or patients with acute pain, remains uncertain. To gain a better understanding of the implications of these findings in a broader population, future research should consider investigating the relationship between accelerometer parameters and head-trunk coordination in different populations. This would provide valuable insights into the potential applicability and validity of these findings across diverse clinical contexts.

Fourthly, kinesiophobia was not assessed or included as a variable. The findings reported in the literature demonstrate a significant association between kinesiophobia and various outcomes. Specifically, kinesiophobia is shown to be a significant predictor of pain intensity, proprioception, and functional performance. Additionally, there is a significant correlation observed between kinesiophobia and pain intensity, indicating that individuals with higher levels of kinesiophobia tend to experience greater pain. Furthermore, individuals with high levels of kinesiophobia are reported to have lower levels of education and higher scores on measures such as the Million Visual Analogue Scale, Neck

Disability Index, Hospital Anxiety and Depression Scale, and Nottingham Health Profile. (Asiri et al., 2021; Bilgin et al., 2019.)

# 7 CONCLUSION

This master's thesis aimed to explore the use of an accelerometer for assessing head-trunk coordination. The use of a low-cost, open-source IMU is an ethically appealing choice but comes with significant development constraints. Despite this initial choice, utilising the triaxial accelerometer and prioritizing the analysis of the X axis, the results of the study do not seem to be significantly compromised. However, it is worth noting that with greater resources, such as increased human, financial, and technical support, there is potential for further improvements in precision and reliability. This could also involve incorporating gyroscope and magnetometer data.

The intra-session reliability of the HTCT showed a moderate to good level, except for the X variance. The inter-session reliability, although lower, was still reasonable. However, this variability in measurements between sessions is likely more attributable to individual differences among subjects rather than to technical limitations.

The testing protocol was well-tolerated by participants, as it did not result in an increase in pain or dizziness intensity, and no dropouts or adverse events were reported. It indicates its safety. These findings suggest that the modified HTCT can be cautiously used to document a patient's progress but not as a diagnostic test. Careful interpretation is necessary when tracking changes in a patient's condition over time.

The correlation analysis did not reveal significant relationships between the NDI or DHI scores and the accelerometer parameters. The observed

correlation coefficients were below the expected value of 0.6, indicating limited associations between these variables.

Regarding the influence of visual feedback, the mirror had a significant effect on reducing head movements, as reflected by the X abs mean parameter. However, for most other parameters, no substantial differences were observed between the wall and mirror conditions.

These findings hold particular importance for their clinical implications. As such, it appears that the mean of acceleration in absolute values is the most effective parameter. This is because it is most sensitive to the influence of external factors like visual feedback and also exhibits promising reliability values. This parameter could serve as a more consistent measure for assessing head-trunk coordination, thus offering clinicians an additional tool for monitoring patient progress.

The adoption of the X abs mean as metric could enhance the way physiotherapists approach the assessment and treatment of disorders affecting head-trunk coordination, such as chronic neck pain. Further research may explore whether this parameter has prognostic value, such as predicting the course of a condition. Additionally, this tool could facilitate interdisciplinary collaboration, as a standardised and reliable measure is easier for professionals from different medical backgrounds to understand and utilise. It could also support more personalised treatment plans; its sensitivity to visual feedback may provide better insights into individual patient responses and help in fine-tuning treatments, such as by varying the visual feedback.

Moreover, due to its promising reliability, this parameter could contribute to the development of a user-friendly app that processes accelerometer data in real-time, benefiting both patients and physiotherapists. This would simplify data collection for clinicians during routine examinations or specialised assessments.

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# APPENDIX 1: SWISSETHICS AGREEMENT

canton de vaud
COMMISSION CANTONALE D'ÉTHIQUE DE LA RECHERCHE SUR L'ÊTRE HUMAIN
CER-VD
Av. de Chailly 23
1012 Lausanne

Monsieur François Tharin
Physio Barillette Sarl
Route des Tattes d'Oie 99
1260 Nyon

Lausanne, le 15/11/2022
Réf. JMA/jp/cc

**Décision de la Commission cantonale (VD) d'éthique de la recherche sur l'être humain (CER-VD)**

| | |
|---|---|
| **Project-ID** | 2022-01205 |
| **Titre du projet** | Head-trunk coordination in neck pain |
| **Travail de master/de thèse de** | Tharin, François |
| **Direction du projet** | François Tharin |
| **Promoteur** | Physio Barillette Sarl, Nyon – François Tharin |
| **Centres** | François Tharin, Physio Barillette Sarl, Nyon |

