Sensorimotor function in chronic neck pain

Objective assessments and a novel method for neck coordination exercise

Ulrik Röijezon
To all the people that have been involved in the work of this thesis
CONTENTS

ABSTRACT .................................................................................................................. 6
SVENSK SAMMANFATTNING .................................................................................. 8
ABBREVIATIONS ..................................................................................................... 9
ORIGINAL PAPERS .................................................................................................. 10
INTRODUCTION ...................................................................................................... 11
  NECK PAIN DISORDERS .................................................................................... 12
  ALTERED SENSORIMOTOR FUNCTIONS IN NECK PAIN DISORDERS ............. 15
  MOTOR CONTROL .............................................................................................. 18
  PATHOPHYSIOLOGICAL MODELS AND MOTOR CONTROL ......................... 22
  REHABILITATION OF NECK PAIN DISORDERS ........................................ 25
  MOTOR LEARNING ............................................................................................ 27
AIMS OF THE THESIS ............................................................................................ 30
METHODS ............................................................................................................... 31
  SUBJECTS ......................................................................................................... 32
  ETHICAL APPROVALS .................................................................................... 33
  PRECISION OF GOAL-DIRECTED ARM MOVEMENT (STUDY I) ................. 34
  POSTURAL SWAY IN QUIET STANCE (STUDY II AND IV) ....................... 35
  KINEMATICS IN CERVICAL ROTATION (STUDY III AND IV) ................. 36
  PAIN ASSESSMENT AND QUESTIONNAIRES ............................................ 38
  NECK COORDINATION EXERCISE ............................................................. 39
  STATISTICS ...................................................................................................... 41
RESULTS ............................................................................................................... 46
  GROUP DIFFERENCES IN SENSORIMOTOR FUNCTIONS ............................ 46
  TEST-RETEST RELIABILITY (STUDY III) ....................................................... 50
  ASSOCIATIONS BETWEEN ALTERED SENSORIMOTOR FUNCTIONS AND SELF-RATED
    CHARACTERISTICS (STUDY I, II AND III) ............................................. 52
  NECK COORDINATION EXERCISE (STUDY IV) ........................................ 52
DISCUSSION ............................................................................................................ 55
  MAIN FINDINGS .............................................................................................. 55
  SENSORIMOTOR FUNCTIONS IN CHRONIC NECK PAIN ............................ 55
  ASSOCIATION BETWEEN SENSORIMOTOR FUNCTIONS AND SELF-RATED
    CHARACTERISTICS .................................................................................... 58
  RELIABILITY OF MEASUREMENTS ............................................................. 58
  NECK COORDINATION EXERCISE ............................................................. 59
  METHODOLOGICAL CONSIDERATIONS ...................................................... 63
  IMPLICATIONS FOR REHABILITATION .................................................... 64
  FUTURE RESEARCH ....................................................................................... 65
CONCLUSIONS ........................................................................................................ 66
ACKNOWLEDGEMENTS ....................................................................................... 67
REFERENCES ....................................................................................................... 69
ABSTRACT

Chronic neck pain is a widespread problem that causes individual suffering as well as large costs for the society. The knowledge about the pathophysiology is poor and therefore specific diagnosis and causal treatment are rare. Important knowledge for characterization of the disorders has been gained from research on sensorimotor functions in people with neck pain. Moreover, rehabilitation regimes including sensorimotor exercises indicate promising results.

The main objectives of this thesis were to extend the knowledge on sensorimotor dysfunctions in chronic neck pain, and to develop a new exercise method for improving sensorimotor functions of the neck. The studies focused on aspects of postural control and movements of the arm and neck. These are vital functions for many activities of daily living. People with chronic (>3 months) neck pain were compared to healthy controls (CON). Neck pain related to trauma was referred to as whiplash associated disorders (WAD), while neck pain without association to trauma was referred to as non-specific (NS).

Arm-functioning was assessed in a pointing task. WAD and NS had reduced pointing precision compared to CON. The reduced precision was associated with self-rated difficulties performing neck movements, physical functioning, and in WAD, also pain and balance disturbances.

Postural control was assessed in quite standing on a force platform without vision. The center of pressure signal was decomposed into its slow and fast components. WAD and NS were compared to CON. The results revealed an effect of age on the magnitude of the fast sway component, but no effect of group. The magnitude of the slow component was elevated in both WAD and NS. This increase was associated with self-rated balance disturbance, arm-functioning, difficulties to run and sensory alterations in WAD, while in NS, the increase in the slow sway component was associated with concurrent low back pain.

Neck movements were assessed in a cervical axial rotation test with maximal speed. In total 8 variables representing basic kinematics, including variables reflecting movement smoothness and conjunct motions were calculated. NS were compared to CON. Linear discriminant modelling indicated Peak Speed and conjunct motions as significant classification variables that together had a sensitivity of 76.3% and specificity of 77.6%. Retest reliability was good for Peak Speed but poor for the measure of conjunct motions. Peak Speed was slower in NS compared to CON, and even slower in a sub-group of NS with concurrent low back pain. Reduced Peak Speed was associated with self-rated difficulties performing neck movements, car driving, running, sleeping disturbances and pain.

The clinical applicability of a novel method for neck coordination exercise was assessed in a pilot study on persons with NS. The results supported the applicability and indicated positive effects of the exercise: reduced postural sway in quite standing and increased smoothness in cervical rotations. Indications on improvement in self-rated disability and fear of movement were seen at six months follow up.

In conclusion, sensorimotor functions can be altered in chronic neck pain, particularly in neck disorders with concurrent low back pain and WAD. The discriminative ability and clinical validity displayed in pointing precision, postural sway and cervical axial rotation speed imply that such tests can be valuable tools in the assessment of chronic neck pain patients, and for selecting and evaluating treatment interventions. Indications of improvements seen in the pilot-study support a future RCT.
Key words: Neck pain, Whiplash, Sensorimotor, Motor Control, Motor Learning, Neck Coordination Exercise, Postural Control, Cervical kinematics, Reliability.
SVENSK SAMMANFATTNING


Armfunktion undersöktes i ett test med en målriktad handrörelse. WAD och NS hade minskad precision jämfört med CON. Den minskade precisionen var kopplad till självskaftade svårigheter att utföra nackrörelser, begränsningar i fysisk funktion, och hos WAD även med små och balansstörningar.

Postural kontroll undersöktes i stillstående på kraftplatta med slutna ögon. Signalen från kraftplattan som anger tyngdpunktens förflyttning delades upp i dess långsamma och snabba komponent. WAD och NS jämfördes med CON. Resultatet visade en effekt av ålder på den snabba komponenten, men ingen effekt av grupp. Störleken på den långsamma komponenten var ökad hos både WAD och NS. Ökningen var kopplad till självskaftade besvär med balans, armfunktion, att springa och med sensoriska störningar hos WAD, medan hos NS var ökningen i den långsamma komponenten kopplad till samtidig förekom av ländryggssmärta.

Nackrörelser undersöktes med cervikala axila rotationer utförda så snabbt som möjligt. Totalt 8 variabler som representerade basal kinematik, inklusive variabler som avspeglar rörelsens mjukhet och kopplade rörelser beräknades. NS jämfördes med CON. Linjär diskriminantanalys indikerade maxhastighet och kopplade rörelser som signifikanta klassifikationsvariabler som tillsammans hade en sensitivitet på 76.3% och specificitet på 77.6%. Reliabiliteten vid upprepade tester var god för maxhastighet men dålig för kopplade rörelser. Maxhastigheten var lägre hos NS jämfört med CON, och ännu lägre i en delgrupp av NS med åtföljande ländryggssmärta. Minskad maximal hastighet var associerad med självskaftade svårigheter att utföra Nackrörelser, körda bil, springa samt sömnhälsa.

Den kliniska användbarheten av en nyutvecklad metod för Nackkoordinationsträning utvärderades i en pilotstudie på personer med NS. Resultaten stödde metodens användbarhet och indikerade positiva effekter av träningen: minskat postural svag i stående och minskad ryckighet vid cervikala rotationer. Indikationer på självskaftade förbättringar av funktionstillstånd och rörelserädda uppmättes vid sexmånadersuppföljning.

Slutsatser: Sensomotoriska funktionsstörningar är vanliga vid Nackbesvär, särskilt vid Nackbesvär med åtföljande ländryggssmärta och WAD. Den diskriminativa förmågan och kliniska validiteten som framkom vid mätningarna av precision vid pekrörelser, posturalt svag och hastigheten vid cervikala axiala rotationer, visar att sådana test kan vara användbara vid undersökning av patienter med långvariga Nackbesvär, och för val och utvärdering av behandlingsmetoder. Indikationerna på förbättringar som framkom i pilotstudien stöder en framtida randomiserad kontrollstudie.
### ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
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<tbody>
<tr>
<td>AE</td>
<td>Absolute error</td>
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<tr>
<td>ANCOVA</td>
<td>Analysis of covariance</td>
</tr>
<tr>
<td>ANOVA</td>
<td>Analysis of variance</td>
</tr>
<tr>
<td>BMI</td>
<td>Body mass index</td>
</tr>
<tr>
<td>BP</td>
<td>Bodily pain index of SF-36</td>
</tr>
<tr>
<td>C-CF</td>
<td>Cranio-cervical flexion (as a test and as an exercise)</td>
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<tr>
<td>CE</td>
<td>Constant error</td>
</tr>
<tr>
<td>CNS</td>
<td>Central nervous system</td>
</tr>
<tr>
<td>CoM</td>
<td>Centre of mass</td>
</tr>
<tr>
<td>CON</td>
<td>Healthy control group</td>
</tr>
<tr>
<td>CoP</td>
<td>Center of pressure</td>
</tr>
<tr>
<td>CR</td>
<td>Coefficient of repeatability</td>
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<tr>
<td>CV</td>
<td>Coefficient of variation</td>
</tr>
<tr>
<td>DASH</td>
<td>The Disability of arm shoulder and hand questionnaire</td>
</tr>
<tr>
<td>EMG</td>
<td>Electromyography</td>
</tr>
<tr>
<td>GH</td>
<td>General health index of SF-36</td>
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<tr>
<td>ICC</td>
<td>Intra class correlation</td>
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<tr>
<td>IHA</td>
<td>Instantaneous helical axis</td>
</tr>
<tr>
<td>MANOVA</td>
<td>Multivariate analysis of variance</td>
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<tr>
<td>MCS</td>
<td>Mental component summary index of SF-36</td>
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<tr>
<td>MH</td>
<td>Mental health index of SF-36</td>
</tr>
<tr>
<td>MP</td>
<td>Mean amplitude of peaks of the sway density curve</td>
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<tr>
<td>NDI</td>
<td>The Neck disability index</td>
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<td>NRS</td>
<td>Numeric rating scale</td>
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<tr>
<td>NS</td>
<td>Non-specific neck pain group (non-traumatic)</td>
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<td>O-PLS</td>
<td>Orthogonal projection to latent structures</td>
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<tr>
<td>PCS</td>
<td>Physical component summary index of SF-36</td>
</tr>
<tr>
<td>PF</td>
<td>Physical functioning index of SF-36</td>
</tr>
<tr>
<td>PLS</td>
<td>Partial least squares regression (Projection to latent structures)</td>
</tr>
<tr>
<td>Ra</td>
<td>Rambling</td>
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<tr>
<td>RCT</td>
<td>Randomized controlled trial</td>
</tr>
<tr>
<td>RE</td>
<td>Role limitation emotional index of SF-36</td>
</tr>
<tr>
<td>ROM</td>
<td>Range of motion</td>
</tr>
<tr>
<td>RP</td>
<td>Role limitation physical index of SF-36</td>
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<tr>
<td>SEM</td>
<td>Standard error of measurements</td>
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<tr>
<td>SES</td>
<td>The Self-efficacy scale</td>
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<td>SF</td>
<td>Social functioning index of SF-36</td>
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<tr>
<td>SF-36</td>
<td>The Short form-36 item health survey</td>
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<tr>
<td>SID</td>
<td>Standard index of deviation</td>
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<td>Tr</td>
<td>Trembling</td>
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<tr>
<td>TSK</td>
<td>The TAMPA scale of kinesiophobia</td>
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<td>VAS</td>
<td>Visual analogue scale</td>
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<tr>
<td>VE</td>
<td>Variable error</td>
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<tr>
<td>VEr</td>
<td>Variable error controlled for retention time</td>
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<tr>
<td>VIP</td>
<td>Variable importance in the projection</td>
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<tr>
<td>VT</td>
<td>Vitality index of SF-36</td>
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<tr>
<td>WAD</td>
<td>Whiplash associated disorders</td>
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This thesis is based on the following papers:


INTRODUCTION

Virtually every person can expect to experience neck pain at some time point in life. Commonly, this experience will be transient and it will not cause any significant activity limitations. Nevertheless, neck pain disorders do contribute to distress, disability and even inability to work for a considerable group of people, as well as large costs for the society. The impact on society can be exemplified by recent survey data from The Swedish Work Environment Authority [2] showing that 6% of all women in working life in Sweden report that they had experienced neck pain of such severity that it had negative impact on their ability to work.

Increasing prevalence have been reported already in younger ages [3, 4], which indicate that the problem is not likely to diminish. More knowledge is continuously obtained regarding the aetiology, the pathophysiology, the impact on specific physical functions and the effects of different treatment interventions. There are, however, still large gaps in the understanding of neck pain disorders. This is illustrated by the fact that neck pain disorders are mostly considered as non-specific, that is, without a known pathophysiology. Moreover, there is a large variation of treatment interventions, but few have been evaluated as efficient [5, 6]. Best support for clinical evidences in chronic pain has been reported for multimodal interventions and professionally supervised exercise regimes [5, 6]. A growing research field within musculoskeletal pain disorders involves the association between pain and alterations in sensorimotor functions, such as control of muscle activation, movements and posture. Research on sensorimotor functions in neck pain advanced both the understanding of the pathophysiology and the development and evaluation of treatment regimes. The work included in this thesis will, hopefully, add more knowledge to this field. The assessments of sensorimotor functions in the present thesis were focused on aspects of postural control and movements of the arm and neck. These are essential motor functions that are involved in many everyday tasks. The subjects included are limited to chronic (> 3 months) non-specific neck pain disorders in working age populations. Neck pain related to trauma is here referred to as whiplash associated disorders (WAD), while neck pain without association to trauma is referred to as non-specific (NS). For comparison, we also included healthy control subjects (CON) in the cross sectional studies (see paper I-III). The overall purpose of this thesis is to shed further light on alterations in sensorimotor functions in chronic neck pain disorders and to develop a new exercise method aiming at improving sensorimotor functions of the cervical spine. The present work constitutes part of the preparatory research for a future randomized controlled trail (RCT) on treatment interventions for people with neck pain disorders.
Neck pain disorders

Prevalence and incidence

Neck pain is a common global problem [7, 8]. In a review from 2006, Fejer et al. reported the point prevalence of neck pain ranging from 5.9% to 38.7% and the one-year prevalence ranging from 16.7% to 75.1% on adult populations [7]. A recent review reported that most estimates of one-year prevalence are between 30% and 50% [8]. Neck pain prevalence peak at middle age and is generally higher among women [7-9]. The annual incidence rate in the general population was reported to vary between 0.037 and 213 per 1000 persons [8]. This large variation is likely due to the shifting designs of the studies, with some performed in clinical settings investigating specific neck disorders, while others included wider groups using questionnaire data [8].

Cote and co-workers reported 11% to 14% the working population experienced activity limitations due to neck pain each year [9]. Particular high prevalence and incidence of neck pain was found in office and computer workers, health care workers such as dentists and nurses, and manual workers.

Care seeking at hospital due to WAD from traffic collisions has increased in some western countries during the past 30 years [10]. The annual incidence of reported WAD is estimated to be at least 3 per 1000 inhabitants in the western world [10]. A study from northern Sweden reported that 30% of the population with chronic neck pain had a history of neck injury [11].

Risk and prognostic factors

Neck pain disorders are most often a result from complex relationships between individual and external risk factors [12]. Risk factors for neck pain disorders in the general population includes previous neck pain, musculoskeletal complaints, poor psychological health, exposure to tobacco, genetics and age [8].

Work related risk factors include poor physical work environment, awkward postures, sedentary work, repetitive and precision work, low physical capacity, high quantitative job demands, low social support and job insecurity, [9, 13]. Another review on work related neck-shoulder pain concluded that there is evidence for increased risk for neck-shoulder pain associated with repetitive movements of the upper extremity, such as the shoulder and the hand-wrist, as well as repetitive neck flexion and neck flexion involving static loading and force [14].

