Position-matching and goal-directed reaching acuity of the upper limb in chronic neck pain: Associations to self-rated characteristics

Jonas Sandlund
To my family

“The great phase in a man’s advancement is that in which he passes from subconscious to conscious control of his own mind and body”
F.M. Alexander

“But many that are first shall be last; and the last shall be first”
Matt 19:30
ABSTRACT

Neck-shoulder pain is common in the general population and causes individual suffering as well as large costs for the society. Despite substantial efforts, there is still a shortage of methods for objective diagnosis and effective rehabilitation of such disorders. Thus, there is a great need to develop and evaluate new methods for these purposes. From clinical observations and recent research it has become evident that sensorimotor control can be impaired in people with neck-shoulder pain and may play a role in the pathogenesis of these disorders. In this thesis, precision of goal-directed arm movements, a previously unstudied class of movements in neck-shoulder pain, was studied.

The main aim of the thesis was to investigate if people with chronic neck-shoulder pain have a reduced acuity of goal-directed movements of the upper extremity. A second aim was to study associations between reduced movement acuity and symptoms and self-rated characteristics.

Upper limb repositioning acuity was assessed in blindfolded subjects performing tests of active, ipsilateral position-matching of two target positions (long and short) in movements constrained to horizontal-adduction of the shoulder. Reduced repositioning acuity, suggesting impaired shoulder proprioception, was found for both subjects with whiplash associated disorders (WAD) and non-specific neck-shoulder pain (NS). The degree of reduced acuity was shown to correlate with self-ratings of various health concepts, functioning and pain. A conspicuous finding was that there was lack of correlation between short and long target errors, along with the fact that associations between repositioning acuity and symptoms and self-rated characteristics was primarily found for the short target position.

To further investigate the possible mechanisms underlying the disassociation between long and short target movement control, the association pattern between the outcome of several variants of ipsilateral position matching and velocity-discrimination tests, were studied. It was found that the perception of limb position in position-matching of short target locations appears to be predominantly based on movement velocity, whereas perception of limb position in movements to longer target locations may rely on a location-based perception mechanism.

To extend the research on reduced upper extremity proprioception in neck-shoulder pain to a more natural movement situation, acuity of goal-directed pointing including full vision and 3D multi-joint movements was investigated in WAD, NS and healthy controls subjects. The results revealed a reduced acuity for both neck-pain groups. Moreover, distinct associations between end-point acuity and neck movement problems, limitations of some physical functions and, in WAD; some aspects of pain, were revealed.

The findings demonstrate that the precision of upper limb movements can be reduced in chronic neck-shoulder pain. Substantial associations with symptoms and self-rated functioning suggest a clinical relevance of acuity measures of goal-directed arm movements. The findings indicate that tests of sensorimotor control can provide objective measures that may be useful in biopsychosocial profiling and characterization of subgroups of patients with chronic neck-shoulder pain, and that training target control of goal-directed movements should be considered in rehabilitation programs of people with these disorders.

Key words: Neck pain, Whiplash injuries, Shoulder, Proprioception, Kinesthesia, Vision, Psychophysiology, Somatosensory disorders, Psychomotor performance, Self assessment
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ABBREVIATIONS

AE Absolute error
AlgE Algebraic error
ANCOVA Analysis of covariance
ANOVA Analysis of variance
BMI Body mass index
BP Bodily pain index of SF-36
CE Constant error
CNS Central nervous system
CON Healthy control group
DASH The Disability of arm shoulder and hand questionnaire
EMG Electromyography
GH General health index of SF-36
ICD International classification of diseases
ICF International classification of functioning, disability and health
JND Just noticeable difference
MANOVA Multivariate analysis of variance
MCS Mental component summary index of SF-36
MH Mental health index of SF-36
NDI The Neck disability index
NS Nonspecific neck pain group (nontraumatic)
O-PLS Orthogonal projection to latent structures
PC Principal component
PCA Principal component analysis
PCR Principal component regression
PCS Physical component summary index of SF-36
PDI The Pain disability index
PF Physical functioning index of SF-36
PLS Partial least squares regression, (or Projection to latent structures)
Q² Goodness of prediction
R² Goodness of fit
RCT Randomized controlled study
RE Role limitation emotional index of SF-36
RP Role limitation physical index of SF-36
RT Retention time
SES The Self-efficacy scale
SF Social functioning index of SF-36
SF-36 The Short form-36 item health survey
TSK The TAMPA scale of kinesiophobia
VAS Visual analogue scale
VE Variable error
VEr Variable error controlled for retention time
VIP Variable importance in the projection
VT Vitality index of SF-36
WAD Whiplash associated disorders
This thesis is based on the following papers, referred to in the text by their Roman numerals.


II. Mats Djupsjöbacka, Jonas Sandlund, Ulrik Röijezon, Martin Björklund, Shoulder proprioception in chronic neck pain - associations with symptoms and self-rated characteristics, *Manuscript*

III. Dmitry Domkin, Jonas Sandlund, Mats Djupsjöbacka, Effect of target presentation mode and movement extent on correlations of ipsilateral position-matching test outcomes, *Manuscript*

IV. Jonas Sandlund, Ulrik Röijezon, Martin Björklund and Mats Djupsjöbacka, Acuity of goal-directed arm movements to visible targets in chronic neck pain, *Journal of Rehabilitation Medicine*, In press

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PREFACE

The motive for me to enter the path of research was mainly one out of curiosity – to find out more about how musculoskeletal pain develops and how it may compromise movement control and function – but also a concern, as practicing physiotherapist, about the adequacy of existing methods for clinical assessment and treatment of musculoskeletal disorders. The opportunity for me to study these aspects came by a contact with late Professor Håkan Johansson and MD Jern Hamberg who both encouraged me to place focus on sensorimotor control in chronic neck pain conditions.

It should be recognized that during my time as a PhD-student significant progress has been made in the area of pain research and knowledge are also accumulating rapidly in movement sciences, not least in physical therapy that relates to my research. Still, I dare to say, there is a long way to go before knowledge of musculoskeletal disorders approaches the advances made in many other medical fields where individualized mechanism-based treatment has lead to remarkable breakthroughs.