**Décision**

- ☒ Autorisation accordée
- ☐ Autorisation avec charges
- ☐ En l'état, l'autorisation ne peut pas être accordée
- ☐ Autorisation non accordée
- ☐ Non entrée en matière

**Classification**

☒ Projet de recherche au sens de l'ORH — Catégorie : A

- ☒ recherche sur des personnes
- ☐ réutilisation du matériel biologique ou des données personnelles liées à la santé
- ☐ sur des personnes décédées
- ☐ sur des embryons et des fœtus
- ☐ avec rayonnements ionisants

**Procédure de décision**

☐ Procédure ordinaire ☐ Procédure simplifiée ☒ Procédure présidentielle

La Commission certifie se conformer aux principes ICH GCP.

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**Taxes et émoluments**

Déjà facturé.

**Voies de recours**

La présente décision peut faire l'objet d'un recours au Tribunal cantonal, Cour de droit administratif et public. L'acte de recours doit être déposé auprès du Tribunal cantonal dans les **30 jours** suivant la communication de la décision attaquée ; il doit être signé et indiquer les conclusions et motifs du recours. La décision attaquée est jointe au recours. Le cas échéant, ce dernier est accompagné de la procuration du mandataire.

**Copie pour information à :**

☐ OFSP

☒ Autre(s) Markus Ernst, markus.ernst@zhaw.ch

**Signature**

p.o. Arthur Zinn, secrétaire général

Prof. Jean-Marie Annoni
Vice-président

**Annexes:** -Obligations du requérant
-Signification des décisions possibles
-Liste des documents soumis les 01.07.2022, 07.07.2022, 25.10.2022, 10.11.2022

## Annexes

**Obligations du requérant (promoteur ou direction du projet) :**

**Soumission de documents** : les documents modifiés et les nouveaux documents relatifs à l'étude/au projet de recherche sont soumis via le dossier existant. Les documents qui ne sont plus valides sont effacés et remplacés par les nouveaux. Les documents révisés doivent être soumis une fois en mode « suivi des modifications » et une fois en mode « modifications acceptées » (« track changes » et « clean »). Les documents d'information et de consentement ainsi que le protocole doivent être transmis dans un format permettant la recherche (PDF navigable) ou scannés avec une fonction OCR (Optical Character Recognition). Le cas échéant, les documents révisés sont également mis à disposition des autorités compétentes pour approbation.

Remarque: La commission d'éthique compétente examine, dans le cadre du processus d'autorisation, les feuilles d'information et déclarations de consentement dans une des langues officielles suisses: allemand, français ou italien. La commission d'éthique ne fait qu'accuser réception des feuilles d'information et déclarations de consentement écrites dans d'autres langues. Le promoteur ou la direction du projet est responsable de la traduction correcte des documents.

**Obligations d'annonce** : Les obligations d'annonce (p.ex d'évènements indésirables, d'interruption d'étude) et de soumission pour autorisation des modifications essentielles obligatoires s'appliquent (Ordonnances). Le rapport final est à remettre à la commission d'éthique compétente dans un délai d'une année à compter de la fin ou de l'arrêt de l'étude.

**Devoir d'enregistrement** : Le promoteur d'un essai clinique doit procéder à l'enregistrement dans un registre primaire reconnu par l'OMS ou dans le registre de la bibliothèque médicale nationale des Etats-Unis d'Amérique (clinicaltrials.gov) puis indiquer le numéro de l'étude sur le portail BASEC. Le transfert des données vers le Swiss National Clinical Trials Portal (SNCTP) est effectué automatiquement suite à l'autorisation de l'étude par la commission d'éthique, sous réserve de l'accord du requérant. Les données relatives à l'essai clinique figurant sur les deux registres sont accessibles au public. Swissethics publie également sur son site des informations sur chaque étude ayant reçu une autorisation, à l'exception des essais cliniques de phase I.