Studies on prognostic factors indicate that 50-85% of people who experience neck pain in the general population will report neck pain one to five years later [15]. This indicates that most people with neck pain do not recover completely. Factors associated with recurrence or persistence of neck pain in the general population includes initial pain intensity, duration, pain-related difficulties in performing activities, prior neck-shoulder pain,
Introduction

comorbidity of low back pain, self-perceived poor health and psychosocial factors [15]. In WAD, variables such as history of headache and head trauma and early symptoms and signs of high pain intensity, restricted motion, neurological disturbances and CNS symptoms have been reported to predict increased risk for persistent complaints [16].

Symptoms

The bodily illness of chronic musculoskeletal pain has been described as a process characterised by uncontrollable fluctuations [17]. Except for pain in the cervical region, neck pain disorders are often associated with decreased range of cervical motion in one or more directions, and symptoms such as headache, ache and stiffness of the yaw and radiating pain to shoulders and the upper limb. Weakness, numbness and tingling may be present in the upper limb. Dizziness, balance disorders and nausea are sometimes coinciding with neck pain [18]. WAD has been associated with a wider range of symptoms and symptom severity compared to NS. Besides the symptoms mentioned above, additional symptoms that are frequently occurring in WAD involves back pain, temporomandibular symptoms, visual and auditory disturbances, sleeping problems as well as cognitive and emotional/psychological problems (for review, see [16]).

Diagnosis and classification

An important issue regarding diagnostics of neck pain disorders is the lack of objective diagnostic methods and, thus, a lack of causal treatments. Diagnostic imaging is frequently used for specific disorders such as myelopathy, fracture or atlanto-axial subluxation. Imaging has, however, limited value in explaining the pathology behind the majority of neck pain disorders. In a systematic review on the assessment of neck pain disorders it was concluded that there is evidence for computerized tomography (CT) scans compared to radiographs in assessing severely injured neck patients [19]. In contrast, there was no evidence that specific MRI findings are associated with neck pain, cervicogenic headache, or whiplash exposure. Nor was there evidence supporting the use of cervical provocative discography in evaluating neck pain [19]. This emphasizes the need to assess neck pain with a broader view than anatomical or structure-based divergences. Therefore, various systems for diagnosis and classification have been developed.

One of the more widespread diagnostic systems is the International Statistical Classification of Diseases and Related Health Problems, 10th revision (ICD-10) by the World Health Organization (WHO) [20]. The ICD 10 is primarily designed to classify diseases and injuries with formal specific diagnosis. Since not every health problem, including the majority of neck pain conditions, can be classified this way, the ICD 10 also provides codes for a variety of signs, symptoms, complaints, abnormal findings and social circumstances. Accordingly, some codes for neck pain disorders are based on pathology, e.g., M50 (cervical disc disorders), M54.1 (radiculopathy), while others are based on pain location, e.g., M54.2 (Cervicalgia), M53.0
(cervicocranial syndrome). Also, separate codes are used for injuries, e.g., S12 (cervical fracture), S13 (sprain and strain of cervical spine due to injury).

Another classification system by WHO, based on health and health-related domains, is The International Classification of Functioning, Disability and Health (ICF) [21]. It provides a classification system for body, individual and societal perspectives. In contrast to ICD 10, ICF focus on the disability rather than the cause. Furthermore, ICF takes into account environmental factors and the social aspects of disability and does not see disability only as a 'medical' or 'biological' dysfunction.

A commonly used clinical-anatomic system for classification of whiplash injuries was proposed by the Québec Task Force (QTF) [22]. It defines five grades that roughly correspond to severity. Grade 0: no complaint about the neck and no physical signs. Grade I: neck complaint of pain, stiffness or tenderness only, with no physical signs. Grade II: neck complaints and musculoskeletal signs, including decreased range of motion (ROM) and point tenderness. Grade III: neck complaints and neurological signs, including decreased or absent deep tendon reflexes, weakness and sensory deficits. Grade IV: neck complaints and fracture or dislocation. A new integrating model including classification systems for traumatic as well as non-traumatic neck pain disorders was recently proposed by the Bone and joint decade 2000-2010 Task Force on Neck Pain and Its Associated Disorders (Neck Pain Task Force) [12]. This model is largely a revision and extension of the QTF classification system with integrating concepts from ICF and other models from the scientific literature.

The systems mentioned above may be valuable for classifying patients with neck pain disorders into groups but have limited utility for the treatment decision making in clinical settings. However, systems including a biopsychosocial view, with enhanced focus on function, such as the ICF and the new classification model from the Neck Pain Task Force, may contribute to the therapeutic management. Various therapeutic concepts have been developed, on the basis of the anamnesis and the clinical physical examination, to identify specific subgroups of neck pain [23-25]. These concepts are intended to form different “function”- or “working” diagnosis, which are used for treatment decisions and for the prediction and evaluation of treatment effects. Although many physical examination methods lack reliability and validity there is evidence for the clinical use of some, including features of inspection, cervical ROM, strength, palpation and provocation [19]. However, the variety of therapeutic concepts has evolved from different theoretical models about the underlying pathology of spinal pain disorders, e.g., whether the pain originates from a disc, facet joint or a muscle. The variety of diagnose systems, concepts and methods increase the risk that different diagnostic criteria and names are used for the same disorder. This contributes to confusion for the patient and may also aggravate communication and teamwork among clinicians. These concerns have been highlighted in a recent paper proposing a theoretical model of a diagnose-based clinical decision rule for spinal pain disorders [26]. To conclude, there is a large need of further research and clinical development.
Introduction

to approach a unifying model of diagnoses and subgroup definitions. The standardisation and validation of clinical assessment methods and the development of valid objective measurements are vital to reach that goal. In the case of chronic neck pain disorders, important progress has been made for objective assessments of alterations in sensorimotor functions.

Altered sensorimotor functions in neck pain disorders

Chronic musculoskeletal pain conditions are often associated with influences on various domains of a patient’s life. This has been highlighted in the biopsychosocial model [27], which has contributed with important influence on the clinical management and research on chronic musculoskeletal pain disorder. As the name implies, the interactive contribution of factors in each of the biological, psychological and social domains is described in the model. Well aware of this complexity, the present thesis focus primarily on sensorimotor functions associated with chronic neck pain disorders. Altered motor functions are common clinical findings in neck pain disorders and over the last 10-20 years a large amount of research studies, using objective assessment methods, has reported findings of sensorimotor dysfunctions. Results from this research are presented below.

Cervical range of motion

The assessment of cervical ROM in neck pain is routine in clinical practice and research. Numerous studies report decreased cervical ROM in subjects with chronic neck pain of both traumatic and non-traumatic origin [28-36]. Reduced concurrent motions in the associated planes, especially during cervical axial rotation, have been found in both NS and WAD [36]. Increased ROM variability has also been reported in chronic neck pain [35, 37], but findings are inconclusive [36].

Cervical movement speed

In most studies on cervical kinematics have movements been performed with slow or self phased speed. However, a few studies have also assessed cervical movement characteristics performed with fast [37] or maximal speed [38, 39]. A decreased movement speed has been revealed in subjects with WAD compared to NS and healthy controls [38, 39] and in NS compared to controls [38].

Cervical movement smoothness

Smooth movements are, according to the minimum jerk model (see page 20), an indicator of good motor control. Reduced cervical movement smoothness has been revealed in people with chronic neck pain [37, 38, 40]. Although the same theoretical model is used, the measures of movement smoothness vary. Sjölander et al. found increased jerkiness in cervical
Introduction

rotation [37]. Grip et al. revealed more irregularities of the position and direction of the axis of motions, measured as increased number of zero-crossings [38]. Feipel and co-workers reported less harmonic speed profiles, measured as increased root mean square difference between data and model fit [40].

Cervical repositioning and movement acuity

With the objective to investigate cervical position and movement sense (proprioception), several studies have examined the repositioning acuity in active head movements to different target positions without vision. The results varies considerably, with some studies reporting reduced acuity in subjects with neck pain [37, 41-46], while others report minimal or no differences compared to healthy controls [33, 36, 47, 48]. Impaired repositioning acuity has been reported for both WAD [42, 44, 49, 50] and NS [37, 44, 45]. Pinsault and co-workers [45] compared cervical repositioning acuity in NS and in vestibular labyrinthine-defective patients with controls and found increased reposition errors only in the NS group compared to CON. Cervical movement sense has been investigated in an unpredictable pursuit task, where a slowly moving marker on a computer screen is traced by performing small movements with the head. It was found that women with chronic WAD deviated more from the target marker trace compared to healthy controls [51].

Shoulder and arm positioning acuity

Position sense in arm movements has been investigated with similar tests as for the cervical spine, i.e., the blindfolded subject performs a movement to a pre-presented target position as accurately as possible. Reduced acuity was found in people with WAD in a shoulder repositioning test [52], and in elbow repositioning with the head rotated [53]. Results from our research group showed reduced acuity in shoulder repositioning in a group with NS but not in WAD [54]. Another test approach involved estimation of the shoulder position [55]. The authors found that people with recurrent unilateral neck pain reported an over-estimation of shoulder position during passive elevation of the painful shoulder.

Cervical muscle activation patterns

Electromyographic (EMG) measurements of the deep and superficial cervical flexor muscles have revealed altered activation patterns in people with neck pain [56, 57]. The alterations were shown as a reduced activity of the deep cervical flexors, longus capitis and longus colli [57] and an increased activity of the superficial muscles, such as sternocleidomastoideus and anterior scalenei. This was found in both isometric contractions [58] and for cranio cervical flexion [32, 59] as well as during repetitive upper limb task and computer work [60, 61]. Increased activity has also been found in the cervical extensor muscles of neck pain subjects during an unilateral upper limb tasks [32]. In addition, people with neck pain demonstrate
delayed onset of the deep and superficial cervical flexor muscles in association with rapid arm movements, which indicates a deficit of the feed forward movement control (see page 23) [56].

Cervical muscle strength
Reduced muscle strength of the cervical muscles has been demonstrated in chronic neck pain [e.g., 30, 62, 63-67]. Reductions compared to healthy controls of about 20-50% [30, 63, 67] and even up to 90% [64] have been reported.

Jaw-neck motor function in WAD
A compilation of studies, emanating from the same research group, on WAD with concomitant pain and dysfunction of the jaw revealed findings of decreased amplitude of mandibular and head-neck movement, disturbed jaw-neck coordination such as delayed start of head movements, and reduced chewing endurance [68].

Occulomotor function
Disturbed occulomotor function, such as altered smooth pursuit eye movements, has been reported in acute and chronic WAD [69-75] and in tension type headache [76]. A Smooth Pursuit Neck Torsion Test (SPNTT) was designed for assessment of occulomotor function in neck pain disorders. The subjects followed a moving target with the eyes, keeping the head still in a neutral forward position and the trunk rotated 30-45° [70, 73]. Reduced smooth pursuit gain was found particularly in WAD with symptoms of dizziness [e.g., 70, 73, 74]. SPNTT has also been reported to be of value for differentiation between dizziness due to WAD and unilateral acoustic neuroma [77]. Kongsted et al. did not find any differences in smooth pursuit gain between WAD and healthy controls [78]. However, a prospective study from the same group reported a correlation between altered gain of smooth pursuit eye movements neck pain one year after the accident, but test results from the acute stage could not predict chronicity [79].

Postural control
Reports of altered postural control in people with neck pain disorders of both traumatic and non-traumatic origin are abundant [33, 80-87]. Many of these studies include postural sway measurements in unperturbed quiet standing [e.g., 33, 85, 87, 88]. There are indications of more prominent alterations in postural control in WAD compared to NS [81, 85] and in neck pain disorders when symptoms of dizziness/balance disturbance is present [80, 87]. Most studies involved people with persistent neck pain but altered postural control has also been reported in acute WAD [89]. Altered postural control reactions have been revealed in patients with cervicogenic dizziness of non-traumatic origin in studies using perturbation by vibrating the calf
and neck muscles, and by using galvanic stimulation of the vestibular nerve [82, 90].

Additional findings

Some aspects of sensorimotor functions that have been investigated to a lesser extent, but still are of interest for the understanding of motor control in neck pain disorders are summarised here. **Cervical force reproduction:** Increased variability was reported in people with persistent WAD when instructed to exert 50% and 75% of maximal voluntary contraction during isometric neck extension and flexion test. The WAD group also used a longer time to reach the target force [91]. **Cervical stability:** Reduced stability of the cervical spine, shown as an increased head translation during perturbation by dropping load from a rod hold with straight arms, was found in people with chronic WAD [85]. **Sitting posture:** A reduced ability to maintain an upright posture during a computer task was found in people with neck pain, who intended to change into a more flexed and forward head posture [61, 92]. **Grip force:** Patients with non-specific neck and upper extremity pain was found to use higher grip forces compared to healthy controls in a repetitive lifting task [93]. **Motor variability:** Decreased variability of arm and trunk acceleration and reduced EMG activity was found in a group of butchers with chronic neck-shoulder pain during performance of a standardised motor task in a laboratory setting [94].

**Motor control**

The cervical spine involves highly complex structures. The configuration of the vertebrae admits six degrees of freedom in each segment and coupled, or conjunct, movements in multiple directions. The soft tissues are richly innervated with proprioceptors (see below 19). This enables large freedom of movements and precise positioning and movements of the head. Stability and movement control of the cervical spine is mediated by the passive structures such as joints and ligaments, and to a major extent by the neuromuscular control. Cervical stability and movement control are crucial also for arm and hand function. Biomechanically, the shoulders are connected to the neck via superficial muscles such as the upper trapezius, levator scapulae and rhomboideus minor. From a neurophysiological point of view, the eye-head-hand link constitutes a 'functional unit' whose output is coordinated via complex voluntary and reflexive neural pathways. The large amount afferent information conveyed to the central nervous system (CNS) by the cervical structures and their sensory connections to the visual and vestibular systems contribute to the postural control. The present thesis focuses on measurements of accuracy in goal-directed arm movements, postural control and cervical movements in people with chronic neck pain disorders. Some aspects of motor control that are of significance for the interpretation of these assessments will here be summarized.
Central control

It has been argued that intended movements are controlled by the CNS by motor programs [for review see e.g., 95]. These programs require specific parameters to express the intended movement, e.g., the target position and the force of the contractions. It has also been suggested that a corollary discharge or efference copy [96] of the motor program is simultaneously sent from the motor cortex to sensory and processing areas of the brain for comparison of the intended movement with feedback from the executed movement. This allows for corrections of movements to be made and is highly important for motor learning [97]. Moreover, an internal representation of the state of the body, the so called body schema [see e.g., 98], is necessary for accurate movement performance. Sensory information (e.g., visual, somatosensory and vestibular) is essential for motor control and learning. The sensory systems provide the CNS with information before, during and after a movement. Sensory information prior to a movement is used to update the body schema, which in alliance with the efference copy of the motor programs allows for the feedforward control (open-loop control), i.e., anticipatory motor actions. Postural responses to maintain stability during movement represent an example of feedforward control. Feedback control (closed-loop control) refers to motor actions that occur in response to sensory information during the movement [see e.g., 99]. Very fast movements principally rely on feedforward control, while slower movements also include feedback control. Since the on-line feedback from sensory receptors is too slow to be useful in fast movements, it has been suggested that the sensorimotor system utilize an internal forward model of the predicted motor behaviour and sensory consequences based on the efference copy of the outgoing commands [see e.g., 100]. This allows the CNS to estimate and predict the state of the body without peripheral information.

Proprioception

A common definition of proprioception is a perception of the position and movement of a body part in relation to another body part, without the aid of other senses such as vision, touch or vestibular organs [101]. Proprioception is integrated information derived from mechanoreceptors (also called proprioceptors) located in muscles, muscle tendons, joints and skin [102]. A major source of proprioceptive information derives from the muscle spindles, which consists of afferent nerve endings wrapped around specific muscle fibres (intrafusal muscle fibres). The muscle spindles are located in all skeletal muscles and lie between regular (extrafusal) muscle fibres, often near the tendinous insertion. The cervical muscles, particularly the deep muscles, are richly innervated by muscle spindles [103-105]. They provide sensory information about muscle length and muscle length changes, which is transmitted by Ia and II spindle afferents. The sensitivity of the muscle spindles is adjustable through efferent innervation of the intrafusal muscle fibres by the γ-motor neurons [e.g., 106]. The cervical proprioceptors have central and reflex connections to the vestibular and visual systems and are
involved in the cervico-collic reflex, the cervico-ocular reflex and the tonic neck reflex [for review see e.g., 107]. Together this implies that cervical proprioceptive information is highly important for the function of cervical movements, goal-directed hand movements and for postural control.