My research has had a physiological starting point in a pathophysiological model (Johansson and Sojka 1991) based on basic research (on the level of muscle receptors) that suggests a direct relationship between musculoskeletal pain and proprioception. However, in the exploration and quest of trying to understand functional sensorimotor control in conditions of musculoskeletal pain and the use of psychophysical methods have lead me out into a borderland were clinical science blend with behavioural traditions and (cognitive and computational) neuroscience, which has broadened my perspectives well beyond any single physiological model. Here I have tried to outline the main features of relevance for my studies but, naturally enough, some perspectives and many steps along the way may not be evident from this text.
1 INTRODUCTION

Movements like pointing, reaching, grasping and catching are basic functions that allow us to interact with the environment. However, to be meaningful these movements need to be precisely performed in time and space as part of an action, seeking to achieve a goal. In this sense goal-directed pointing or reaching can be seen as the building blocks for more complex actions that can be measured and used in the study of processes of sensorimotor control. Skilled motor behaviour as part of normal movements looks easy but is, at closer inspection, very intricate reflecting complex interactions at many levels of the motor system from cortical and neural systems to mechanical properties of the musculoskeletal system. It is only when we observe the clumsy movements of a small child or the challenges that confront patients with movement disorders that we usually become aware of the inherent difficulties of motor control.

Some professions have with training and experience learned to identify movement abnormalities and the possible causes behind them. Such abnormalities are sometimes rather obvious like in the case of neurological disease or in specific orthopaedic conditions and the underlying mechanisms may be well known. Quite often however, in the clinic, observations of a patient may only leave a vague feeling that the movements are cautious, hesitant, coarse, or just unusually slow without us being able to define what fails or what may be the underlying cause. This is often the case when pain is involved.

On a behavioural level it is easy to see that cautiousness, withdrawal and restriction of movement are natural responses for protection and to avoid further pain provocation. However, pain has a profound effect on our whole being. We are shaped to prioritize pain sensation when encountered and virtually all systems of the body and mind are prepared to respond. There is an increasing amount of research that show effects of pain on sensorimotor control all the way from peripheral reflexes to higher levels of central processing pertaining to planning and execution of movements (Galea 2004) and a number of theories have been formulated on the possible mechanisms involved (Sterling et al. 2001b; Moseley and Hodges 2004). Furthermore, technological advances have provided the means to monitor and register movement kinematics and kinetics that have not been possible to access before and new methods how to indentify and analyse also subtle movement deviations are continuously developing. This has opened up a new field to be explored that may prove to be valuable for understanding the mechanisms behind various forms of abnormal movement in musculoskeletal pain, which is the topic of the present thesis.

In neuroscience, research on motor systems has not been nearly as influential as that of the sensory system, possibly because the findings generally have been much more difficult to relate to other fields of neurophysiology and cognitive neuroscience. This has, however, changed with new knowledge on how the brain works and emerging interest in how we control our movements. Some of the advances in this aspect also relates to the development of sophisticated computational models that has provided for a deeper understanding of how actions are planned and performed. Moreover, the same models have also provided fundamental tools for understanding cognitive functions and studies of the motor system have, hence, obtained a much broader scope (Rizzolatti and Wolpert 2005).
In the medical clinic, motor control aspects appears to have been poorly understood for a long time, maybe with the exception of specialized neurologist concerned with the devastating effects of motor system damage. For fascinating reading see the works of Oliver Sacks (Sacks 1984; Sacks 1985). Clinical findings of abnormal motor control in other groups of patients are still often interpreted as and described in terms of muscle strength or endurance deficits or as signs of sensory deficit. However, some of these misconceptions or simplifications are understandable since proper tests and outcome measures for motor control assessments in the clinic is essentially lacking and many of the possible motor control abnormalities have, as already mentioned, not until recently been possible to analyse accurately.

The fact that the control of movements is strongly dependent on sensory signals that affect motor outputs is in this thesis acknowledged by using the term sensorimotor control. In this document I want to draw attention to sensorimotor control impairments presented in many people suffering from musculoskeletal pain. Specifically, this thesis addresses the issue of arm movement control and the potential impact of neck pain on sensorimotor functions related to end-point acuity of the upper extremity. First, however, a review is presented on the background to why these aspects may be important.
2 GENERAL BACKGROUND

2.1 Neck pain disorders

2.1.1 Magnitude of the problem

Pain in the neck-shoulder area is a world-wide health problem causing individual suffering and large costs for the society. In the industrialised countries neck pain has been estimated to affect about half the adult population during their lifetime (ranging between 14%-71% in different studies) (Fejer et al. 2006). Neck pain is common in all age-groups and represents one of the most common causes to both short- and long-term sick leave (Ferrari and Russell 2003). Moreover, investigations have indicated that neck pain, for some reason, appears to be more persistent than pain from other organs (Kjellman et al. 2001; Cote et al. 2004). In a recent study from northern Sweden Guez et al. (2002) showed that 43% of the population reported neck pain and about half of them (18% of the population) also reported chronic pain – a frequent cause of disability and reduced quality of life for the ones affected. Thirteen percent were found to be of non-traumatic origin while about one third (5%) of the total population with chronic neck pain had been exposed to some form of neck trauma (Guez et al. 2002).

Since ‘neck pain’ is defined differently in different studies ranging from self-reported pain to relatively well-defined clinical diagnoses, the incidence and prevalence of neck–shoulder disorders are somewhat hard to compare across studies and countries. Large variation in study populations, definitions of pain and the anatomical borders of the neck may further contributes to comparison difficulties. For example, where the neck ends and where the shoulder begins are debated and may easily lead to variable classification of pain conditions. Moreover, neck pain disorders are difficult to diagnose because they are often associated with headache, shoulder pain, arm pain or thoracic spine pain, which may complicate coding in diagnose and symptoms registers used in epidemiological research (Van Eerd et al. 2006; Cote et al. 2008a). Recent research has also highlighted the episodic or recurrent nature of neck pain which means that the disorder is somewhat of a moving target (Cote et al. 2008a). Regardless of the methodological problem inherent in epidemiological research, it stands clear that pain in the neck/shoulder area is a big problem causing individual suffering and large costs for the society.