**Signification des décisions possibles**

**Autorisation accordée** : L'étude peut commencer selon le plan de recherche accepté. Elle doit être menée dans le cadre des dispositions légales en vigueur. D'autres obligations d'autorisation (Swissmedic/OFSP) doivent être respectées.

**Autorisation avec charges** : L'étude peut commencer selon le plan de recherche accepté. Elle doit être menée dans le cadre des dispositions légales en vigueur. Les charges doivent être remplies dans un délai de 30 jours. Les documents modifiés seront réévalués en procédure présidentielle. D'autres obligations d'autorisation (Swissmedic/ OFSP) doivent être respectées.

**En l'état, l'autorisation ne peut pas être accordée** : L'étude ne peut pas commencer. Prière de répondre point par point aux conditions de la commission d'éthique et de nous faire parvenir les documents révisés avec les modifications apparentes et la mention de la date de la nouvelle version.

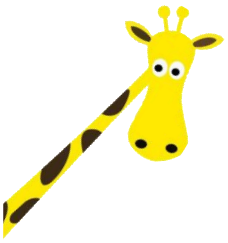
**Autorisation non accordée** : L'étude ne peut pas commencer dans sa forme actuelle. Une nouvelle soumission reste possible.

**Non entrée en matière** : Justification, voir ci-dessus, par exemple la commission d'éthique n'est pas juridiquement compétente pour accorder une autorisation ou l'étude ne nécessite pas d'autorisation.

**Liste des documents soumis**

| **François Tharin, Physio Barillette Sarl, Nyon** | | |
|---|---|---|
| nom du fichier | date du fichier | version |
| **1. Cover Letter** | | |
| coverletter-v2.pdf | 25/10/2022 | |
| **3. Participant information sheet and informed consent (ICF)** | | |
| feuilleinfo-20221020-v3-track-changes.pdf | 10/11/2022 | V3 tc |
| feuilleinfo-20221020-v3-clean.pdf | 10/11/2022 | V3 clean |
| **4. Study plan (protocol), signed and dated** | | |
| project-plan-2022-01205-v3-track-changes.pdf | 10/11/2022 | V3 tc |
| project-plan-2022-01205-v3-clean.pdf | 10/11/2022 | V3 cleab |
| **5. CRF (Case Report Form)** | | |
| crf-2022-01205-v2-track-changes.pdf | 10/11/2022 | V2 tc |
| crf-2022-01205-v2-clean.pdf | 10/11/2022 | V2 clean |
| **6. Investigator's CV, dated** | | |
| cv-2022-ft.pdf | 25/10/2022 | |
| **8. Details on infrastructure suitability and availability at the location where the trial is executed** | | |
| qualifikationpruefort-f.pdf | 25/10/2022 | |
| **10. Insurance** | | |
| rc-4-001-382-162.pdf | 06/10/2022 | |
| **11. Other documents handed over to study participants** | | |
| affiche-v4.pdf | 25/10/2022 | V4 |
| **12. Details on nature and scope/value of compensation for participants** | | |
| There is no compensation for the participation in this study | | |
| **14. Information on secure handling of biological material and personal data, and in particular on the storage thereof** | | |
| see doc/cat: **4**, page/ref: **QUALITY CONTROL AND DATA PROTECTION p.15** | | |
| **39. Miscellaneous / Varia** | | |
| 2022-01205-form-rep-completed-v2.pdf | 10/11/2022 | V2 |
| responsabilitepb20221013.pdf | 13/10/2022 | V2 |
| movesense-md-ec-certificate-c-01-1205-754-20.pdf | 04/12/2020 | |

# APPENDIX 2: RECRUITMENT POSTER



## Nous avons besoin de vous pour une recherche sur la coordination!

Vous souffrez de douleur à la nuque depuis plus de 3 mois et vous avez plus de 18 ans?

**Buts de l'étude :**

- étudier la coordination de la tête et du tronc chez des personnes souffrant de douleur à la nuque.
- explorer les liens potentiels entre des mesures effectuées avec un accéléromètre et la douleur, les vertiges, ou l'origine du problème.

**Déroulement :** 2 séances de mesures (1ère mesure = 30' puis entre 1 et 7 jours après : 2ème mesure = 20') à l'aide d'un capteur fixé sur la tête.

Les données seront traitées de façon confidentielle. Il n'y a pas de bénéfice direct ni de compensation financière.

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