Kinematics of cervical rotation – movement smoothness

In the study on kinematics in maximal speed cervical axial rotations (paper III) and as an outcome variable in the pilot study (paper IV) we evaluated movement smoothness following the "minimum jerk model" [108]. This model was first developed to explain an invariant characteristic of point-to-point hand movements; namely, the fact that such movements could best be described as ‘roughly straight’ and that the resulting speeds have a characteristic unimodal “bell-shape” profile. These similarities can be described by a mathematical model where jerk is defined as the rate of change of acceleration, i.e., the third derivate of position with respect to time, and it is a mechanical estimate of how smooth a movement is. Within such a model, hand movements are assumed to be planned in task coordinates based on extrinsic information. By comparing experimental data to a minimum-jerk speed profile, several smoothness estimates can be calculated. Asymmetry of the of the speed profile can be estimated by calculating, e.g., time to peak speed, deviation of the normalized peak speed from the expected model result, the acceleration/deceleration ratio, and a speed index of deviation from the minimum-jerk speed profile. A measure of movement jerkiness normalized with respect to the length and duration of the movement has been used as Jerk Index [109]. The different variables represent different aspects of movement smoothness but none in isolation can be used to categorically characterize smoothness. Thus, it can be valuable to include the several variables in the assessment. Smoothness has been studied in different age groups for arm movements [110, 111] and in various neurological disorders, e.g., [112, 113]. It was found that children, elderly and patients with neurological disorders performed less smooth movements compared to healthy adults. These findings suggest that maximally-smoothed movements may be a good indicator of healthy motor control.

Goal-directed hand movements

Performing precise hand movements, with or without visual input, is reliant on an accurate proprioception. Proprioception provides information both for the planning of motor actions (feedforward control) and for on-line adjustments during the movement (feedback control). During visual hand movements the CNS weights the visual and proprioceptive sensory sources to minimize uncertainty of the hands position [114]. This weighting is flexible and varies with condition, such as active or passive movements, but also with direction. Vision is more dominant in the horizontal direction, while proprioception is more dominant in depth direction. In movement tasks with the goal to perform fast and accurate movements, there is an
inverse relationship between the speed and the precision of the movement, the so called speed-accuracy trade off. The relationship between movement amplitude, speed and accuracy was highlighted by Paul Fitts in a series of experiments [115]. The relationship can be described with a mathematical equation and has become known as Fitts’ law. Movement precision can be quantified with various variables, representing different aspects of motor control. Some of the more frequently used variables are Absolutely Error (AE), Constant Error (CE) and Variable Error (VE) [see e.g., 99]. AE is often used in clinical trials for measuring overall performance in tests like cervical repositioning. However, the use of AE has been criticized for not revealing the underlying pattern of individual’s errors. AE is a non-linear combination of CE and VE, where CE provides an estimate of the spatial centre of the distribution and VE provides an estimate of the variability around this centre. In aspects of motor control, CE reflects inherent systematic biases in the motor control system and VE reflect the precision of sensorimotor processes [116].

Postural control

The postural control system acts to maintain postural orientation and equilibrium. The CNS integrates multiple sources of sensory information (visual, vestibular, somatosensory) to produce coordinated motor actions and reactions in order to control posture [e.g., 117]. The interactions of these processes are based on the individuals’ experiences and abilities, and damage to a specific underlying system will result in a context specific instability [118]. The cervical sensory input has an important role for the postural control. Cervical proprioceptors provide the CNS with information about the movement and location of the head in relation to the trunk. This is necessary for correct interpretations of inputs from the vestibular and visual organs, which provide information about the movement and position of the head in space. Incorrect information from any of these modalities will cause a sensory mismatch, which may cause disturbance of the postural control system [e.g., 119]. Postural control is frequently assessed by measuring the postural sway in quite stance. It has been concluded that the postural sway in quite stance includes a slow component, characterised by a low frequency, and a fast component, characterised by a high frequency [120-122]. These components are considered to represent different mechanisms of the postural control. The magnitude of the slow component is attributed to noise in sensory information and central processing when estimating the location and movement of the body’s centre of mass (CoM) [120]. The fast component has been ascribed to the restoring forces, such as the mechanical stiffness and anticipatory motor commands, which act in order to control the CoM [123, 124]. For further investigation into the controlling forces, Baratto and colleagues [125] proposed the use of the sway density variables mean inter-peak distance (MD) and mean value of peaks (MP), in clinical posturography. MD was argued to correspond to the amplitude of the anticipatory motor commands, while MP was quantified as the time between one rapid shift and another.
The importance of correct sensorimotor functioning is apparent in everyday tasks in daily life. When we eat, reach for a flying ball, or play a music instrument we are dependent on a fine tuned eye-head-arm coordination to perform the task with desired precision. Lifting and carrying heavy objects and performing fast arm and head movements require cervical muscle coordination and strength for spinal stabilisation. Every time a body part or the surrounding moves, the body's centre of mass is shifted and needs to be corrected by the postural control system to prevent falling. It is easy to see that neck pain disorders with altered sensorimotor functions can interfere in daily life activities. An important and relevant question is however: which are the pathophysiological mechanisms associated with altered sensorimotor functions in neck pain disorders?

Pathophysiological models and motor control

Based on the empirical findings of altered sensorimotor functions, along with data from experimental studies, several models on the pathophysiological mechanisms behind the associations between musculoskeletal disorders and altered motor behaviour have been proposed. Some of the most recognised models are presented in this section. These models agree on some viewpoints and disagree on others, but to a large extent they complement each other. Together they supply valuable explanations about possible mechanisms behind origin, recurrence and persistence of musculoskeletal pain and its association with altered motor control.

Muscle spindle model

Johansson and co workers proposed a model with the muscle spindle system in the centre of events leading to disturbances in sensorimotor functions, and possibly also to the development, maintenance and spread of muscle pain [126-128]. According to the model, proprioceptive information may be disturbed in painful conditions due to altered neural reflex activity of the γ-motoneuron - muscle spindle system. The disturbed proprioceptive information, transmitted from ensembles of muscle spindle efferents, is described to derive from a change in the activity and sensitivity of muscle spindle afferents. This, in turn, can arise from excitation of γ-motoneurons by activation of chemosensitive group III and IV muscle afferents. Also, the model consider influence on the γ-motoneuron- muscle spindle system from other peripheral and central sources, such as joint afferents and the sympathetic system [for review see e.g., 129, 130]. The model has received support from research on animal models, for example showing that muscle injections of inflammatory substances elicited profound effects on muscle spindle afferents from the same as well as neighbouring muscles [131, 132]. Furthermore, in both animal and human experimental models it was shown that muscle fatigue had a deteriorating effect on proprioception [133, 134]. The importance of cervical sensory information for the motor control is supported by studies using experimental manipulation of cervical sensory
information. For instance, altered postural sway have been reported following cervical muscle vibration [135, 136], experimental pain [137] and neck muscle fatigue [138]. Vibration of cervical muscles was also found to reduce elbow position sense acuity [139].

Pain adaptation model and neuromuscular pain adaptation

Lund et al. proposed the pain adaptation model to describe the link between nociceptive stimuli and coordination of muscles [140]. The model predicts a reduced muscle activity in the agonistic phase and an increased muscle activity in antagonistic phases during muscle contractions at the painful area. This adaptation would lead to reduced movement amplitude and velocity and thereby decrease the risk for further injury. The model has been supported in several experimental pain studies [e.g., 141, 142].

As an extension to the pain adaptation model, a more complex model of altered muscle activation patterns associated with neck pain has been presented [143, 144]. EMG studies have revealed deficits in the motor control in people with neck pain. As described above (see page 16), these motor control deficits are exemplified by a disturbance in the neck flexor synergy, where a reduced activity of the deep muscles, important for segmental control and support, appears to be compensated for by increased activity in the superficial muscles [59, 60]. Moreover, people with neck pain have demonstrated indications of disturbance in the feed forward adjustment of the cervical flexor muscles during rapid arm movements [56]. Experimental studies using induced muscle pain have confirmed associations between cervical pain and altered muscle activations patterns, not only between muscles but also within the same muscle [for references see e.g., 145]. It has been proposed that these changes are due to spinal reflex and cortical mechanisms. Possibly, these adaptations are beneficial in the acute phase to avoid increased pain. In the long run, however, these changes may lead to disuse of some muscles and “overuse” of others. This could deteriorate spinal stability and movement control, and increase the risk for persistence or recurrence of neck pain.

Neuromotor noise model

The neuromotor noise model was initially developed to explain Fitt’s law (see above). The model propose that increased muscular stiffness is a possible mechanism to adjust movements during repetitive or complex motor tasks (e.g., write or draw) when increased physical and psychological demands are added to the task [146, 147]. It was further proposed that increased muscle co-contractions can be an important factor behind inadequate movement strategies contributing to work related neck and upper extremity disorders [148]. Experimental studies have confirmed that external stressors and cognitive demand may cause increased muscle activity and limb stiffness [149, 150].
Introduction

Cortical reorganisation

Associations have been reported between changes in motor cortex organisation and severe pain syndromes, such as phantom limb pain [151, 152] and complex regional pain syndrome [153, 154]. With regard to spinal pain, association between low back pain and reorganization of networks in motor cortex was recently demonstrated [155]. The reorganization was found to be associated with delayed activation of the deep trunk muscle transversus abdominis. The authors proposed the cortical reorganization to contribute to deficits in feedforward postural control. Whether findings of cortical reorganisation also apply for neck pain disorders has, to my knowledge, not yet been investigated.

Fear-avoidance model

Studies investigating behavioural factors in people with musculoskeletal disorders have reported a strong association between persistence or recurrence of symptoms and a fear that movements and physical activity may worsen their condition [e.g., 156, 157]. The fear-avoidance model proposes that increased fear avoidance beliefs lead to avoidance behaviour, altered movement patterns and reduced physical activity, contributing to a deteriorating effect on the general physical and psychosocial functioning [158]. In support of this model, studies on neck pain disorders have reported associations between fear of movement and persistent disability [159-162], as well as a decrease in muscle activation of the upper trapezius muscle during a physical task [163]. In a recent review it was however stated that the evidence for the prognostic value of the model for development of chronic WAD is limited and needs further research [164].

As illustrated by the different pathophysiological models, various mechanisms at both peripheral and central levels may be involved in the complex interactions between sensorimotor functions and pain. It is, however, yet to be revealed whether altered sensorimotor functions are a cause or an effect of musculoskeletal pain disorders. According to the models mentioned above there seems to be possibilities for both ways. For example, healthy people performing complex manual tasks may adapt to increased physical and psychological demands by increased co-contractions of the neck-, shoulder-, and arm muscles [148]. Such sensorimotor adaptations may be useful to adequately perform the task but may be harmful if it continuous over a prolonged time period. Sustained muscle activation increases the risk for development of muscular fatigue and/or pain as proposed e.g., in the Cinderella hypothesis [165]. Both muscle fatigue and activation of muscle nociceptors have in animal experimental studies been found to alter the muscle spindle sensitivity [132, 134] which thereby may harm movement precision [133]. Moreover, experimental pain has been found to alter the activation both between muscles and within the same muscle [for review see 145]. In conclusion it seems reasonable to believe that altered sensorimotor functions can occur prior to the development of pain, e.g., due to high task demands, stress and muscle fatigue, as well as be a
consequence to painful conditions due to various neurophysiological mechanisms. In other words, altered sensorimotor functions may contribute to the development, sustention and aggravation of musculoskeletal pain.

**Rehabilitation of neck pain disorders**

Since the knowledge about the pathological structures and pain generators behind neck pain disorders are scarce, treatment intervention are mainly directed to reduce symptoms and improve function. The clinical evidence for rehabilitation interventions for neck pain disorders is presented in this section. This is followed by a presentation of randomized controlled trials (RCT) on exercise regimes including proprioception and coordination exercises.

**Clinical evidence for rehabilitation interventions**

Several systematic reviews evaluating the efficacy of conservative treatments for neck pain disorders have recently been published [166-168]. A common conclusion is that multimodal approaches including physical exercise and mobilisation/manipulation for reducing pain and improving function have strong clinical evidence for effect [166, 168]. There is evidence for benefit of various types of physical exercise [166, 168-171], but not for mobilisation/manipulation alone [166, 168, 172]. However, Vernon and colleagues found evidence for clinical improvements from mobilization/manipulation for chronic NS without arm pain [173]. Also, there is evidence for acupuncture to be effective for pain relief in the short, but not in the long term [166, 168, 174]. Other modalities that show positive effects for immediate or short term pain management are low-level laser therapy and pulsed electromagnetic field [166, 168]. The efficacy of multidisciplinary treatment for chronic musculoskeletal pain disorders was evaluated in a systematic review by Scascighini and colleagues [175]. They found strong evidence in favour of multidisciplinary treatments compared to no treatment and moderate evidence compared to ordinary non-multidisciplinary treatments. The results of these reviews are largely in line with the report Methods of Treating Chronic Pain, from The Swedish Council on Technology Assessment in Health Care [6].

**Exercise interventions**

Classifying exercise regimes into separate specific types of training, such as exercises for mobility, coordination, stability, endurance or strength, is difficult due to the multiple functional nature of most exercises. To classify separate studies on exercise interventions into specific types of training is even more complex as specific interventions commonly include various exercises. A special case of confusion around types of training is the specific exercises for activation of the deep stabilising muscles of the spine [176]. In some reviews this exercise intervention is classified as strength or endurance exercises [169]. In the present thesis, however, these particular exercises are
regarded as neuromuscular coordination exercises due to their specific aim to facilitate activation of the deep muscles with simultaneous relaxation of the superficial muscles.

**Clinical evidence for exercise interventions for neck pain disorders**

Several recent systematic reviews have evaluated the effect of exercise interventions for neck pain disorders. Common findings are evidence for the benefit of neck strengthening exercises, short term benefit of proprioceptive exercises and that people with acute WAD benefit from ROM exercises [166, 168-170]. In a recent review, it was concluded that training interventions should target the cervical muscles, be of long-term and of high intensity to provide long term pain reduction [171]. Specific exercises for spinal stabilization, i.e., neuromuscular coordination exercises, seem beneficial for cervicogenic headache [177].

**Coordination and proprioception exercises**

Eight weeks of neck-specific proprioceptive exercise regimes, including eye-head-neck coordination, for chronic NS [178] and WAD [179] resulted in short-term improvements in kinaesthetic sense, cervical ROM and pain [178], as well as reduced neck disability [179] compared to control groups. Also, a 4-week exercise regime on chronic neck pain patients, consisting of eye-head-neck exercises twice daily, reduced pain and improved cervical repositioning compared to controls [180]. None of these studies included long-term follow up assessments. A neck specific low load cranio-cervical flexion (C-CF) exercise has been developed to improve the neuromuscular coordination of the deep cervical flexor muscles. The C-CF exercise was performed together with low-load exercises for scapular muscles, cervical co-contractions and postural corrections twice daily in a 6-week intervention on patients with chronic cervicogenic headache [176]. The short and long term results revealed reduced intensity of headache and neck pain, as well as reduced frequency of headache, compared to a control group. The C-CF exercise has also been compared to other neck exercise regimes, such as endurance-strength training of cervical flexor muscles [92, 181, 182] and conventional proprioceptive eye-head-neck exercises [183]. The interventions were equal effective to reduce pain. Other outcome variables indicated in some cases exercise specific effects on motor control functions corresponding to the type of training [92, 182].

Studies that included proprioception and/or neck coordination exercises in multimodal regimes for chronic NS [184, 185] and WAD [186] have reported beneficial effects compared to controls groups. Results showed reduced pain after intervention [184-186] and at 6-month follow up [184, 186]. Also, increased return to work [186] and improved self-reported working ability [185] was reported.

The effects of general low load coordination exercises involving the whole body have been investigated on neck pain in several studies. Body awareness exercise was compared to strength training, endurance training and controls. All training groups showed short term [187], but not long term
effects on pain [188], with similar results between groups. Qigong was evaluated compared to neck-shoulder exercise, in neck pain of working age subjects [189] and elderly [190]. Lansinger et al. [189] reported equal improvements in the qigong and the neck-shoulder exercise groups, with positive effects remaining at 12 month follow-up. No improvements were however found in the elderly population [190]. A 16-weeks Feldenkrais intervention for woman with neck and shoulder pain was compared to physical therapy (including posture awareness and various exercises) and a control group [191]. A significant decrease in neck pain prevalence and disability during leisure time was reported for the Feldenkrais group after intervention. However, the outcome variable neck pain prevalence was significantly lower for the physiotherapy and control groups before intervention, which may have biased the results.