2.1.2 Defining neck pain

Neck pain disorders include a heterogeneous group of conditions where several pathomechanisms may interplay and act simultaneously. The pain can originate from many structures, mainly the spine and soft tissues (i.e., discs, joint, muscles and nerves), but the cause of neck pain is often complex and in many cases multifactorial. Only in rare cases are specific pathologies like infection or tumours the cause of neck pain, and other specific pathology-based diagnoses, such as spinal stenosis, disc herniations or spondylolsisthesis, comprise only a small proportion of all cases (Riddle and Schappert 2007). In most cases
clinicians are unable to reliably identify the source of pain or allocate the symptoms to any structural injury or specific disease. Radiographic or MRI findings rarely give sufficient information of the anatomical origin of pain (Spitzer et al. 1995; Nordin et al. 2008) and there are usually not any physical or laboratory findings that can confirm a specific pathology. Hence, the majority of neck pain disorders are often labelled non-specific (or idiopathic) and the used diagnoses are primarily symptom-based i.e., based on medical history and findings in manual examination. The focus of the present thesis is nonspecific neck pain including Whiplash associated disorders (WAD) as a special case of traumatic nonspecific neck pain. The definition of the anatomical area used to denote the neck according to Margolis (1986) is used in this thesis and outlined in Fig 1.

Fig. 1. The anatomical area defined as the neck in this thesis. A is view from front, B is view from behind

The problems with symptom-based diagnoses are several. First, the diagnostic criteria of non-specific neck pain are vague and the terminology variable. Consequently, many different, partly overlapping diagnoses are used in parallel in clinical practice as well as in research. Second, the reliability of manual tests used for diagnosing, usually by provocation of the major symptoms (e.g., pain intensity, pain location and character, referred or radiating pain), have generally been found to be poor, or at best fair (e.g., Viikari-Juntura 1987; Bertilson et al. 2003; van Trijffel et al. 2005). Thus, there is no consensus on diagnostic methodology. Third, the discrepancy between the weak, or sometimes absent, objective findings and the sometimes severe problems experienced by the individual can be a major source of mistrust between clinicians and patients. A prolonged debate about the link between musculoskeletal pain disorders and specific etiologic factors (i.e., whether the pain may originate from specific work place conditions or whiplash type trauma to the neck) and a discussion whether patients overestimate, exaggerate or simulate symptoms in the purpose to benefit from insurance systems (malingering) has also paralysed much of the scientific progress in this field.

However, new research during the past decade has provided invaluable knowledge related to how persistent pain stimuli set off sensitization processes in the CNS that may explain many of the puzzling findings of variable and seemingly exaggerated pain perception. There is today a large body of evidence of changes both in the central and peripheral nervous
system responsible for enhanced nociceptive sensitivity such as hyperalgesia and allodynia and much of what has previously been considered psychogenic pain is now better understood as sensitization or ‘neuropathic pain’ (Woolf and Salter 2000; Wright and Zusman 2004). This knowledge dramatically change the way of how to interpret the symptoms of especially chronic pain conditions, but has only recently penetrated current thinking and started to affect clinical practice.

2.1.3 Symptoms and signs

Neck/shoulder pain is frequently associated with headaches and/or arm pain and, occasionally, neurologic symptoms such as arm weakness, numbness, and/or sensory deficits which may become persistent and debilitating. There are, however, a large number of other associated symptoms and disorders that may occur such as: intrascapular pain, muscle stiffness, reduced range of motion, paresthesias in arms and hands, fumbling, dizziness, balance disturbance, temporomandibular symptoms, autonomic dysfunction, oculomotor and (acutely in WAD) auditory symptoms, cognitive problems like decreased concentration and memory problems as well as emotional and psychological disturbances, irritability and fear of movement (for reviews see e.g., Hildingsson and Toolanen 1990; Radanov et al. 1991; Cote et al. 2001; Nederhand et al. 2004).

It is important to acknowledge that traumatic injuries may cause different structural damages than non-traumatic and that other unique features like post-traumatic stress sometimes may have to be considered (for a review see e.g., Sterner and Gerdle 2004). It is generally held, but without much scientific support, that patients with chronic WAD may differ from neck pain without traumatic origin primarily in self-assessed quality of life and psychosocial indicators (Söderlund et al. 2000). Higher prevalence of temporomandibular pain disorder have also been found in patients with WAD compared to non-traumatic neck pain patients (Haggman-Henrikson et al. 2002; Eriksson et al. 2004; Klobas et al. 2004; Visscher et al. 2005). Furthermore, in traumatic injuries receptors/pathways conveying proprioceptive information, usually responsible for correct motor control, can be inured at the trauma. The consequent malfunction or misuse of the affected muscles, maintained over time, may in turn enhance and/or maintain the pain, as will be discussed later. However, after the initial acute phase, it is usually difficult to distinguish between patients showing symptoms as a result of road accidents or other whiplash trauma and those presenting non-traumatic neck problems. The symptom panoramas coincide (2005; Passatore and Roatta 2006)

2.1.4 Diagnosis and classification

As today, there is no standard way of labelling or defining neck pain conditions. One of the historic problems in the field of neuromuscular pain is the absence of scientific knowledge of the underlying pathomechanisms and the subsequent non-specificity of non-specific neck pain opens up for numerous possible interpretations and categorization approaches. The way disorders are conceptualized and which criteria they are based on are largely determined by the professional background of the inventor and by the purpose for which the system was developed – if used, for example, to guide clinical treatment, examine prevalence in work places or to consider insurance claims. Thus, the diagnostic labels have different derivations. Many labels involve a description of the general anatomical area of pain (e.g., ‘trapezius myalgia’, ‘cervicalgia’, ‘cervicobrachialgia’), some are derived directly from clinical
symptoms and signs (e.g., ‘tension neck syndrome’) or from the presumed causes of onset (e.g., ‘postural syndrome’, ‘whiplash injury’, ‘repetitive strain injury’), or from a pathophysiologic hypothesis (e.g., ‘minor facet subluxation’, ‘disc derangement’, ‘thoracic outlet syndrome’).