To summarize, there is strong support for exercise interventions for treatment of neck pain disorders, especially when incorporated in multimodal approaches. There are beneficial effects of proprioception and coordination regimes, particularly for neck specific exercises, but the long term effects needs further evaluation. Indications of exercise specific effects on motor functions are reported, but the effect on pain reduction between the different exercise regimes seems small.

Motor learning

The previous paragraph on effects of coordination and proprioception exercises, i.e., sensorimotor function exercises, indicates a value for these regimes in the rehabilitation of people with neck pain disorders. A common feature of these exercises is that they are performed with slow movements and are highly predictable. According to theories of motor learning, exercise tasks which are less predictable can be beneficial for rehabilitation of neck pain disorders. Valuable guidelines for designing exercises targeting motor skills can be found in the large research field of motor learning. Some general theories about motor learning that are of relevance for rehabilitation of musculoskeletal disorders will here be presented.

Motor learning can be defined as a set of processes associated with practice or experience leading to relatively permanent changes in the capability of movement skills [page 264 in 99]. An exercise with the purpose to learn or improve a motor skill is therefore different from e.g., strength or endurance training, which is known to have temporary effects if the exercise is not maintained. The more permanent effects of motor learning are likely related to central changes, an assumption that is supported by findings of differences in plastic changes in the CNS between skill training and strength training [e.g., 192]. The lasting changes of motor skills are designated as retention effects, i.e., the new skills are remained also after a longer time period without exercising. Another desirable effect of motor learning is a transfer effect to other tasks or task contexts [99]. Movement tasks can be divided into closed skills tasks and open skills tasks. Closed skills task are predictable tasks performed in a predictable environment, and the
movement can be planned in advance (feedforward control), e.g., when typing on a keyboard. Open skills task are more unpredictable and movements need to be corrected during the task (feedback control), e.g., when playing table tennis. The grade of predictability/unpredictability varies for different tasks and task contexts.

Factors for enhancement of motor learning

In motor skill learning it is important that the level of task difficulty is adjustable to the individual patient's skill level to ensure that the exercise is neither too difficult nor too trivial to perform. This aspect has been highlighted in the challenge point framework [193]. The optimal challenge point represents the degree of task difficulty needed for an individual of a specific skill level to optimise learning. By adjusting the task difficulty to the change in ability, the optimal challenge point is maintained. Learning motor skills also involves acquiring cognitive skills [194]. Motor learning exercises should therefore be designed to enhance repeated problem solving of the motor task, rather than solving it once and then repeat the same movement without cognitive effort. Different variables can be used to adjust the cognitive effort and the task difficulty, e.g., augmented feedback and variation [99, 194]. Basically, all learning involves feedback. Intrinsic feedback includes sensory input before, during and after a movement which is used for comparison with the intended movement in order to improve the performance. Augmented feedback is additional information like visually or verbally presented knowledge about the performance or results of the task. The grade of variation can be adjusted by the way the exercise tasks are distributed. Blocked distribution means that all practice trials of the task are completed before practicing the next task. In random distribution, on the other hand, the tasks are randomly switched from one task to another throughout the practice, thereby increasing the cognitive effort. Motivation to practice can be stimulated by making the task such that it seems important and by using goal-setting, e.g., solving a motor task as accurate or as fast as possible. The specificity of learning hypothesis suggests that learning should occur in conditions similar to the conditions for which the skills will be used [99, 195]. This implies that exercises should preferably be performed in functional positions and contexts.

Phases in learning motor skills

The progress of motor learning can be divided into different phases: the cognitive, associative and autonomous phases [196]. The cognitive phase includes understanding of what to do. During this first phase performance is often inconsistent but the gains are very large. The associative phase begins when the individual has determined the most effective strategy for doing the task. Performance is now more consistent but improvements are more gradual. In the autonomous phase less attention to the task is needed and other activities can be performed simultaneously.
Opportunity for further development of sensorimotor function exercises.

The clinical evidence for effects of exercise regimes targeting sensorimotor functions, together with the current knowledge about motor learning, infers that there are prospects for further development of treatment methods in this field. In summary, for new motor skills to be pertinent in daily life, that is, leading to retention and transfer effects, and be automatically used in daily activities, some specific considerations should be regarded when designing exercise regimes in clinical settings. The level of difficulty should be adjustable to the individual skill level and to the progression throughout the treatment period. The exercise should include variation and cognitive effort, and in some cases augmented feedback of performance and result of the task. Many of these considerations are inherent in open skills tasks. Moreover, the exercise should preferably be performed in a functional position and task context.
AIMS OF THE THESIS

The overall aim of this thesis was to shed further light on sensorimotor functions in people with chronic neck pain, and to develop a new treatment method based on neck coordination exercise. The work was intended to lead to 1) increased insights into the alterations in sensorimotor functions in chronic neck pain; 2) improved potential for clinical applications of objective measurements of sensorimotor functions; 3) development and evaluation of the applicability of a new method for neck coordination exercise, and a preliminary estimation of its effects on sensorimotor function, self-rated characteristics and pain. Together this work will make ground for a future RCT.

Specific aims of the thesis

Paper I
To evaluate whether the precision in a fast goal-directed arm movement task is reduced in people with chronic neck pain of either traumatic (WAD) or non-traumatic aetiology compared to healthy controls. In addition, to investigate whether possible alteration in movement precision is associated with self-rated characteristics.

Paper II
To evaluate whether people with chronic neck pain of traumatic (WAD) and non-traumatic aetiology have increased postural sway compared to healthy controls. To evaluate whether possible differences can be attributed to the slow or the fast component of postural sway. To investigate whether possible alterations are associated with self-rated characteristics.

Paper III
To evaluate whether women with non-traumatic neck pain perform maximal speed axial cervical rotations slower compared to healthy controls, and whether group differences are present in movement smoothness and conjunct motions. To evaluate whether possible group differences are associated with self-rated characteristics. To evaluate the test-retest reliability of the kinematic variables.

Paper IV
To evaluate the applicability of a novel method for neck coordination exercise on people with non-specific neck pain, and to obtain preliminary indications of the effects on sensorimotor functions, pain and self-reported characteristics.
Methods

**METHODS**

An overview of the data collections, samples in the individual studies, designs, primary outcome measures and intervention of the 4 studies included in this thesis is presented in Table 1.

Table 1. Overview of the samples, design, primary outcome measures and intervention included in the studies.

<table>
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<tr>
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<th>Study IV</th>
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| Interview           | X     |

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<th>Neck coordination exercise</th>
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Samp: Sample; CON: Healthy control group; NS: Non-specific (non-traumatic) neck pain group; WAD: Whiplash associated disorders; VAS: Visual analogue scale; NRS: Numeric rating scale; SF-36: The Short form-36 Item health survey; NDI: The Neck disability index; DASH: Disability of arm shoulder and hand questionnaire; SES: The Self-efficacy scale; TSK: The TAMPA scale of kinesiophobia.
Methods

Subjects

The cross-sectional studies (study I, II and III) were single-blinded, i.e., the test-leading were blinded to whether subjects had neck pain or belonged to the control group.

Data collection 1 (study I and II)

Data collection 1 was included in study I and as the first sample in study II. The data collection consisted of 45 subjects with chronic neck pain, with or without traumatic association. The subjects with neck pain related to trauma were referred to as WAD (n = 21, 11 women), whereas those without traumatic association were referred to as non-specific (NS) (n = 24, 14 women). The subjects were recruited from a vocational rehabilitation centre (Alfta Rehab Center), from general practitioners and physiotherapists in the community and by advertising in local papers. The inclusion criteria for the neck pain groups were neck pain, validated by pain drawings according to Margolis et al. [197], of at least 3 months’ duration and score > 10 on the Neck Disability Index (NDI) [198] (scale 0–100). For subjects with WAD the symptoms should have presented within 2 weeks after the accident. Age- and sex-matched healthy control subjects (CON) (n = 22, 13 women) were recruited by advertising in local papers. One healthy male was excluded in study II due to invalid measurements. Inclusion criteria for controls were no history of head, neck or shoulder trauma and no current neck or shoulder pain or longer periods of constant or recurrent neck-shoulder pain. All subjects had to be right-handed and 20–50 years of age. Exclusion criteria for all groups were surgery of the neck, shoulder or back, reported injuries with fractures or luxations to the neck or shoulders, conditions of neurological or rheumatic disease (rheumatoid arthritis, pelvospondylitis) or fibromyalgia. All subjects had to be able to perform arm elevations above 110 degrees and at least 25 degrees axial rotation of the head. Mean age and median pain duration of the groups were: WAD, 37 ± 10 years and 60 months duration; NS, 37 ± 9 years and 73 months duration; CON, 36 ± 5 years.

Data collection 2 (study III)

The subjects were included as the first sample in study III and consisted of 16 NS women (mean age 48 ± 7), with a median pain duration of 132 months, and 16 healthy controls (mean age 45 ± 10). Subjects were recruited by advertising in local papers and by written and verbal information to job holders at various working places at the city of Gävle, Sweden. The inclusion criteria were neck pain of non-traumatic origin with duration of at least three months, a decreased physical functioning according to the Disability Arm Shoulder Hand (DASH) questionnaire [199] (at least 9 normalized points on question 1-19), and woman of 20-55 years of age. Pain drawings were used to confirm the location of pain in the neck region. Subjects with pain distributed below the elbow were investigated with manual examination for possible cervical radiculopathy. Subjects reporting dizziness
Methods

and/or balance disturbance were clinically investigated for possible vestibular disorder. Subjects were excluded if the clinical examination for cervical radiculopathy or vestibular disorder was positive. Other exclusion criteria were evidence of trauma in relation to the onset of symptoms, surgical operation or injury with fracture or luxation of the spine or shoulder or evidence of neurological, vestibular, psychiatric or rheumatic disease.

Data collection 3 (study II and III)

Data collection 3 was included as the second samples in study II and III. 6 subjects were excluded in study II due to previous injuries to the lower extremities, which could have influenced the postural sway assessments. In study II the sample consisted of 98 NS subjects (mean age 52 ± 9 years), with a median pain duration of 120 months and 32 healthy controls (mean age 48 ± 9 years). In study III the sample consisted of 102 NS subjects (mean age 51 ± 9 years), with a median pain duration of 120 and 33 healthy controls (mean age 47 ± 10 years). The recruitment procedure of data collection 3 was the same as for data collection 2, but invitations were also sent to women with neck pain via the social insurance authority, primary health care and occupational health services. The inclusion and exclusion criteria were the same as for data collection 2 except for age. Here women of 25-65 years of age were included.

Data collection 4 (study IV)

Fourteen NS (10 females), with the mean age of 35 ± 10 years, and a median pain duration of 60 months were included in study IV. The subjects were recruited from Alfta Rehab Center and by advertising in the surrounding area and constituted a subsample of data collection 1. The inclusion criteria were non-traumatic neck pain, location confirmed with pain drawings, with duration of at least three months, age of 18–50 years and a disability score of 10 or more on the NDI (scale 0–100). Subjects were excluded if they had evidence of surgical operation or injury with fracture or luxation of the spine or shoulder, neurological or rheumatic disease, or if they were unable to rotate the head 25° bilaterally or balance a light flat pillow on the head for five seconds (s).

Ethical approvals

All studies were approved by the Regional Ethical Review Board in Uppsala and written informed consent was obtained from all subjects before the start of each study.
Methods

Precision of goal-directed arm movement (study I)

Apparatus and data collection

The subject was seated in a rigid chair with the torso strapped to the back of the chair in order to fixate the torso while allowing free movement of the shoulder. An arm rest with an adjustable rim was placed at waist height on the subject’s right side. The rim was placed in the frontal plane to mark the starting position of the hand. A wooden pointer, extending 20 cm from the fingertip of the third digit, was attached to a plastic plate which was fixed to the hand. The target was a soft stick made of foam-rubber which was placed at eye-level in front of the subject at the distance of an arm-length to the wrist and 20 centimetres to the left of acromion. The target was positioned in the frontal plane, pointing medially to the right. Kinematic data of arm movements were recorded with an electromagnetic tracking system (FASTRAK, Polhemus Inc., USA) at a sampling rate of 30 Hz. A schematic illustration of the apparatus and test procedure is shown in Figure 1.

Figure 1. A Schematic illustration of the pointing movement task. A and C illustrate the starting position, while B and D illustrate the target position. The axes in the centre illustrate the orientation of the laboratory coordinate system. From Sandlund et al. [200]. Re-printed with permission from the Foundation for Rehabilitation Information.
Methods

Testing procedures

The task was to perform a pointing movement to the target tip as fast and accurate as possible without corrections. The movement was initiated with the command "go". The arm was held still for a second at the target position and thereafter the subject was instructed to "go to the starting position". Fifteen movements were repeated with full vision. Each movement started from the predetermined position on the arm support. At the starting position the hand with the plastic plate was held against the rim with the wrist near full dorsal extension and the lower arm was resting with the ulnar side on the arm support. 3-5 practice trials were performed before the test.

Data processing and outcome measures

The 3D coordinates of the position and movement of the pointer tip were calculated from the movement profile of the sensor attached to the plastic hand plate. The data were represented in a common global coordinate system where the coordinate axes X, Y and Z corresponded to the horizontal, depth and vertical directions respectively, in relation to the body. The start and stop of the movement were defined by a threshold of 10% of peak velocity of the pointer. The end-point precision was measured 500 ms after the stop threshold to ensure that the pointer tip remained still.

For evaluation of the end-point precision, the variable error (VE) was calculated along the separated coordinate axis (X, Y and Z). VE was calculated as the population standard deviation of the algebraic errors, i.e., the distance between the pointer and the target, for the 15 trails. In order to remove any systematic drift in the errors, which is unrelated to the response variability but will affect VE [201], the algebraic errors were detrended prior to calculation of VE. In a fast and accurate movement there is a well known trade off between speed and accuracy [115]. Peak Velocity was therefore calculated and used as a covariate in the analyses. Pointer tip velocity was calculated as the first derivate of the coordinate data with application of a low pass 4th order Butterworth filter with a cut-off frequency of 3 Hz.

Postural sway in quiet stance (study II and IV)

Apparatus and data collection

In study II (sample 1) and in study IV a static force platform (Kistler Force Measurements, type 9807, Kistler Instrumente AG, Switzerland) was used for measuring the CoP migration. The sampling frequency was 30 Hz. In study II (sample 2), a static force platform (AMTI biomechanics force platform model OR6-5, Advanced Mechanical Technology, Inc., USA) was used with a sampling frequency set to 200 Hz.

35
Testing procedures

In study II (sample 1) and in study IV, the test was performed standing barefooted in the Romberg position; with feet together, heel-to-heel and toe-to-toe. The eyes were closed and the arms were held crossed over the chest. The instruction given was, “stand as still as possible” and the test duration was 30 s. A ten s training session was given prior to the test. In study II (sample 2) the test was first performed on a firm surface and thereafter on a foam surface. Same procedures as for sample 1 were used with the following exceptions: The feet were 18 mm apart on the firm surface and 35 mm apart on the foam surface and the test duration was extended to 190 s.

Data processing and outcome measures

In study II (sample 1) and in study IV, the CoP trajectory from 26 s of the trial, excluding 4 s at the beginning of the trial, was used in the analysis. In study II (sample 2) the CoP trajectory from 182 s, excluding 8 s at the beginning of the trial, was used in the analysis.

For all samples in study II and IV, the CoP trajectory was decomposed into a slow, rambling (Ra), and a fast, trembling (Tr) component according to the method described by Zatsiorsky and Duarte [121]. The anterio-posterior (Y) and medio-lateral (X) planes of the CoP trajectory were decomposed separately and the 95% confidence area of the ellipse was calculated for the separate Ra and Tr components in the XY-plane. In study II only, the sway density variables mean distance (MD) and mean peak (MP) were calculated according to the method described by Baratto et al. [125].

Kinematics in cervical rotation (study III and IV)

Apparatus and data collection

In study III and IV cervical kinematics was measured with an electromagnetic tracking system (FASTRAK™, Polhemus Inc, USA), with a sampling rate of 60 Hz. Two receivers were used for recording the axial head rotation relative to the trunk. One receiver was positioned on the forehead and the other above the dorsal spinal process of Th2. A quintic spline (generalized cross-validation spline) [202] was used for low-pass filtering and differentiation of the angular data. The tests were fully automatized in the computer software and the instructions were pre-recorded and transmitted by loudspeakers.