Since there is little agreement on terminology and methodology and because there are many different schools of thought and practice in this field, a number of diagnose systems may describe the same disorders even though they may not all use the same criteria to define them. And conversely, different systems or theories may use different labels to describe the same disorder (Van Eerd et al. 2003). Furthermore, although most researchers and practitioners agree on the importance of identifying homogeneous sub-groups in this very heterogeneous group of patients, there is no agreement today on how such further subclassifications should be conducted, i.e. what parameters or entities that should be addressed, what tests that should be used or what the subsequent tests findings might indicate (McCarthy and Cairns 2005). A patient will therefore, very likely, hear different explanations of and names for their neck pain and get different suggestions of what the best treatment would be if consulting a physiotherapist trained in, for example, manual therapy or the McKenzie methods (i.e., the McKenzie system of mechanical diagnosis and therapy®; MDT). Yet other interpretations and therapeutic suggestions would be provided if the patient is examined by a general practitioner or a chiropractor. This is, obviously, not very reassuring for the patients seeking a second opinion on their neck pain.

Still, a diagnosis is important. The health care systems in most western countries demand a diagnosis in order to reimburse the patient for treatment and sick-leave and a diagnosis serves as entrance ticket for referrals, disability assessments, rehabilitation programs etc. To receive a diagnosis is also of great psychological value for most patients in order for them to understand and legitimize their suffering.

Wikipedia defines diagnosis as: (1) “the recognition of a disease or condition by its outward signs and symptoms” and (2) “the analysis of the underlying physiological /biochemical cause of a disease or condition”. As scientific causalities and the pathophysiologic mechanisms behind many medical conditions have been found there has been a shift from the first towards the second definition. It is important to recognize the differentiation of the term diagnosis because extensive disagreement exists between clinicians whether the mechanisms for various diseases and disorders are known or unknown. If the mechanisms are known, then genuine cures can potentially be obtained by remedy the causal abnormalities. If the mechanisms are unknown, then palliative treatments to reduce symptoms or interventions in order to improve reduced function are the best treatment options (see Rehabilitation and treatment later in this text).

The most accepted and widely used classification system for classification of disease for epidemiologic, statistic and diagnostic purposes, is the International Classification of Diseases (ICD) (1980). The ICD provides codes to classify diseases and a variety of signs, symptoms, abnormal findings, social circumstances and external causes of disease or injury that are used world wide. As such the ICD has provided a system for decision support in medicine and for communication between different professions in health care and social security systems. However, the usefulness of ICD in classifications of neck and upper extremity disorders has been questioned due to its substantial overlap of diagnoses (Buchbinder et al. 1996; Van Eerd et al. 2003). Moreover, because the first revisions of ICD provided no clear guidelines of what
clinical criteria the included diagnoses rely on, the diagnoses do not meet clinometric standards of content or face validity. This implies serious limitations of the conclusions that can be drawn in most studies using ICD classifications (Buchbinder et al. 1996). Furthermore, unspecific and unsubstantiated diagnoses (regardless of a reverential name) may not be very helpful in guiding clinical treatment. Some of these concerns have been addressed in other diagnostic systems that have been suggested to be more useful in identifying distinct subgroups of people with neck pain (McKenzie 1990; Radanov et al. 1991; Ohlsson et al. 1994; Verbrugge and Jette 1994; Andersson et al. 1996). Also, the current revision of the ICD has the ambition to incorporate both clinical code and procedure code for all health conditions in order to better describe the clinical picture of the patient. Even so, in most diagnostic classification systems used today for neck pain, there is generally a lack of attention paid to the measurements used to define the diagnoses (Buchbinder et al. 1996; Van Eerd et al. 2003).

2.1.4.1 Clinical assessment

The lack of definite pathophysiological explanations designates nonspecific neck pain to the category where the diagnosis relies on assessments of the signs, symptoms, and the results of various diagnostic tests. An inconvenient fact is, however, that few clinical entities related to diagnostic testing of neck pain have been systematically investigated and are in many areas poorly validated even at the most elementary level (Nordin et al. 2008). As exemplified above and pointed out in a recent, very ambitious, systematic review of the current evidence of clinical assessments of neck pain; the literature on spinal musculoskeletal pain is littered by “diagnoses of convenience” which often is used without confirmation of the entity implied in the diagnoses (Nordin et al. 2008). The lack of golden standards for comparison is problematic although efforts have been made, with some progress, to more specifically link test findings to specific structural lesions like cervical radiculopathy (Viikari-Juntura et al. 1989; Sandmark and Nisell 1995; Wainner et al. 2003). Yet, clinical physical examination is generally more effective at excluding (‘rule-out’) than confirming (‘rule-in’) the presence of structural lesions (Nordin et al. 2008). Evidently, there is a need to more systematically establish and confirm validity, reliability and utility of almost all commonly used clinical musculoskeletal neck examination tests, including manual tests, imaging tests, endurance and strength tests, functional tests and self-assessment/questionnaire tests (Nordin et al. 2008).

Importantly, the above cited review highlights some potentially promising techniques that deserve further attention; assessments of movement accuracy and control of movement patterns and functional tests (Viikari-Juntura et al. 1989; Sandmark and Nisell 1995; Wainner et al. 2003; Nordin et al. 2008). This suggestion concord with the view of Punnet & Wegman (2004) that classical diagnostic criteria in clinical examinations might not provide sufficient relevant measures, and call for supplementary objective criteria to be developed (Punnet and Wegman 2004). Theoretically, many non-specific health problems can be better understood from a physiological or functional perspective than from an anatomical or structure-based framework.

2.1.4.2 A Biospsychosocial disorder

One of many developments over the past decades in the field of spinal pain management and research is that of defining spinal pain in a biospsychosocial model (Waddell 1992). This has significantly improved the understanding of the multidimensional nature of the pain and
disability. This shift of perspectives has involved recognition acknowledgement of not only the processes of pain but also of neuromuscular and psychological systems, social and environmental aspects and, importantly, on how they interact and affect patients personally and functionally. This perspective provides for new approaches for characterization that may be especially important for nonspecific syndromes like spinal pain in order to match intervention to the specific needs of these patients (Boyling and Jull 2004).