Testing procedures

In study III the cervical rotations were performed in a sitting position. Each movement started from a neutral position with the head facing forward. The subject was instructed to turn the head as fast as possible to the right and to the left, after a beeping sound, in an alternating order with eyes closed.
Methods

Three rotations were performed in each direction, with half the group starting with rotation to the right and half the group to the left in randomized order. Two practice trials, one to each side, were performed prior to the test. The assessments were performed with the same method and in the same laboratory for the two different samples, but with different test leaders.

In study IV the cervical rotations were performed in a standing position with the feet together and the eyes closed. The movements were executed in two blocks of eight consecutive trials, one block of trials to the left and one block of trials to the right. In randomized order, half the group started with rotations to the left and the other half to the right. The task was to make a fast rotation of the head, from a neutral self selected starting position, as far as possible. The subject was instructed to memorize the starting position prior to each trial, and to reproduce this position as accurately as possible after each head rotation. The instructions given were "memorize your head position", "make a fast rotation of your head as far as possible" and "return to the starting position as accurately as possible". The subject was given two practice trials prior to each block of test trials.

Data processing and outcome measures

In study III, the rotation matrix of head and upper body was constructed for each time sample from the Euler angles using the ZYX cardan sequence [203]. The helical angle of head relative to upper body was then extracted from this rotation matrix. The 3D rotation velocity was calculated based on Poisson equation, which takes both body attitude and time derivative of body attitude into consideration [204]. The direction vector of the finite helical axis was estimated for each time frame, using a moving window of 4 degrees [38]. Eight variables were calculated for the outward rotation. For each trial the helical angle and 3D angular velocity data was up-sampled to 100 Hz to increase the resolution. The Peak Speed of the rotation was determined from the maximum of the 3D angular velocity profile. The start of the movement was defined as the time point when the 3D velocity passed below 10% of the Peak Speed when seeking from the Peak Speed towards the start. The stop of the movement was defined identically. ROM for the movement was calculated as the difference in helical angle between the start and stop. The definition of start and stop of movement based on the 10% of Peak Speed threshold caused the speed profile to start and end at non-zero levels. Thus the speed profile was extrapolated to zero at both ends using a quintic spline function based on the history of the profile. From this extrapolated speed profile we determined the variables; movement time (Move Time = duration of the extrapolated speed profile), time to peak speed (TTP = time from start of the of the extrapolated speed profile to Peak Speed), normalized peak amplitude (NPA = Peak Speed / Mean speed), acceleration-deceleration ratio (ADratio = TTP / (Move Time - TTP)) and speed index of deviation (SID). The latter was used as an index of how well the speed profile could be described by an optimally smooth speed profile. SID was calculated as the
Methods

root-mean square error (in %) between a fitted minimum jerk speed profile [108] and the extrapolated speed profile. To assess the magnitude of change in the direction of the rotational axis during the movement, the condition number (COND) for the direction vectors of the finite helical axis within the 10% of Peak Speed window was calculated. In general, the condition number reflects the degree of similarity between vectors in a matrix. A relatively small condition number indicates that the rotational axis direction has changed relatively much during the rotation. For all variables mean values over the 6 trials were calculated and used in the analysis. Left and right rotations were pooled since evaluation of pain location showed that a majority of the subjects had central or bilateral neck pain (sample 1; n=11 and sample 2; n=76).

In study IV, five outcome variables were calculated from the cervical rotation test. ROM was calculated as the maximal angular excursion from the starting (normal) head position. Move Time, Peak Speed and Jerk Index were calculated for the cervical rotation movement from the starting position to maximal excursion angle. A threshold of 5% of the peak angular velocity was used to define the start and stop of the movements. The variable error (VE) was used to evaluate the acuity of cervical repositioning. VE was calculated as the population standard deviation of the algebraic errors, which were calculated as the difference between the reproduced angle and the starting angle for each rotation. The Jerk Index was calculated from the third time derivative of the head-trunk angle according to the method described by Kitazawa et al. [109]. This algorithm normalizes the jerk cost with respect to movement distance and time. After removal of outlier trials (± 2 SD), pooled trials for left and right rotations were used for analyses. Mean values were calculated for all variables except for ROM where the maximal value was used.

Pain assessment and questionnaires

Pain assessment

In study I, II (sample 1), III (sample 1) and IV, self-rated pain was assessed as “pain at the moment” on a blank 100 mm visual analogue scale (VAS), on which 0 mm corresponds to “no pain at all” and 100 mm to “worst imaginable pain” [205]. For sample two in study II and III, self-rated pain was assessed as “average pain during the past week” with an 11-point numerical rating scale (NRS), ranging from 0, “no pain”, to 10, “worst imaginable pain” [206].

Questionnaires

Self-reported characteristics were assessed by five different questionnaires and additional questions. The Short Form 36 (SF-36) was used to assess general health and well being. SF-36 provides indices across 8 dimensions: limitations in physical activities (PF), limitations in social activities (SF),
limitations in usual physical role activities (RP), limitations in usual role activities because of emotional problems (RE), bodily pain (BP), general mental health (MH), vitality (VT) and general health perception (GH). It also provides 2 summary scales; the physical and mental component summary scales (PCS and MCS) [207]. Severity of symptoms and disability related to neck pain was assessed with the Neck Disability Index (NDI) [198]. The TAMPA Scale of Kinesiophobia (TSK) was used to assess fear of movement and re-injury due to movement [208]. The Self-Efficacy Scale (SES) was used to assess confidence in performing tasks and activities of daily living [209]. The Disability of the Arm, Shoulder and Hand (DASH) questionnaire was used to assess upper extremity disability and symptoms [199]. The indices of the questionnaires were normalized, i.e., expressed as percentage of the maximum score. Note that higher scores denotes more disability in NDI and DASH and greater fear of movement in TSK, whereas higher scores denotes better general health and well being in SF-36 and higher confidence in own capability in SES. The questionnaires SF-36, NDI, TSK and DASH were used for all samples in study I-IV and SES was used in study I and IV.

In study I, II and III, additional questions about symptoms and functional aspects that were not covered by the various questionnaires, but were presumed to be of importance for the performance in the various sensorimotor function tests, were included. A 6-level scale was applied for each question with alternatives corresponding to: (1) not at all/nothing, (2) weak/mildly, (3) moderate, (4) quite high/somewhat strong, (5) high/strong, (6) almost unbearable/maximal. See the description of the O-PLS association analysis below for the additional questions included in the studies (cross ref).

**Neck coordination exercise**

**Apparatus**

A novel neck-coordination exercise device (patent SE serial # 530879) was used in study IV in which the exercise task was to fine control the movements of a metal ball (weight 220 gram) on a plate fixed onto the head (Figure 2). The device consisted of a plate with exchangeable surface and a rim, weighing altogether 760 gram (Figure 2). Four different surfaces was used to increase difficulty (i.e., reduce rolling resistance) in the following order: fleece fabric (Malden Mills Polartec® Classic 100), cotton fabric, copy paper (80 g/m2), all glued on a Plexiglas board, and finally an uncovered Plexiglas board. The location of the ball at starting and target positions was monitored by LED-photocell detectors. The signals from these detectors were monitored by a PC and allowed for automation of the training, including delivery of pre-recorded verbal instructions via loudspeakers and visual instructions via light emitting diodes. A modified adjustable office chair (Kinnarps SynchroneTM 8000, Kinnarps AB, Sweden) and a custom made mirror stand, with one mirror in front of the subject and one above, were used to ensure good posture and visual feedback during the exercise.
Exercise procedures

The exercise was performed in a seated position. The subject was instructed to sit upright with lumbar support and the head balanced in line with the torso, the hips and knees about 90° flexion and the lower arms resting on armrests. The trunk was fixed to the chair via a strap placed around the subjects’ torso in order to promote movements with the neck and head rather than with the trunk. The exercise task was to move the metal ball from a starting position, by controlled movements of the head, to the centre of the plate and hold it still for three s. After succeeding with the task, or after 47 s if the task was not successfully completed, the subject was instructed to move the ball to another starting position. Light emitting diodes indicated the starting position and when the ball was at the centre of the plate. The difficulty of the task was increased by changing to a surface with less rolling resistance when the subject had acquired the skill to complete at least five trials in a block of six trials, with each trial completed within 30 s. Eight training sessions were performed two-three times per week over a four week time period. Each session included three blocks of six trials and lasted 10–15 minutes.

**Figure 2.** Schematic of the apparatus for the neck coordination exercise. From Röijezon et al. [1]. Re-printed with permission from Journal of NeuroEngineering and Rehabilitation.
Data collection, processing and outcome measures

The improvements in performing the neck coordination task was evaluated by monitoring the rate of progression to successively faster surfaces during the intervention period and by recording the trial times. The slope of the linear regression of the median trial times for each block on the fastest surface was calculated for each subject. The subject was interviewed after the last training session by the test leader asking predetermined questions in order to assess the subjective experiences of the method. Questions included in the interview were: (1) What is your overall opinion about the training method? (2) How comfortable was the plate on the head? (3) Were the instructions easy to understand? (4) Did you experience tiredness, discomfort or pain from the training? (5) Did you use any strategy when trying to succeed with the exercise task? The answers were divided into a few categories based on representative replies for each question.

To obtain information about indications on possible effects from the exercise, sensorimotor function tests and self-rated characteristics were collected before and after the intervention. Baseline assessment included postural sway, cervical rotation, NDI, DASH, SF-36, TSK, SES and VAS pain ratings. Post intervention measurements included postural sway, cervical rotations and VAS pain ratings. Six months follow up was accomplished with NDI, DASH, SF-36, TSK, SES and VAS pain ratings. (For description of outcome measurements see above)

Statistics

Statistical analyses were performed using SPSS 13.0 and 15.0 for Windows (SPSS Inc., Chicago, Illinois, USA) and for the O-PLS-analyses SIMCA-P 11.0 (Umetrics AB, Umeå, Sweden) (see Association analyses below). P-values lower than 0.05 were considered significant, except for O-PLS-analyses where other criteria were used (see below).

Group differences

*Precision of goal-directed arm movements (study I)*

Initial analyses were performed to test for possible group differences in the dependent measures. VE was analysed with mixed model analysis of variance (ANOVA) with group (NS, WAD and CON) as between-subject factor and coordinate axis (X, Y and Z) as within-subject factor, while Peak Velocity and Move Time were analysed with univariate ANOVAs. As described by Fitt’s law (see page 20), movement accuracy in a visual arm movement task is strongly related to the speed of the movement, defined as the speed-accuracy trade-off. VE was therefore analysed in a mixed-model analysis of covariance (ANCOVA), using Peak Velocity as covariate with group as between-subject factor and coordinate axis as within-subject factor. Thereafter, univariate ANCOVAs were performed for specific comparison of
pre-planned contrasts (equivalent to Dunnett’s two-sided post-hoc t-test) between neck-pain subjects and controls for the different coordinate axes.

Postural sway in quite stance (study II)

Group differences in the CoP variables Ra area, Tr area, MD and MP were evaluated with one way analysis of variance (ANOVA). Covariates were used in the model (ANCOVA) if the multivariate regression analysis (O-PLS) revealed association between anthropometric and postural sway variables (see below). Dunnett’s two-sided post-hoc test was used for comparisons between each neck-pain group and controls if significant group differences appeared in the analysis of variance. A normal distribution of the residuals of the CoP variables in the ANOVA/ANCOVAs was a criterion for using parametric tests for group comparison. If Levene’s test of homogeneity of variance was significant for the model, robust test of equality of means (Brown-Forsythe) was used.

Kinematics in cervical rotations (study III)

Unpaired t-tests were used to test for group differences and for the effect of concurrent low back pain. Sensitivity and specificity for differentiation between NS and CON were evaluated for each cervical movement variable separately as well as with all variables using stepwise linear discriminant analysis with leave one out cross-validation. For kinematic variables correlated with age, residuals calculated from a linear regression including age and the separate correlated variables were used in the analysis.

Reliability (study III)

Test-retest reliability was evaluated in sample 1 for the NS (n=16) and the CON (n=16) groups separately. Test-retest reliability can be categorised as relative or absolute. Relative reliability evaluates the relationship between sets of repeated measurements, expressed as a correlation coefficient. Absolute reliability refers to the extent to which a person's score varies on repeated measurement and is expressed in actual units or as a proportion of the measured values [210]. Intraclass correlation coefficients (ICC2,1), a two-way random effects single measure model (consistency) was calculated to reflect relative reliability. For absolute reliability the standard error of measurement (SEM) was calculated by dividing the standard deviation of the difference scores (difference between test 1 and 2) with the square root of 2. The average within-subject coefficient of variation (CV) is a measure of the relative error and was calculated using the same formula as for SEM but with the variables log-transformed [24]. CV is expressed as a percentage value and is applied to data in which the degree of agreement between tests does depend on the magnitude of the measured values, i.e., when heteroscedasticity is present. The coefficient of repeatability (CR) was calculated as 2.77 x SEM and represents the range in which 95% of the values will be found. CR is clinically useful as it represents the minimum detectable change in the unit of the measurement. To evaluate
heteroscedasticity, the correlation between the average of test I and test II and the absolute difference between test I and II was tested using Spearman’s rank correlation test. To control for bias between test occasions on group level we used paired t-tests or Wilcoxon signed rank test if data was not normally distributed. The level of significance was set at p<0.05.

Association analyses (study I, II and III)

In study I-III, association between the outcome variables from the sensorimotor function tests and self-rated characteristics (questionnaires, additional questions and pain assessments), were assessed by a modified application of Partial Least Squares projection to latent structures (PLS), i.e., Orthogonal-PLS (O-PLS) [211]. O-PLS was also used in study II to identify anthropometric factors to be included as covariates in the ANCOVAs for evaluation of group differences in the postural sway variables. PLS is a multivariate regression method which compresses information in data blocks with numerous variables into a few principal components (PCs), and reveals latent relationships between two blocks of variables, often called predictor (X) and response (Y) –variables [212]. In the studies included in the present thesis we used O-PLS [211], which separates the variance in X that is correlated to Y from the variance in X that is uncorrelated (orthogonal) to the Y-variable [211]. The O-PLS models are here described with the statistical parameters explained variation (R^2) and predicted variation (Q^2). Q^2 was calculated by cross-validation to test the validity of the model against over-fitting, i.e., incorporating random noise in the model. We considered a model to be significant if the Q^2 >0.05. The relative contribution of each x-variable to the PLS model (i.e., the correlation to Y and the relative importance in the X-block) is expressed as a VIP-value (variable importance in the projection). Generally, a VIP-value larger than 1 is considered as influential (significant) while values lower than 0.5 indicates unimportant variables [213]. We considered VIP-values larger than 1 and with a confidence interval not including 0.5 to indicate a significant x-variable for a model. The data distributions for all variables were evaluated and log transformed if recommended by the built in function of the software. All analyses were performed on mean-centred and scaled data [213].

In study I, the residuals from a linear regression model (VE as dependent variable and Peak Velocity as predictor) was used as the response variable (Y) in the O-PLS analysis. The residuals (VEr) were calculated separately for each coordinate axes. Thereby a velocity controlled VE was obtained for each direction. As predictors (X-variables) we used the subscales PF, SF, BP, MH, VT and GH from the SF-36 and the total scores of the TSK and SES, since each of these subscales/scores may be considered distinct theoretical concepts. Individual questions were used from NDI: pain intensity; headache; concentration difficulties and sleeping disturbances and from DASH: difficulty opening a tight or new jar; difficulty placing an object on a shelf above your head; difficulty doing heavy household chores; difficulty carrying a shopping bag or briefcase; difficulty carrying a heavy object; difficulty changing a light bulb overhead; weakness in arm, shoulder
Methods

or hand; paraesthesia in arm shoulder or hand; pain in the arm, shoulder or hand. Additional questions on symptoms were how much subjects experienced with regard to: dizziness; balance disturbance; sensory disturbance; clumsiness of the hands; tenderness in the neck; neck pain during rest and neck pain during activity. Additional questions on physical functioning were: difficulty with lifting; - carrying and – throwing; difficulty taking a shirt on and off; difficulty bending the head forward; - backward; - to the right; - to the left as well as rotating the head to the right and - to the left. Pain assessments with VAS and pain duration were also included. In total, 40 variables were included as predictors into the models.

In study II, first O-PLS analyses were used to evaluate associations between the CoP variables: Ra area, Tr area, MD and MP and the anthropometric variables: body mass, height and shoe size. A separate model was calculated for each CoP variable, which was set as response variable (Y) and the anthropometric variables as predictors (X). In the second O-PLS analysis, we used the CoP variable/-s that had shown group differences between NS and CON in the ANOVA/ANCOVA, as the response variable (Y). As predictors (X-variables) we used the subscales PF, SF, BP, MH, VT and GH from the SF-36 and the total scores of the TSK, as well as the sum of DASH questions 1-19. Individual questions from NDI: pain intensity; headache; concentration difficulties; sleeping disturbance and symptom questions from DASH: arm, shoulder or hand pain; paraesthesia in arm, shoulder or hand and weakness in arm, shoulder or hand, were used. Additional questions on symptoms: dizziness; balance disturbance; sensory disturbance; jaw disorder; nausea; sensitivity to light; sensitivity to sound; neck pain during rest and neck pain during activity and physical functioning: difficulty running and difficulty bending the head forward; - backward; - to the right; - to the left as well as rotating the head to the right and - to the left. Pain assessments with VAS (sample 1) or NRS (sample 2) and pain duration were included in the models. In total, 33 variables were entered as predictors into the models.

In study III, the cervical kinematic variable that best could discriminate between the groups was set as the response variable (Y). As predictors (X-variables) we used the subscales PF, SF, BP, MH, VT and GH from the SF-36 and the total scores of the TSK, as well as the sum of DASH questions 1-19. Individual questions were used from NDI: pain intensity; headache; concentration difficulties, sleeping disturbances and car driving and from DASH: pain in the arm, shoulder or hand; paraesthesia in arm shoulder or hand and weakness in arm, shoulder or hand. Additional questions on symptoms and physical functions were: dizziness; balance disturbance; sensory disturbance; clumsiness of the hands; neck pain during rest, neck pain during activity; jaw disorder; difficulty swallowing; sensitivity to light; sensitivity to sound; nausea; neck; -stiffness, -tenderness, -tension; -fatigue; -weakness; -crepitations and –lockings, difficulty running; difficulty bending the head forward; - backward; - to the right; - to the left as well as rotating the head to the right and - to the left. Pain duration and level of physical
Methods

activity were also included. In total, 45 variables were included as predictors into the models.

Pre- and post neck coordination exercise differences (Study IV)

For analysis of improved performance of the exercise task, the slope of the linear regression of the median trial time per block were analysed with one sample t-test. Possible correlations between the sensorimotor variables: Ra area and Tr area of postural sway and ROM, VE, Jerk Index, Move Time and Peak Velocity of cervical rotation was tested by calculating Pearson’s correlation coefficient between all variables. Paired t-tests were used to assess changes between the pre- and post-intervention measurements for non-correlated variables, while repeated measures MANOVA was used for correlated variables. If the MANOVA was significant, paired t-tests were performed to identify the variables that contributed to the effect. Variables with skewed distribution were log transformed before analysis. Possible changes in SF-36, NDI, DASH, SES and TSK were analysed with Wilcoxon signed ranks test and the VAS measurements with the Friedman test.
RESULTS

Group differences in sensorimotor functions

Precision in goal-directed arm movements (study I)

Peak Velocity was included as a covariate (due to the speed-accuracy trade-off, cross-ref) in a mixed model ANCOVA with group as between-subject factor and coordinate-axis (X, Y and Z) as within-subject factor. Significant effects were revealed for group (p=0.017), coordinate axis (p=0.038) and for the covariate Peak Velocity (p<0.001), but not for group x coordinate axis (p=0.286). These results indicate that there was a group difference in VE when controlling for Peak Velocity, which was confirmed to be a strong modifier. Moreover, there was a difference in VE between the three coordinate axes, but this difference was similar between the groups. Post-hoc tests revealed larger VE for NS compared to CON (p=0.020) and also for WAD compared to CON (p=0.034) (Figure 3). Comparison of VE for the different coordinate axis revealed lower VE in Z-direction compared to both X- and Y-direction (p=0.002 and p<0.001, respectively), but no difference was found for VE in X-direction compared to Y-direction (p=0.127). Group differences in VE for the separate coordinate axes were tested with univariate ANCOVAs with Peak Velocity as covariate. Increased VE were found in both depth (Y-axis) and vertical (Z-axis) direction, but not horizontal (X-axis) direction for NS compared to CON (p=0.030, p=0.032 and p=0.086, respectively). Increased VE was found for WAD compared to CON in the depth direction (p=0.010), but not the horizontal or vertical directions (p=0.200 and p=0.164, respectively).

Postural sway in quite stance (study II)

Weight was the only anthropometrical variable that was associated with the CoP-derived variables. The VIP value was 1.15 for Tr area, 1.13 for MD and 1.10 for MP. Ra area was not significantly correlated with the anthropometric variables (Q2<0.05). In sample 2 there was no significant correlation between the anthropometric variables and the CoP variables in either the fixed surface or the foam surface conditions (Q2 < 0.05). Weight was therefore included as a covariate in the group analyses for Tr area, MD and MP, but not for Ra area in sample 1, while no covariate was used in the group analyses in sample 2.
Results

Figure 3. Box plots (interquartile ranges) for the end-point variable error (cm) controlled for Peak Velocity separately for the CON, NS and WAD groups and directions. Asterisks indicate significant differences of $p<0.05$ (Dunnett’s t two-sided post-hoc with the CON group). From Sandlund et al. [200]. Re-printed with permission from Foundation for Rehabilitation Information.

Due to a significant difference in age between NS and CON for sample 2, and significant correlations found between age and Tr area, MD and MP, age was used as covariate in the models for these variables in sample 2.

Figure 4 shows representative examples of raw data of the CoP trajectory and the Ra and Tr components for one subject from the control and WAD group separately. Descriptive statistics for the CoP-based variables for each sample and group is shown in Figure 5.

In sample 1, a group difference was seen for Ra area ($F(2,63)=3.951$, $p=0.024$). Post-hoc test revealed a significant difference between the WAD group and CON ($p=0.013$), but not between NS and CON ($p=0.174$). No group difference was seen for Tr area, MD or MP ($p>0.05$), using weight as a covariate in the models.

For sample 2, the residuals of the repeated-measures ANOVA for Ra area and Tr area were not normal-distributed, therefore the square root of these variables were used in the analysis. A larger Ra area was seen for NS compared to CON ($F(1, 126) = 5.565$, $p=0.020$). The surface factor was significant ($F(1, 126) =179.031$, $p<0.001$) but there was no interaction between surface condition and group ($F(1, 126)= 0.360$, $p=0.55$). Tr area, MD and MP were not significantly different between groups ($p>0.05$).
Results

Figure 4. Exemplar plots of Center of Pressure (CoP) data and the rambling (Ra) and trembling (Tr) components from one control subject (A and C) and one subject with whiplash-associated disorders (B and D). A and B show data for the anterior-posterior (AP, upper panels) and medio-lateral direction (ML, lower panels). C and D display the migration of the center of pressure, rambling and trembling in the horizontal plane. Note that the trembling migration is expressed in coordinates relative to the rambling migration.

The analyses of effect of comorbidity of low back or leg pain in the NS group in sample 2 revealed a larger Ra area in the sub-group of neck pain subjects with concurrent low back pain (n=53) compared to neck pain subjects without low back pain (p=0.007). The sub-group of NS with leg pain (n=33) did not differ from the NS subjects without leg pain, nor did the sub-group of NS without low back pain (n = 45) did not differ from CON (p>0.05).
Kinematics of maximal speed cervical rotations (study III)

For evaluation of group differences, the data of the pooled subjects from sample 1 and 2, NS (n=118) and CON (n=49), where included in the analyses. The NS group had a significantly higher age compared to CON. Pearson's correlation analysis was therefore used to evaluate if age had an effect on the kinematic variables of the cervical rotation test. The analysis showed that ROM was negatively correlated with age in both groups. Peak Speed was negatively correlated with age in CON, while there was a positive correlation for NPA with age in NS. Therefore, the residuals from a linear regression analysis between age and the separate variables were used to analyse group differences in Peak Speed, ROM and NPA.

Group differences were revealed for all variables except for NPA and AD-ratio (Table II). For each separate variable we used linear discriminant
Results

-analysis to evaluate their sensitivity and specificity for differentiating between NS and CON. Highest sensitivity was found for Peak Speed, while TTP had highest specificity (Table II).

Several of the variables were significantly correlated with Peak Speed. This correlation implies that the variables share common variance to a substantial extent. In order to evaluate respective contribution of each kinematic variable to discriminate between NS and CON, a linear discriminant stepwise analysis was performed using group as grouping variable. The model rendered Peak Speed (F = 51.5) and COND (F = 28.5) as the only significant classification variables. The model had a sensitivity of 76.3% and a specificity of 77.6%.

Possible influence on the cervical rotation test due to comorbidity was evaluated with separate t-tests between NS with and without concurrent low back pain, and also between NS without low back pain and CON. It was revealed that subjects in the neck pain group with concurrent low back pain (n = 62) had a slower Peak Speed compared to neck pain subjects without low back pain (p = 0.024). The sub-group of NS without low back pain (n = 56) was in turn significantly slower than CON (p = <0.01).

Test-retest reliability (study III)

In study III, test-retest reliability was evaluated for the cervical rotation variables in sample 1 for the separate groups of NS (n = 16) and CON (n = 16) (Table II). There was no significant bias between test occasions for any of the variables (p > 0.05). For Peak Speed, ROM, Move Time, TTP and AD-ratio, ranges for ICC were moderate to high in NS and CON c.f. [214, 215]. These variables displayed reasonably low CV, when compared to SID and COND, in NS and CON. SID and COND showed both low ICCs and high CVs in NS and CON. NPA on the other hand showed low ICC in combination with low CV for both groups. A significant difference between the groups was present for SEM for COND, evident by the fact that the CI did not overlap between the groups.
Table II. Left section: Reliability statistics for the kinematic variables for sample 1 (mean±SD or 95% confidence intervals). Right section: Sensitivity and specificity obtained from linear discriminant analyses using group (NS-CON) as grouping variable, along with t-values for group difference in mean, for sample 1 and 2 pooled together.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Test 1</th>
<th>Test 2</th>
<th>ICC</th>
<th>SEM (0.95-0.97)</th>
<th>CR</th>
<th>CV</th>
<th>Sensitivity</th>
<th>Specificity</th>
<th>t-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Speed (degree/s)</td>
<td>CON</td>
<td>365±125</td>
<td>345±82</td>
<td>0.79 (0.48-0.92)</td>
<td>41 (31-54)</td>
<td>114</td>
<td>12.4 (0-19.6)</td>
<td>74.6%</td>
<td>73.5%</td>
</tr>
<tr>
<td>ROM (degrees)</td>
<td>NS</td>
<td>271±125</td>
<td>253±118</td>
<td>0.92 (0.79-0.97)</td>
<td>33 (25-52)</td>
<td>93</td>
<td>17.6 (12.7-28.6)</td>
<td>64.4%</td>
<td>71.4%</td>
</tr>
<tr>
<td>Move Time (ns)</td>
<td>CON</td>
<td>452±104</td>
<td>469±91</td>
<td>0.64 (0.21-0.86)</td>
<td>4.2 (3.1-6.4)</td>
<td>11.5</td>
<td>6.9 (5.1-10.9)</td>
<td>64.4%</td>
<td>79.6%</td>
</tr>
<tr>
<td>TTP (ms)</td>
<td>NS</td>
<td>624±208</td>
<td>634±178</td>
<td>0.76 (0.41-0.91)</td>
<td>09 (71-149)</td>
<td>266</td>
<td>13.4 (9-21.4)</td>
<td>67.8%</td>
<td>65.7%</td>
</tr>
<tr>
<td>NPA</td>
<td>CON</td>
<td>3.3±0.14</td>
<td>2.3±0.17</td>
<td>0.45 (0.38-0.82)</td>
<td>0.13 (0.10-0.20)</td>
<td>0.36</td>
<td>5.7 (4.1-8.9)</td>
<td>59.3%</td>
<td>36.7%</td>
</tr>
<tr>
<td>AD-ratio</td>
<td>NS</td>
<td>0.8±0.29</td>
<td>0.8±0.18</td>
<td>0.37 (0.16-0.73)</td>
<td>0.11 (0.08-0.18)</td>
<td>0.35</td>
<td>5.0 (3.7-7.9)</td>
<td>61.0%</td>
<td>49.0%</td>
</tr>
<tr>
<td>SID (%)</td>
<td>CON</td>
<td>13.3±5.0</td>
<td>14.5±5.3</td>
<td>0.36 (0.16-0.73)</td>
<td>4.1 (3.0-6.4)</td>
<td>11.4</td>
<td>30.9 (22.0-51.7)</td>
<td>58.5%</td>
<td>69.4%</td>
</tr>
<tr>
<td>COND (a.u.)</td>
<td>NS</td>
<td>18±12.3</td>
<td>15±6.5</td>
<td>0.16 (0.05-0.78)</td>
<td>3.4 (2.5-5.5)</td>
<td>9.4</td>
<td>24.2 (17.3-39.8)</td>
<td>53.4%</td>
<td>69.4%</td>
</tr>
</tbody>
</table>

NS: non-specific neck pain group; CON: healthy control group; ROM: Range of movement; Move Time: Movement time; TTP: Time to peak speed; NPA: Normalized peak speed amplitude; AD-ratio: Acceleration-deceleration ratio; SID: Speed Index of deviation; COND: Condition number for finite helical axis direction vectors; ICC: Intraclass correlation coefficient; SEM: Standard error of measurement; CR: Coefficient of repeatability; CV: Coefficient of variation. † Heteroscedasticity. ** p < 0.01 (t-tests)
Results

Associations between altered sensorimotor functions and self-rated characteristics (study I, II and III)

In study I, II and III, associations between self-rated characteristics and sensorimotor variables that revealed significant group differences were evaluated using O-PLS regression analysis. Table III displays the significant predictors revealed in the O-PLS analyses.

In study I, \( \text{VE}_r \) (VE controlled for Peak Velocity) of pointing precision in depth direction was used as response variable since the variability in depth was largest and discriminated both neck pain groups from controls. The O-PLS model for the NS group explained 68.3% of the variance in \( \text{VE}_r \) and the predictive capacity, obtained from the cross-validation, was 39.8% (\( R^2_Y = 0.683 \), \( R^2_X = 0.122 \), \( Q^2 = 0.398 \)). Seven significant predictors were revealed in the model (Table III). The O-PLS model for the WAD group explained 42.6% of the variance in \( \text{VE}_r \), with a predictive capacity of 24.9% (\( R^2_Y = 0.426 \), \( R^2_X = 0.387 \), \( Q^2 = 0.249 \)). The model revealed 9 significant predictors (Table III).

In study II, \( \text{Ra area} \) was the only CoP-derived variable of the quiet stance test that revealed group differences and was therefore used as response variable in the association analyses. In the WAD group in sample 1, the O-PLS model explained 41% of the variance in \( \text{Ra area} \) and the predictive capacity was 17% (\( R^2_Y = 0.41 \), \( R^2_X = 0.31 \), \( Q^2 = 0.17 \)). The model revealed 7 significant predictors (Table III). No association analysis was performed for the NS group in sample 1 since there was no group difference compared to CON. No significant O-PLS model appeared for the NS group in sample 2 (\( Q^2 < 0.05 \)).

In study III, \( \text{Peak Speed} \) was the kinematic variable of the cervical rotation test that best could discriminate between NS and CON. The O-PLS model explained 18.1% of the variance in Peak Speed and the predictive capacity was 10.2% (\( R^2_Y = 0.181 \), \( R^2_X = 0.213 \), \( Q^2 = 0.102 \)). Eleven significant predictors were revealed for the NS group (Table III).