A major contribution in this move has been the publication of the International Classification of Functioning, Disability and Health (ICF) (2003) which provide a unifying framework to understand the consequences of disease. As mentioned earlier the ICD contains information on diagnosis and health condition, but not on functional status or the consequences of disease which are the focus in ICF. Clinical findings of physical examination and treatment goals may according to ICF be characterized in different dimensions in terms of:

- Body functions and structure
- Activities (related to tasks and actions by an individual) and participation (involvement in a life situation)
- Additional information on severity and environmental factors

The ICF is applicable to all people, whatever their health condition and place the focus on function rather than condition or disease. Doubtless, the use of ICF will facilitate the process of establishing more standardized and comprehensive models to characterize the impact of nonspecific pain conditions. A topical example is a new conceptual model recently presented by the “Bone and joint decade task force on neck pain and its associated disorders”. A model intended to help organize and interpret existing knowledge on neck pain, which includes a classification system partly based on the structure of ICF (Guzman et al. 2008).

An important consequence with the recognition of the ICF approach is a devaluation of ‘one label diagnoses’ in nonspecific health disorders and acceptance of a system of many dimensions pertaining to the biomedical, psychological and social profile of the patient. With this also follows a process of prioritization or weighting among the multiple factors indicated in the patient profile in the purpose to define the predominant barriers to recovery. It is logical that specific treatment designed for patients with similar profiles will have a more favourable outcome than a more generic approach (O'Sullivan et al. 1997; Jull and Moore 2000).

Over-reliance on the traditional biomedical model and failure to recognize that neck pain may be part of a more complex disorder will lead to sub-optimal treatment, poor patient compliance and poor outcomes. However, seen in the light of modern pain theory, researchers and clinicians might have been too quick to allocate unexplained symptoms to psychosocial causes. A biopsychosocial standpoint allows pure, and various combinations of, physical, psychological and social explanations of musculoskeletal pain. But a biopsychosocial approach is not the antithesis of the biomedical model, as is sometimes presented or implicitly communicated. To deliberately avoid pathophysiological explanations of spinal pain because we today do not have the means to objectively quantify them, is a mistake. There may very likely be objective signs in nonspecific neck pain but we have not allocated the means and brains necessary to find them. Until this is done neck pain risks to remain deemed nonspecific and as such, questioned.
Still, management of especially chronic pain problems is complex and necessitates consideration of the whole individual including emotions, attitudes, beliefs, cognitive functions, social and cultural factors. There is rarely, if ever, just a physical problem with a physical solution. A biopsychosocial approach is necessary in order to identify the physical and non-physical barriers to improvement for each patient which allows for successful treatment and rehabilitation.

2.1.5 Risk factors

2.1.5.1 Whiplash injuries

The Québec Task Force on Whiplash-Associated Disorders defined whiplash as “an acceleration-deceleration mechanism of energy transferred to the neck that results in soft tissue injury that may lead to a variety of clinical manifestations including neck pain and its associated symptoms” (Spitzer et al. 1995). Although injuries by this type of whiplash mechanism occur primarily after motor vehicle collisions they can also occur in other mishaps and settings, such as work and sports. The Swedish whiplash commission recently stated that it is reasonable to assume that WAD may arise as a result of a number of different injury mechanisms. Studies have not been able to demonstrate that a specific type of movement causes a specific type of injury. Females and people at younger age seem to be associated with a slightly higher risk for WAD (Holm et al. 2008). These findings suggest that there is no relationship between degenerative cervical changes and risk of WAD since degenerative changes are highly associated with increasing age. There is also preliminary evidence that neck pain before a collision might be a risk factor for acute neck pain after a rear-end collision (Holm et al. 2008).

2.1.5.2 Non traumatic neck pain

Neck pain without traumatic background have been found to be more frequent in some occupations like dentists (e.g., Rundcrantz et al. 1990; Finsen et al. 1998; Akesson et al. 1999) and nurses (e.g., Lipscomb et al. 2002; Trinkoff et al. 2002; Alexopoulos et al. 2003). Similarly, office and computer worker have in a number of studies been shown to have the highest incidence (i.e., number of new cases) (e.g. Gerr et al. 2002; Korhonen et al. 2003; Wahlstrom et al. 2004). Still, it is difficult to precisely determine the exact contribution of work to the onset of neck pain in individuals. Most neck pain appears to develop gradually and follow an episodic course throughout peoples’ lives (Carroll et al. 2008). Obviously, in workers the same symptoms with similar or identical pathophysiology can occur from working conditions as well as from factors outside the work place or working situation and work-related neck/shoulder pain is thus very hard to establish.

However, specific factors may be more or less related to certain occupations, and some factors have been identified as risk factors for developing neck pain (Cote et al. 2008b). Physical exposures in the workplace, including repetitive work, sedentary work position, precision work, physical capacity, work postures, computer workstation setup and head, shoulder and elbow posture while working at the computer, as well as psychosocial exposures including quantitative job demands, job insecurity and social support at work, are risk factors for neck pain in working populations (Cote et al. 2008b). Preliminary evidence has also been presented suggesting that gender, smoking, a history of headache, poor physical work
environment, awkward work postures (i.e., uncomfortable positions or frequent bending and turning of the torso), emotional problems and ethnicity may contribute to the development of neck pain. The role of working with hands above the shoulders, heavy physical work and computer screen height as risk factors is at present unclear, and no scientifically admissible studies examining the role of vibration as a risk factor for neck pain were found in this review. Cote et al (2008) concludes that although all these factors may play a part, their effects are small and nonspecific so that no single factor is likely to cause neck pain on its own. Consequently it is not surprising that prevention strategies targeting a specific factor, like for instance interventions to modify workstations, have been shown to be largely ineffective in reducing the incidence of neck pain (e.g., Gerr et al. 2005) and may also partly, explain the effectiveness of multidisciplinary approaches for rehabilitation (2006; SBU 2006a).

Even though the identified factors with reasonable level of certainty can be said to predispose development of neck pain, there is poor knowledge about how they interact and of the processes involved in developing neck pain and disability. For example, an indication of causal relationships between psychosocial support and neck pain disorder says nothing of how these factors interact with biomechanical and individual factors. Notably, the Neck Pain Task Force review on risk factors did not consider studies in the field of biomechanics and related fields, unless they were population-based studies of outcome from preventative programs (Haldeman et al. 2008). Coexisting risk factors may be correlated and may exert their effects through complex interaction with each other under specific circumstances. Moreover, since neck pain often follows a recurrent course, it is likely that a risk factor for the onset of present neck pain is a result of a previous episode of neck pain.

2.1.5.3 Internal exposure

It is widely accepted that wear and tear processes may cause tissue injury. External exposure factors cause a cascading chain of internal exposure responses which accumulate and may eventually result in musculoskeletal disorders (Mathiassen and Winkel 1991; Winkel and Westgaard 1992). Thus, many of the described external and individual risk factors are in fact more of “effect modifiers”, as they may not be direct causal factors but rather act as an indirect influence on the internal exposure processes and development of musculoskeletal problems (Winkel and Westgaard 1992; Westgaard 1999b; Westgaard 2000). The risk factors listed above may thus have a direct or indirect internal motor control correlate. For example, the strong influence of repetitive and precision work on development of neck pain may work through a stereotyped and selective activation of low threshold motor units (Hägg 1991). As proposed by Hägg (1991), in his well cited “Cinderella hypothesis”, an uneven distribution of tension to a relatively small number of muscle fibres may eventually result in overload injuries to such ‘Cinderella units’ (Hägg 1991). Other models have also been developed to describe the link between external risk factors and the internal responses although these factors have not been specifically described (Mathiassen and Winkel 1991; Winkel and Westgaard 1992; Armstrong et al. 1996). Westgaard (1999) emphasized the importance of studying the intrinsic responses and characteristics in order to improve our understanding of why and how individuals would respond differently when exposed to the same exposure factors. Theoretically, the coordination and recruitment patterns both within and between muscles has major significance for the load exposure on musculoskeletal structures. The close
interaction of mechanical and chemical responses imply that motor control characteristics have a potential direct effect on the internal physiological responses associated with structural injury. This fact has now become increasingly recognized, but is still surprisingly neglected in research (Winkel and Westgaard 1992; Westgaard 1999a; Kumar 2001; Forde et al. 2002; Johansson et al. 2003a).

Hence, in ergonomics and epidemiology there is today little research done on the relationship between musculoskeletal pain and the quality of motor performance and motor control. Postures and movement characteristics are usually only crudely assessed in epidemiological and field studies, for obvious reasons since these aspects may be very difficult and expensive to obtain from large populations. Measurements of working technique variables (e.g., efficiency of movements, activation-relaxation patterns and exposure distribution) and motor control variables (e.g., inter- and intramuscular coordination, activation patterns, co-contraction levels, kinetic and kinematic control) are demanding both methodologically and theoretically and established standards to quantify these parameters are lacking.

Instead, most evidence of the links between motor control abnormalities and musculoskeletal pain originate from laboratory studies with cross-sectional designs that limit the possibility to draw conclusions on causality (but see e.g., Kilbom and Persson 1987; Madeleine et al. In press). Symptomatic individuals may have different patterns of motor control (as well as other physiologic response patterns and psychological characteristics) contributing to their development of symptoms, and on the other hand, they may develop different response patterns as a result of their pain disorder. Nonetheless, research on inter-individual differences in sensorimotor control as well as physiologic response patterns is critical to provide a better understanding of the causal chain between exposure to biomechanical and psychosocial stressors at work and the subsequent development of neck pain. As mentioned in the introduction, new knowledge and technological advances today provide better opportunities to, in larger detail, estimate to what extent internal sensorimotor strategies and physical exposure responses are different between symptomatic and asymptomatic individuals and enable development of innovative ways to prevent and treat musculoskeletal disorders.

2.1.6 Pain

To facilitate comprehension of the many observed deficits relating to motor control, functioning and behaviour and possible symptom panoramas, some aspects of pain in general and neck pain in specific is briefly outlined.

Pain includes both sensory and affective dimensions and is accompanied by a desire to terminate, reduce or escape its presence (Price 2002; Melzack 2005). Pain presents characteristics like slow adaption, temporal summation and spatial spread which dispose us to perceive pain as intrusive for both body and mind and thus make pain more intense than many other types of somatic sensation (Price 2002). Pain is unpleasant and contains emotional components that are formed by contextual factors and by a person’s ongoing anticipations and attitudes. These contextual and cognitive factors are partly the result of the fact that pain often occurs within a situation that is threatening, such as during physical disease or trauma.
2.1.6.1 Clinical neck pain

Pain seen in the clinic can occur in response to tissue damage and inflammation, damage to the nervous system (neurogenic pain) and alterations in the normal function of the nervous system (i.e., pathologic synaptic reorganization, neuroplasticity and central sensitization). Neck pain may feature both spontaneous pain that arises without any apparent peripheral stimulus and hypersensitivity to peripheral stimuli. In some people, neck problems may be the source of pain in other parts of the body. Thus, neck pain is often associated with headache, shoulder pain, arm pain or thoracic spine pain but has also frequently been demonstrated to coexist with low back pain (Guez et al. 2002). Arm pain and upper extremity sensory disturbance symptoms are, however, often misinterpreted as nerve root compression (radiculopathy) which may result in unmotivated magnetic resonance or computer tomography scanning (Sterner and Gerdle 2004). In chronic cervicobrachial pain, increased neural tissue mechanosensitivity, absent of any detectible peripheral neurological deficit, has been shown in up to one third of cases (Allison et al. 2002; Hall and Elvey 2004). When pain is consistently felt in the musculature (neck/shoulder or elsewhere) it may or may not be related to hyper sensitization of CNS pain pathways, that is pain sensitization (Curatolo et al. 2001; Leffler et al. 2003; Scott et al. 2005).