Neck coordination exercise (study IV)

The skill to perform the exercise task was improved by all subjects, shown by the fact that all subjects progressed to the most difficult condition, i.e., the fastest surface, and that the median time per block on the fastest surface decreased significantly (mean slope = -1.4 s/block, \( p < 0.001 \)).
Table III. Orthogonal Partial Least Squares analysis of sensorimotor variables revealing group differences between the neck pain groups and healthy controls in study I-III using self-assessed subject characteristics as predictors. The Variable Influence on Projection (VIP) and the lower limit of the confidence interval (CI) for the VIP are shown for the significant predictors, i.e., with VIP > 1 and a lower limit of VIP CI > 0.5

<table>
<thead>
<tr>
<th>Sensorimotor variable</th>
<th>Predictors for NS</th>
<th>VIP (CI)</th>
<th>Predictors for WAD</th>
<th>VIP (CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>VE pointing precision (study I)</strong></td>
<td>Rotating the head to the left</td>
<td>2.18 (1.54)</td>
<td>Bodily pain (SF-36)</td>
<td>1.74 (1.40)</td>
</tr>
<tr>
<td></td>
<td>Rotating the head to the right</td>
<td>2.16 (1.52)</td>
<td>Balance</td>
<td>1.61 (0.62)</td>
</tr>
<tr>
<td></td>
<td>Bending the head to the left</td>
<td>1.90 (1.51)</td>
<td>Social functioning (SF-36)</td>
<td>1.52 (1.01)</td>
</tr>
<tr>
<td></td>
<td>Bending the head to the right</td>
<td>1.90 (1.53)</td>
<td>VAS</td>
<td>1.32 (0.65)</td>
</tr>
<tr>
<td></td>
<td>Bending the head forward</td>
<td>1.80 (0.75)</td>
<td>Neck extension</td>
<td>1.28 (0.71)</td>
</tr>
<tr>
<td></td>
<td>Take a shirt off and on</td>
<td>1.65 (0.94)</td>
<td>Carry a shopping bag (DASH)</td>
<td>1.22 (0.83)</td>
</tr>
<tr>
<td></td>
<td>Bending the head backward</td>
<td>1.60 (1.01)</td>
<td>Lifting</td>
<td>1.16 (0.50)</td>
</tr>
<tr>
<td></td>
<td>Carrying</td>
<td>1.16 (0.54)</td>
<td>Neck lateral flexion left</td>
<td>1.07 (0.50)</td>
</tr>
<tr>
<td></td>
<td>Ra area postural sway (study II, sample 1)</td>
<td>DASH 1-19</td>
<td>1.98 (0.88)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Running</td>
<td>1.84 (0.88)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Balance disturbance</td>
<td>1.67 (0.58)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sensory disturbance</td>
<td>1.48 (0.61)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sensitivity to light</td>
<td>1.33 (0.67)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Concentration difficulties (NDI)</td>
<td>1.29 (0.79)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Social functioning (SF-36)</td>
<td>1.01 (0.54)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Peak Speed of Cervical rotation (study III)</td>
<td>Running</td>
<td>1.86 (1.29)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sleeping disturbances</td>
<td>1.73 (0.58)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Body Pain (SF-36)</td>
<td>1.57 (0.99)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Arm, shoulder or hand pain (DASH)</td>
<td>1.55 (1.14)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bending the head to the left</td>
<td>1.42 (1.03)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bending the head to the right</td>
<td>1.41 (1.04)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pain intensity (NDI)</td>
<td>1.33 (0.74)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bending the head backward</td>
<td>1.28 (0.64)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rotating the head to the left</td>
<td>1.19 (0.72)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rotating the head to the right</td>
<td>1.16 (0.82)</td>
<td></td>
</tr>
</tbody>
</table>

The interview after the exercise period revealed that all subjects found the instructions easy to understand and none of the subjects were negative to
the exercise method. Experience of tiredness, discomfort and pain from the training, as well as post exercise soreness was common in the initial phase, but were mainly transient. However, one subject reported discomfort from wearing the device on the head as well as temporary pain during the exercise throughout the intervention period. The strategies used to complete the task were deep concentration on the task, take it easy, perform small movements and relax.

The correlation analyses of the sensorimotor variables revealed that Jerk Index, Move Time and Peak Velocity of cervical rotation were correlated (p<0.001), and were therefore analysed with repeated measure MANOVA. There was a significant change pre- to post intervention (p=0.045), with post-hoc tests indicating that mainly Jerk Index contributed to the effect (p=0.032), while no significant changes were found for Move Time (p=0.320) or Peak Velocity (p=0.573). The remaining sensorimotor variables were not correlated and were therefore analysed with paired t-tests. A decrease in Tr area (p=0.019) of postural sway was revealed, whereas the remaining sensorimotor variables Ra area, cervical rotation ROM and cervical repositioning VE did not change significantly (p-values 0.387, 0.480 and 0.208, respectively). There was a non-significant decrease in VAS scores after intervention and at six-months follow up (median and IQR before: 49, 21–75; after: 18, 8–30; follow up: 28, 21–58, p = 0.183. n = 11). The evaluation with questionnaires at the six-months follow up displayed significant improvements in general health for three out of eight dimensions of SF-36; physical functioning (p=0.026), vitality (p=0.006) and social functioning (p=0.007). Also, improved arm-hand function measured with DASH (p=0.038) and a reduced fear of movement was shown as reduced scores in TSK (p=0.013)
DISCUSSION

Main findings

The main findings in study I-III were that subjects with neck pain presented a reduced precision in fast pointing movements (study I), increased postural sway, shown as an increase magnitude of the slow component, in quite stance (study II) and reduced Peak Speed in maximal speed cervical axial rotations (study III) compared to healthy controls.

Associations with self-rated characteristics were revealed for each of the tests in study I-III. Self-rated difficulties performing neck movements were related to reduced precision in arm movements (study I) and reduced Peak Speed in the cervical rotations (study III), while self-rated balance disturbance was one of the significant predictors for increased postural sway (study III) in the subjects with WAD. Concurrent low back pain was associated with increased magnitude of the slow component in postural sway and reduced Peak Speed in maximal speed in cervical axial rotation in NS.

Assessment of test-retest reliability (study III) supported that the test of cervical rotation with maximal speed could be a useful tool for assessment and evaluation of treatment effects in neck pain disorders.

The main findings of the pilot study on neck coordination exercise (study IV) were that the applicability of the method was confirmed as the subjects improved their skill to perform the exercise task and expressed an overall positive opinion about the exercise method. Significant improvements in some of the sensorimotor function variables and questionnaire scores indicate possible positive effects. Together these findings justify a randomized controlled trial evaluating the neck coordination exercise.

Sensorimotor functions in chronic neck pain

Pointing precision in fast arm movements (study I)

In study I we hypothesised that people with chronic neck pain would have a reduced neck-shoulder proprioception which would be reflected by a decreased precision in fast pointing movements. A significant increase in VE was revealed for both NS and WAD. Since Peak Velocity influenced VE, we controlled for Peak Velocity in the analysis. This is in accordance with the speed-accuracy trade off defined by Fitts [115]. Another way to control for speed would be to define a constant trial time for each movement, e.g., via a metronome. This would however make the task more constrained and thus less similar to daily movements. A second hypothesis was that the pointing precision would be reduced mainly in the depth direction, which has been suggested to be more dependent on proprioception compared to horizontal or vertical direction in visual reaching tasks [114]. This hypothesis was not supported by our findings. Although the differences in VE between the neck
patient groups and controls were largest in the depth direction, these were not significantly different from the group differences in the horizontal or vertical directions. However, impaired proprioception may still be an explanation for the reduced precision in the neck pain groups since both proprioception and vision contribute to movement precision in all directions, although to various extent. Further studies including for instance muscle vibration or blindfolded subjects may shed further light on these mechanisms.

Postural sway in quiet stance (study II)

In accordance with earlier studies [33, 81, 85, 87], subjects with WAD and NS presented increased postural sway in quiet stance.

The increased Ra area indicates impaired sensory feedback due to noise in sensory information and/or central processing when estimating the position and movement of CoM [120]. There were no significant group differences in Tr area or MD, which suggest that there was no difference in the control of estimated CoM compared to controls. The lack of any group differences in MP implies that there were no differences in the time interval between the postural commands between the groups.

Weight was correlated to Tr area, MD and MP, but not to the slow component Ra area in the mixed gender group (sample 1). This may be due to that the former variables represent phenomena of the controlling forces counteracting the instability of the toppling gravitational force of the body. The slow component on the other hand is considered to be more related to sensory feedback and therefore less likely to be affected by anthropometrics. The fact that anthropometrics was not significantly associated with any of the postural sway variables in sample 2 may be due to that the sample included women only. The effect of anthropometrics when comparing postural sway between women and men has previously been highlighted [216]. The results also revealed a significant effect of age on Tr area and MP so that their magnitude increased with age. Significant interactions were also found between age and testing condition for Tr area and MP. This finding support recent research showing that the magnitude of the controlling forces in quiet stance increase with age [217]. The effect may be related to an age-related postural adaptation described as a stiffness strategy which has been proposed in previous studies, e.g., [218].

Together these results support that decomposing the CoP signal into its slow and fast component contributes with enhanced insight into the mechanisms behind postural control in quiet stance. The findings also imply that weight and age should be considered as a potential confounder in analysis of the fast component of postural sway when comparing groups including different ages or genders.

Postural control disturbances in chronic neck pain disorders have mostly been attributed to altered proprioceptive information from the neck [e.g., 119]. A sensory mismatch may thereby emerge between visual, vestibular and somatosensory input, which aggravates estimation of the body alignment and movement [119]. This reasoning was partly supported by
Discussion

by the increased magnitude of the slow component of postural sway in neck pain groups. However, the findings that neither pain ratings nor difficulties performing cervical movements was associated with postural performance, display that neck pain per se is not the only mechanism causing postural control disturbance in chronic neck pain disorders. Instead the results showed that concomitant low back pain in NS was associated with an increased magnitude of the Ra area. This may indicate that the altered postural control was largely related to low back pain rather then neck pain, or that generalised spinal pain play a large role on postural control alterations.

Kinematics of fast cervical rotations (study III)

The neck pain group carried out the maximal speed cervical rotation test with slower Peak Speed compared to healthy controls, which is in line with previous studies [38, 39]. In contrast to the present study, Grip et al [38] did not find any group differences in COND, which may be explained by their much smaller sample sizes in combination with the fact that COND had poor test-retest reliability. In spite of the poor reliability the higher COND in the NS group and the fact that COND was significant in the linear discriminant regression model suggests that evaluation of the magnitude of change in rotations axis direction during the movement is useful in assessment of kinematics in fast cervical rotations in people with neck pain. The smaller deviation of the axis of rotation during the movement may be explained by reduced conjunct motions in the NS group, which is similar to the findings of Woodhouse and Vasseljen [36].

From the separate single classification variable discriminant models we saw that other variables, such as ROM, Move Time, TTP and SID, could also discriminate between groups with reasonable sensitivity and specificity. However, these variables were all significantly correlated with Peak Speed, which probably explains why they were excluded in the step wise linear discriminant model. In accordance with this reasoning, COND, that were included in the model together with Peak Speed only showed a weak correlation with Peak Speed. In line with our data, Feipel et al [40] found differences between patients with cervical disc hernia or WAD and healthy controls for a kinematic variable comparable to SID. In our study, however, the group difference for SID could largely be explained by differences in Peak Speed between the groups.

Evident by the unpaired t-tests and the linear discriminant analyses, Peak Speed was the variable that best could discriminate between NS and CON. The slower movements could be due to altered motor control, but also to fear avoidance behaviour. TSK, which was included in the association analysis between Peak Speed and self-rated characteristics, did display a high VIP value. The confidence interval, however, were large and TSK did therefore not turn out as a significant predictor in the model. This speaks against fear avoidance being a main explanation for the slower movements in subjects with neck pain. However, neither can it be completely ruled out as a contributor to the slower speed in NS.
Association between sensorimotor functions and self-rated characteristics

The multivariate regression analyses (O-PLS) revealed significant association between self-rated characteristics and the sensorimotor functions tested in study I-III in the neck pain groups. The predictive ability ranged from 10.2% to 39.8%, with the largest predictive ability for pointing precision and lowest for maximal speed cervical rotations. Significant associations were found between self-rated neck function and reduced precision in a visual pointing task in both NS and WAD in study I. Self-rated neck function was also significantly associated with reduced Peak Speed in the cervical rotation test in study III in the neck pain group. The strongest predictor for a reduced Peak Speed in the cervical rotation test was difficulty driving a car. Notably, car driving may involve fast cervical rotations, for example when quickly scanning for approaching vehicles from the left and the right at an intersection, which may explain this predictor. Together these results support the validity of the sensorimotor tests in chronic neck pain disorders.

Self-rated balance disturbances was a significant predictor for increased postural sway in the WAD group (study II), which is in line with a previous study where increased sway was found in subjects with WAD suffering of dizziness compared to those without dizziness [87]. In WAD, also other predictors such as altered sensations and reduced arm functioning were significant predictors. In the NS group (as mentioned above) it was found that concurrent low back pain was associated with increased postural sway. This indicates that neck pain per se may not be the main contributor to disturbed postural control, but rather more generalized sensory and spinal pain symptoms. This implies that postural control should be addressed in the therapeutic management particularly in WAD with self-reported balance, arm functioning or sensory disturbances and in NS with concurrent low back pain.

A correspondence of the association of arm functioning and postural control was found in the WAD group in data collection 1, which were included in both study I and II. It was found that self-reported poor balance was a significant predictor for poor pointing precision in the WAD group in study I, while the same WAD group, when included in study II, displayed that a reduced self-rated arm functioning was a significant predictor for increased postural sway. These findings indicate a close relation between postural control and arm functioning in chronic WAD.

Reliability of measurements

For measurements to be useful in research and practice, the outcome variables should be reliable, i.e., stable over time and sensitive to detect clinically relevant changes. The reliability analysis (study III) demonstrated the highest relative reliability for Peak Speed among the cervical kinematic variables. The absolute reliability for Peak Speed also supported the
usefulness of this variable for evaluation purposes. COND, on the other hand, displayed low relative reliability values and less precise estimates of absolute reliability, which needs to be considered when evaluating possible differences between or within groups. Nevertheless, COND turned out a significant discriminator between the groups in study IV, which implies that it is possible to detect differences in larger samples.

The relative reliability indicated by the ICC values is considered moderate to high [214, 215] for all variables except NPA, SID and COND. For NPA, this may partly be explained by a small between-subject variation in the measurement values, displayed by the low CV of about merely 5%. The low test-retest variability for TTP and NPA, which are descriptors of the shape of the speed profile, suggest that they represent stable motor control aspect of the movement. This is in accordance with the minimal jerk model, predicting that a point-to-point movement is planned by the CNS to be maximally smooth with a symmetric bell-shaped speed profile [108]. The relatively high CV in SID and AD-ratio is, however, not in line with the minimal jerk model. The large variation between test occasions in these variables could be explained by an extensive variability of the deceleration phase of the movement. It is possible that this would be different if the movement task involved an explicit target, such as pointing with a head mounted laser pointer, or using audio feedback or kinesthetic guiding.

**Neck coordination exercise**

**Applicability of the method**

The applicability of the exercise method was confirmed by the fact that all subjects improved their skills to perform the coordination task and most subjects were overall positive to the exercise. Transient adverse effects such as tiredness, discomfort, pain and post-exercise soreness were common in the early phase, and were regarded as normal reactions due to unaccustomed exercise. One subject, however, found the device uncomfortable to wear and also experienced transient pain throughout the intervention period. It is possible that some modifications, e.g., using a lighter ball could have solved this inconvenience. Due to standardisation issues, this was not tested in the study. We considered the design of the task and the progression of level of difficulty well adapted for the target population. The intervention was however short, only four weeks, and additional levels of increased difficulty is most likely necessary during longer intervention periods to optimise the effect.

**Changes in sensorimotor functions, pain and self-rated characteristics**

The reduction in Tr area of postural sway and in the Jerk Index of cervical rotations indicate that there may have been transfer effects from the exercise task to non-task specific sensorimotor functions, such as improved postural
control and cervical movement smoothness. These effects may on the other hand be simple retest effects. Former test-retest data on the same variables did, however, not show any retest effects, which contradicts such an interpretation. In agreement with our findings, improvements in postural sway have been reported in previous intervention studies for neck pain using exercises for cervical muscles [219, 220]. There was no effect of training on cervical repositioning, which is in contrast to previous studies on cervical proprioception and coordination exercises [178, 183]. This contrasting finding may imply that cervical position sense was not influenced by our exercise. Another explanation may be the different methods used for assessment of cervical repositioning. Cervical repositioning was in our intervention study assessed with the subject in a standing position, performing fast movements. The previous studies [178, 183] included tests with the subject seated, performing slow movements.

No significant improvements were found in VAS pain ratings, which is contrary to several reports on cervical proprioception and coordination exercises [178, 180, 183]. It may be that the exercise has no effect on pain, or that the short intervention period and the small dosage (8 exercise occasions) was insufficient.

Significant improvements were seen in some of the questionnaire scores at 6-months follow up. Since we did not have a control group we cannot at this point distinguish intervention effects from natural recovery over time. The self-rated improvement in arm, shoulder and hand function measured with DASH indicates a positive effect on arm functioning. The association between arm function and neck pain disorders is supported by study I, showing a reduced pointing precision in fast arm movements in subjects with chronic neck pain of both traumatic and non-traumatic origin. This underpins the value of assessing sensorimotor function of the arm and hand in neck pain. Also TSK showed reduced score at the 6 month follow up, which may indicate an exercise effect of reduced fear of re-injury due to movement. This is in accordance with a previous study on WAD, where positive effect were found in TSK at 3-months follow up after supervised individually adjusted physical exercise compared to home exercise [221]. The effect on TSK in the supervised WAD group was however abolished at 9-months follow up.