2.1.6.2 Pain sensitization

There is a large body of evidence for pain sensitization occurring in both the peripheral and central nervous system in response to long lasting nociceptive stimulation. The mechanisms behind this phenomenon are beginning to be revealed as is described elsewhere (Merskey and Bogduk 1994; Woolf and Salter 2000; Ji et al. 2003; Wright and Zusman 2004). Briefly, however, sensitization is an increase in the excitability of neurons, so that normal inputs begin to produce abnormal responses. As such it may be viewed as a simple form of learning and synaptic plasticity. Consequently, although the pain feels as if it originates in the periphery, it is in fact a manifestation of abnormal sensory processing within the CNS. It is thought that increased sensitivity is biologically useful to protect injured structures while they are healing. Neuronal plasticity provides one mechanism for pain to spread and become generalized and persistent (Woolf and Salter 2000). A straightforward relationship between pain perception and the state of the tissues can under these circumstances no longer be assumed and may become less predictable as pain persists.

2.1.6.3 Chronic pain

Eventually, when pain has been present for some time often several pain mechanisms can be involved. If it persists for 3 to 6 months or more, it is likely that pain will have other detrimental health effects like; fatigue, anxiety, depression, loss of sleep, irritability, anger, frustration, loss of interest in sex, family difficulties as well as pain in other areas of the body. This cluster of symptoms is by some referred to as chronic pain (e.g. Verhaak et al. 1998). This complication of the condition is widely recognized but it may, even so, be appropriate to note that it is a normal adaptation to long-term pain (2005). To cope with a multitude of ongoing stressors is demoralizing and tends to deplete one’s emotional reserve. Inability to function as normal may also lead to a loss of role and self-esteem. The origin, duration, intensity, and specific symptoms of chronic pain vary but a consistent fact is that, as a disorder, it cannot be understood in the same terms as acute pain. How the symptoms are
perceived to interfere with one’s life and the emotional feelings directed towards the long-term implications of having pain (i.e., ‘suffering’) is important for secondary pain affect. A dimension of pain that also relates to the attitudes, memories and beliefs about pain and that with time occupies more and more of the clinical picture. As the sensory, noxious aspect of pain becomes gradually less apparent other dimensions tend to increase in importance and will have to be addressed in any therapeutic approach to help. Thus, chronic pain depends on a cascade of events that is initiated, but not necessarily sustained, by the injury stimulus. Chronic pain is clearly not a warning signal to prevent physical injury or disease– it is a disease (Melzack 2005).

2.1.6.4 Central pain modulation

It is well known that noxious input are modulated at the spinal cord not only by other non-noxious input from the periphery but also by descending input from higher centres (Melzack and Wall 1965). A number of findings have confirmed that pain is modulated by many factors in the somatic, psychological and social domains (e.g., Miron et al. 1989; Stamford 1995; Cervero and Laird 1996; Dubner and Ren 1999). For example, certain cognitive styles, attitudes or beliefs like catastrophic thinking, fear avoidance behaviour, maladaptive coping and hyper vigilance, have been shown to be associated with substantial amplification of pain (e.g., Jensen et al. 1994; Crombez et al. 1999; Sullivan et al. 2001; Ploghaus et al. 2003).

2.1.6.5 Pain and the brain

Pain is related to sensory input that originates from nociceptors in somatic or visceral tissues. Brain regions (i.e., the thalamus, anterior cingulate cortex (ACC), anterior insular cortex, somatosensory cortex and, notably, premotor cortex) that receive input from nociceptor-specific and wide dynamic range neurons are related to sensory-discriminative, cognitive-evaluative, and affective processing of somatosensory nociceptive input (Coghill et al. 1994; Casey 1999). It is accepted as a general principle that the brain adapt to changes that takes place in the body. An increase in input results in an increase of cortical representations whereas a deprivation of input results in size reduction of representational space (e.g., Pascual-Leone and Torres 1993; Nudo et al. 2001). Musculoskeletal pain forms a dramatic disturbance of the integrity of the body and the brain adapts in many ways to this intrusion of the afferent-efferent equilibrium (Flor et al., 2003). Recent brain imaging studies show that various types of chronic pain is associated with extensive reorganization of cortical representation of sites encoding peripheral input in the somatosensory cortex (Flor et al. 1997; Maihofner et al. 2003; Pleger et al. 2005; Tegenthoff et al. 2005), and that there is a relationship between the amount of pain and the degree of cortical disorganisation (Byl et al. 1997; Flor 2003; Maihofner et al. 2003; Pleger et al. 2005).

2.1.6.6 The pain neuromatrix

In his analysis of phantom limb pain phenomena, Melzack suggested that the qualities of the body we normally feel, including pain, originates in neural networks in the brain and may be felt also in the absence of input from the body (Melzack 1990). Sensory stimuli may trigger the patterns responsible for the perception but do not produce them. The widespread brain network – the neuromatrix – he proposes, is the anatomical substrate of the “body-self” which is largely an extension of the concept of body schema (i.e., the internal, dynamic
representation of the spatial and biomechanical properties of one’s body) described later in this text (see *Proprioception*). The spatial distribution and synaptic processes underlying the neuromatrix are initially “built-in” by genetic specification and later shaped by sensory inputs. According to the theory sensory inputs undergo processing in the neuromatrix so that characteristic patterns are impressed on them. The continuous output from the body-self neuromatrix (the *neurosignature*) is converted into a continually changing stream of awareness of the qualities of one’s body. In parallel to awareness there is also a steady output stream of behaviour and homeostatic regulation (Melzack 2005).

A critical implication of this model is that the brain’s response to pain may be conditioned or ‘learned’, for example to situations where it usually occurs. Thus, non-painful stimuli pertaining to threatening situations may be enough to provoke pain (Moseley et al. 2003; Moseley and Arntz 2007), and that it is virtually impossible to distinguish between physically and psychologically caused pain. Although the mechanisms of the body-self neuromatrix remain to be explored empirically, this is a valuable model for explaining the phenomena of phantom limb pain, which is often triggered by supraspinal (e.g., affective, emotional, and cognitive) experiences. The model is also increasingly acknowledged by experts in the field of musculoskeletal pain as one mechanism responsible for persistent chronic spinal pain (e.g., Moseley and Hodges 2004; Sterner and Gerdle 2004; DeLeo 2006).