Possible mechanisms behind the exercise effects

The improved skill to perform the task is likely related mainly to neurological rather than morphological muscle adaptations since the intervention period lasted for only four weeks. Early improvements in strength training are mainly due to neurological factors, e.g., coordination of muscle activation, while changes in muscle morphology become more evident after several weeks of training [see e.g., 222].

Possible mechanisms behind the improvements in sensorimotor functions and self-rated characteristics may relate to restoring of mechanisms that have been proposed in pathophysiological models described in the introduction (see page 22). One possible mechanism behind
the improvements in postural sway and smoothness of cervical movement after the exercise period may be enhanced proprioceptive signal transmission and neuromuscular function of the deep cervical muscles. According to the muscle spindle model [128] it seems likely that exercises involving small controlled movements of the head may improve the function of the deep cervical muscles, which are highly important for sensing the movement and position of the head in relation to the trunk. Moreover, disuse related to immobilization of the cervical spine by a one week constant use of a cervical collar was associated with a deteriorating effect on sensorimotor functions such as eye-movements and postural control [223].

A puzzling finding, though, is that in study II we found an increased postural sway of the slow component in the neck pain groups, while in study IV, a reduced sway of the fast component was indicated after the neck coordination exercise. A mechanistic interpretation of this result is that increased postural sway in people with chronic neck pain is mainly due to increased noise in the input or processing of sensory information. The improvement after exercise, however, indicates reduced amplitude of the controlling forces. A speculative explanation is that the postural control system may use alternative strategies. Possibly the effects of the exercise were due to generation of new motor behavior rather than just normalisation of sensorimotor functions. The fact that no changes were seen for the slow component of the postural sway, or in cervical repositioning, challenges the idea of improved cervical proprioceptive input. However, the assessments of these variables were associated with some methodological considerations, which are discussed below.

Since the exercise task involved movements of the head with visual feedback of the task performance via mirrors it is uncertain to what extent the cervical proprioceptors supplied the sensory feedback to control the head movements. Choosing a heavy metal ball instead of a light ball was based on the intention to increase the sensory input from the cervical proprioceptors. Still, it is possible that the vestibular or visual input outweighed the input from the cervical proprioceptors. However, the vestibular system is reported to have a higher thresholds to movement and velocity compared to both proprioception and vision [224], which speaks against vestibular input as a main sensory source since the exercise involved very small movements of the head. The visual input, on the other hand, was crucial during the exercise. The use of audio feedback instead of visual feedback to indicate ball position made the task exceptionally difficult to perform.

Another possibility, which does not contradict the muscle spindle model, is that the exercise may have had beneficial effects on the muscle activation synergies between the deep and superficial cervical muscles [e.g.,143]. Improved neuromuscular coordination could thereby lead to improved movement control and spinal stability. However, the activity of the deep and superficial cervical muscles was not investigated in study IV. Thus, the possibility of improved muscle activation synergies remains speculative.

Motor learning is by definition an acquisition of motor skill that is more or less permanent, in contrast to strength or endurance training (see
The successively improved task skill as well as the possible transfer effects, suggest that the exercise task may induce persistent changes within the CNS. It is well established that learning motor skills induce structural and functional adaptations within several motor areas of the CNS, e.g., the basal ganglia [225], cerebellum [226] and cortical areas [227].

The improvements in TSK indicate that the exercise may involve behaviour effects. It is possible that the experience of being able to perform neck specific exercises, with successively improved performance and increased difficulty, without provocation of the symptoms can reduce the fear avoidance beliefs and behavior. In that sense, individually adjustable exercise tasks with successive progression of difficulty can in specific cases be considered equivalent with exposure therapies commonly used in cognitive and behaviour therapy for treating anxiety and phobia, for review see e.g., [228].

Considerations about exercise design and motor learning

A major difference between the neck coordination exercise presented in this thesis compared to the previous studies on cervical proprioception and coordination exercise, [178, 179, 183] regards the task design. While previous studies mainly involved closed skills tasks (i.e., they are highly predictable), our method involved a more open skills task via an unstable system (controlling a metal ball on a plate on the head). The exercise was thereby more unpredictable and demanded on-line adjustments to fine control the movement of the ball. The exercise also included a goal-specific task, i.e., to move the ball to the centre of the plate and hold it still for 3 s. Using a goal-specific task may be useful to enhance the motivation for the exercise. It may also increase the cognitive effort of the task, which is known to be an important factor for retention and transfer of motor skills [194]. In order to enhance the cognitive effort, the start position was randomised for each trial. The involvement of cognitive effort was supported by the interview after the intervention period as a majority of the subjects mentioned deep concentration on the task to be an important exercise strategy. Augmented feedback of the task result was supplied via mirrors which made it possible to adjust the movements and thereby improve performance. In accordance with the specificity of learning hypothesis [195], the subjects were instructed to sit with a good erected posture in a functional position during the exercise. The criteria for progression of difficulty with regard to improved skills assured that the task was neither too difficult nor too trivial to perform. This is a vital factor for optimisation of motor learning according to the challenge point frame [193]. A fast improvement in the skill to perform the task was seen for all subjects during the 4 week exercise period. Further progression of difficulty, e.g., by variation of the exercise task, may therefore be necessary if the exercise is used for longer time periods. It is reasonable to believe that as the skills becomes more automatic, other tasks can be performed simultaneously, e.g., sitting on unstable surface or performing accurate arm movements while performing the exercise.
Motor learning and exercise specific effects

In study IV we saw improved skills to perform the task and indications on transfer effects to postural control and movement smoothness of cervical rotations. Effects on transfer tests have been evaluated in some previous studies on cervical proprioception and coordination exercises. As mentioned in the introduction (see page 26), the C-CF exercise has been compared to other neck exercise regimes, such as endurance-strength training of cervical flexor muscles [92, 182, 229] and conventional proprioceptive eye-head-neck exercises [183]. Even though no differences were found on pain reduction the results revealed some interesting findings on motor control variables after intervention. The C-CF exercise improved the ability to maintain a neutral cervical posture during prolonged sitting compared to endurance-strength training [92]. Strength-endurance exercise, on the other hand, led to an increase in maximal voluntary contraction force and a reduced fatigue of the superficial cervical flexor muscles [182]. No difference was, however, found on an isometric C-CF endurance test [229], and neither exercise led to a change in EMG amplitude of the sternocleidomastoideus muscle during a functional repetitive upper limb task [181]. When comparing C-CF training with conventional proprioception training, similar improvements were revealed on cervical reposition [183]. These findings indicate that there are some exercise specific effects due to exercise regime, but also some overlap between exercises. Apparently, increased neck strength does not automatically lead to improved posture, which instead appears to be related to increased function of the deep cervical muscles. Since we did not compare the neck coordination exercise in study IV with another training regime, we can not conclude whether the effects are specific to our method or if they are general to any exercise.

Methodological considerations

In study I-III we investigated possible alterations in sensorimotor functions in neck pain disorders. These studies where however not designed to resolve the question whether altered sensorimotor functions are the causes or consequences of chronic neck pain disorders. According to current pathophysiological models (see page 22), altered sensorimotor functions may explain the emerging pain as well as, recurrence, persistence and spread of pain. To penetrate this important question, longitudinal studies are necessary.

The assessments of sensorimotor functions used in this thesis entail some uncertainties regarding the interpretation of the test results. Firstly, the tests involved complex integrations of multiple sensory input, central processing and coordinated motor output. The specific role of cervical sensory information for the test results therefore remains largely theoretical. Secondly, motor tests, such as the sensorimotor assessments included in this thesis, involves influencing factors like motivation, concentration and attention. Other factors that that should be taken into account are test instructions, the length and number of trials and calculation of outcome...
variables. Although not possible to abolish these uncertainties, we made attempts to reduce them. For example, the choices of outcome variables for all tests were, to a considerable extent, based on theory of their mechanistic representations (see page 18). Association analysis between the sensorimotor variables and self-rated characteristics may also contribute to further understanding of the mechanisms involved. Moreover, all test procedures were highly standardised and the instructions were pre-recorded in the computer.

The evaluation of test-retest reliability in study III included a rather small sample size which may have limited the precision of the reliability estimates.

There are several methodological limitations to be discussed regarding study IV. Obviously, the most critical limitation is the lack of a control group. No firm conclusions can therefore be drawn regarding the effects on sensorimotor function tests, questionnaires and pain measurements. The exercise dose was relatively small, eight training sessions of 10-15 minutes, which suggest that there may be potential for further effects by extending the exercise period. The sensitivity of the sensorimotor function tests can likely be improved. The increased postural sway found in sample 2 but not in sample 1 in study II indicate that the time period of 30 s used in sample 1 (compared to 180 s used in sample 2) is insufficient for reliable test values. The various results of sample 1 and 2 in study II is, however, also likely influenced by the fact that sample 2 was larger. Nevertheless, the importance of sufficient test durations has been stated in a recent study by Harringe and colleagues [230] who concluded that the reliability of postural sway tests during 30 s were not acceptable. Moreover were test periods for 120 s in most cases more reliable than for 60 s. Longer sampling periods for the postural sway test would probably improve the reliability of the slow component specifically, since only a few sways of the slow component is captured during a 30-s test period, which was the sampling period used in study IV. Using perturbation, such as translational movement of the force plate, vibration of the neck or calf muscles or galvanic stimulation of the vestibular nerves, could increase the understanding of the mechanisms behind altered postural control in neck pain disorders. The cervical repositioning test may be more sensitive if performed with slow movements in a sitting position instead of fast movements in standing, which was the case in study IV. If that was the reason for the insignificant result of that variable is, however, unknown. The neck coordination exercise study in the present thesis is limited to investigation of the clinical applicability on subjects with chronic non-traumatic neck pain in a working age population. Further exploration is needed for application of the method in rehabilitation of age groups and disorders.

**Implications for rehabilitation**

The results from this thesis imply that various sensorimotor functions may be altered in chronic neck pain conditions of both traumatic and non-
traumatic aetiology (study I-III). Objective assessments of sensorimotor functions can be used for categorization of neck pain disorders, give an estimate of the severity of the dysfunctions and provide important information on what modalities to incorporate in the rehabilitation. Objective assessments are also valuable for evaluation rehabilitation effects. Assessment of sensorimotor functions and other relevant domains, such as mechanical dysfunction, sensitisation and fear avoidance belief would improve the categorisation into subgroups, which may benefit the rehabilitation of the large group of neck pain patients without an objectively verified specific diagnosis. Interventions including regimes targeting sensorimotor functions should be considered in rehabilitation of neck pain disorders. The findings from the pilot study on neck coordination exercise (study IV), along with the results from previous studies on exercises for cervical proprioception and coordination, indicate that such methods can be effective.

**Future research**

Further research is needed to evaluate whether assessments of sensorimotor dysfunctions can predict treatment outcome in neck pain disorders. The neck coordination exercise method here presented (study IV) needs to be evaluated in a RCT study. Preferably, future evaluation of the exercise method should include selected subjects with sensorimotor alterations, e.g., postural control disturbances. The sample group in study IV included adults with chronic non-traumatic neck pain. Other possible applications that may be valuable to investigate is rehabilitation of acute neck pain, WAD, balance disorders due to vestibular or neurological diseases as well as elderly with fall risk. EMG studies of the deep and superficial neck muscles during the exercise could shed further light on the neuromuscular mechanisms involved in the exercise method. Further investigations on how cervical proprioception and coordination is best exercised, e.g., using open or closed skills tasks, high or low load, with or without visual feedback, is also warranted.
CONCLUSIONS

This thesis shows that chronic neck pain disorders are associated with a variety of alterations in sensorimotor functions, such as reduced pointing precision, increased magnitude of the slow component of the postural sway and reduced speed in maximal speed cervical axial rotations. These functions are highly integrated in daily tasks and are often central in tasks like precision work, sports or playing musical instruments. The clinical validity of the tests was supported by the associations found between altered sensorimotor functions and self-rated functional limitations and symptoms.

Specifically, NS with concurrent low back pain and WAD were found to be disposed to sensorimotor function disturbances.

Outcome variables from sensorimotor function measurements that are based on theory of their mechanistic representation contribute with enhanced understanding of the results. For example, by decomposing the CoP signal into its slow and fast components, the increased postural sway in neck pain could be attributed to sensory feedback mechanisms, while age and anthropometrics was found to influence the controlling forces.

The test-retest reliability of kinematic variables of fast cervical rotation support that the test may be useful in clinical management and research.

The novel method for neck coordination exercise was found to be feasible in people with chronic NS neck pain, shown by the improved skill to perform the task and the overall positive opinion about the exercise. The indications on positive effects on sensorimotor functions may suggest transfer effects from the exercise to other non-task specific motor functions. These findings, together with the indications on positive effect on self-rated arm-hand functioning, general health and fear of re-injury due to movements justifies a future RCT. The results from this thesis can be of clinical importance for characterization and rehabilitation of neck disorders. Assessments and treatments designed to target sensorimotor functions should be considered in rehabilitation of neck pain disorders, particularly for NS with concurrent low back pain and WAD.
ACKNOWLEDGEMENTS

I would like to thank all the people that have supported me and in different ways contributed to the work in this thesis.

Mats Djupsjöbacka, my supervisor and “research father”, for guiding me through the complex field of motor control and learning, with the specific focus on sensorimotor function. Thanks’ for sharing your great scientific knowledge and for inspiring discussions about proprioception, slow and fast postural sway components and fly fishing. It is all connected and it all makes beautiful sense.

My co-supervisors: Martin Björklund for excellent leadership as the head of Alfta research foundation, and who, together with Mats, has been involved in all the projects of this thesis, during weekdays as well as weekends. Thanks for your immense enthusiasm and for inspiring clinical discussions regarding implication and implementations of our research. Thanks also for expertise in questionnaires and great reviewing skills. Charlotte Häger-Ross for specific guidance in reliability, you are highly reliable. Dario Liebermann for your helpfulness and generosity when introducing me to the ideas of movement smoothness. My other co-authors: Jonas Sandlund, Thomas Rudolfsson, Helena Grip and Mikael Bergenheim. Valuable reviewing comments from Pelle Sjölander.

Jern Hamberg for your infinite enthusiasm and support during my years at the Alfta Rehab Center. As a pioneer in orthopaedic medicine, you inspired me already before we had met.

The engineering help in the lab and computer support: Nisse Larson “the engineering genius” who was an invaluable help in the lab in Alfta. Thanks also to Per Gandal, Göran Sandström and Teo Klestrup Röijezon for computer support. Maria Frykman for invaluable assistance work. Margareta Marklund for graphical work. Majken Rahm and Kerstin Nilsson for always lending a helping hand finding the right literature. Kalle Aspbäck for excellent bowling coaching. Marina Heiden and Per Liv for statistical support. Christina Jacobsson for monetary issues. Gabrielle Grahl and Christina Ingmansson, the present and former chiefs of staff.

All my present and former PhD-student colleagues at the CBF: Jenny, Guil, Mahmoud, Malin, Peter, Dmitry, Ulrika, Gerd, Nebojsa. All the researchers at the CBF: Svend-Erik, Pelle, Margareta, Albert, Fredrik, Hans, Eugene, Per, Katarina. To all PhD-student colleagues and researchers at the Department of physiotherapy, Umeå Universitet. Professor Gunnevi Sundelin for accepting me as a PhD-student and for valuable support.
A special thanks to Gwen Jull and Paul Hodges and colleagues for letting me visit you in Brisbane. Thanks also to Eythor Kristjansson for inspiring discussions. You have all inspired and influenced me in my clinical practice as a physiotherapist as well as in my research work as a PhD-student.

My clinical mentors Conny Lindberg and Totte Sandberg for generously sharing your great knowledge in manual therapy.

My mother Gunlög “the deaconess”, Pelle “the Poet” Friman and Gunnar Burman for love and spiritual guidance. My father Göran for endless support and problem solving. My sister Hanna and my nephew William for enthusiasm and helpfulness. All our family and friends from Ytterberg (Härjedalen) to Te Puke (New Zeeland), thanks for being there. A special thanks also to my wife Louise’s family who always support us.

To my family Louise, Teo and Tor. Thanks’ for all your love, patience and support. I am miraculously privileged to live my life together with you. As I now close the work of this thesis I am curious to find out were we will go from here. It will be exciting to find out...
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