**2.1.7 Pain and motor control**

To escape and prevent danger and promote survival is a basic biological function of pain that implies that pain is essentially motoric and operative when action is required (Wall and Melzack 1999). Therefore, it is not surprising that a number of motor system changes, from alteration of simple reflexes to modification of higher order motor behaviour, have been identified as clinical features of many musculoskeletal pain conditions (Sterling et al. 2001a; Galea 2004).

**2.1.7.1 Sensorimotor control in neck pain**

A number of findings of abnormal sensorimotor function have been reported in neck pain conditions including: reduced movement speed (e.g., Alund et al. 1992; Sjölander et al. 2008) reduced range of motion (e.g., Hagen et al. 1997; Lee et al. 2004), reduced cervical proprioceptive function and movement precision (e.g., Revel et al. 1991; Heikkila and Astrom 1996; Kristjansson et al. 2003; Armstrong et al. 2008), increased jerkiness of movements (Sjölander et al. 2008), altered and variable axis of rotation (Grip et al. 2007); impaired postural stability (Karlberg et al. 1995; Malmstrom et al. 2007), altered muscle activation patterns (Elert et al. 1992; Edgerton et al. 1996; Falla et al. 2004a), inhibition of deep cervical muscles (Falla et al. 2004c). Some of the findings will be described further in this section and the next where they are discussed in relation to different models that may explain effects of pain on sensorimotor function.

The sensorimotor system of the neck is extremely complex. The neck has a relatively vast degree of mobility at the expense of mechanical stability and the complex muscle system of the cervical spine must allow head movement in all dimensions, while maintaining the stability. Head movements are executed around several cervical joints at once and the muscles must distribute loads not only from the weight of the head but also from the upper extremities (Bland and Boushey 1992). For instance, muscles like the trapezius and levator scapulae can
exert torque on both the neck and upper limbs. Moreover, since most of our sensory systems are located in the head, the neck is involved in the important task to inform ourselves of the world around us (Guitton et al. 1986). Furthermore, to assist in the central function of spatial orientation, the cervical motor system is tightly coupled with reflexes influencing eye, head and postural stability (i.e., the cervico-colic, cervico-ocular, and tonic neck reflex), that rely on accurate afferent information from the vestibular, visual and proprioceptive system. It has been shown that if information on motion from these divergent sensory systems is incongruent, the resulting “sensory mismatch”, if powerful enough, produces a sensation of spatial disorientation and dizziness (Karlberg et al. 1995; Dieterich 2004) as well as a reduced postural control (Magnusson 1994; Karlberg et al. 1995).

Observations of poor balance in neck pain conditions are frequent (e.g. Karlberg et al. 1995; Michaelson et al. 2003; Treleaven et al. 2003; Field et al. 2007; Malmstrom et al. 2007). For example, larger sway areas and reduced ability to perform more challenging balance tasks have been observed in patients with chronic neck pain, with greater balance disturbances in traumatic than non-traumatic neck pain subjects (Michaelson et al. 2003; Field et al. 2007). Cervical receptor function could be altered as a result of direct trauma to the mechanoreceptors or their afferents, which could explain balance disturbance after for example a whiplash type accident (Lu et al. 2005; Chen et al. 2006). However, Karlberg et al. (1991) also demonstrated that restricting neck mobility with the use of a cervical collar impairs postural control and affects voluntary eye movements also in healthy subjects (Karlberg et al. 1991). These findings imply a crucial role of cervical proprioception for sensorimotor functions (see Proprioception below). The importance of proprioceptive sensation from the neck is also underscored by the high densities of muscle spindles located in the cervical and cephalic muscles (e.g., Bakker & Richmond, 1982). Muscle spindles are mechanoreceptors of great importance for proprioception and will be described later in this text (see Afferent sources of information for proprioception). Experimentally, this has been demonstrated in both human and animal studies where anaesthetic injections into the deep tissues of the neck produce unsteadiness, ataxia and a tendency to fall (e.g., de Jong et al. 1977).

Impaired cervical proprioception is also one of the most frequently reported sensorimotor findings in people with neck pain (for a review see Armstrong et al. 2008). After the first reports by Revel and co-workers (1991; 1994), reduced position-matching ability of the neck in people with both traumatic and non-traumatic neck pain has been verified in many studies (for a review see Armstrong et al. 2008). Usually, position-matching have been measured in the ability to, without the aid of vision, relocate the natural straight ahead position (Revel et al. 1991) or some other predefined reference position (Loudon et al. 1997). Other test methods have also revealed signs of impaired movement control such as increased jerkiness of cervical movement (Sjölander et al. 2008) and uneven movement paths in a head tracking task (Kristjansson et al. 2004). These findings have usually been interpreted as signs of altered cervical Proprioception.

Interestingly, findings suggesting impaired upper-limb proprioception in neck pain have also been presented. Knox and co-workers (2006b) found that subjects suffering from WAD had significantly reduced position-matching acuity of the elbow joint compared to healthy control subjects. However, with the exception of this single study, the movement accuracy of the upper limbs in neck pain, which is the main subject of the present thesis, is an unexplored
aspect of sensorimotor disturbances in neck pain. This is surprising considering the tight functional coupling between the neck and shoulder and that reports of fumbling or clumsiness of the hands is not uncommon in neck pain patients (Bring and Westman 1991). It is also known that changes in head and neck position affect the accuracy of movement of the upper limb in healthy people, which have been suggested to be due to disruption in the integration of sensory information (Fookson et al. 1994; Berger et al. 1998; Guerra et al. 2003). Since accurate movements of the upper limbs require integration of sensory information of both the external environment and of the relative position of internal body segments, changes in the sensory estimates of head position could affect the position of the arm causing error in proprioceptive tasks of the upper limb. In support for this idea it was demonstrated that distorted proprioception introduced by vibration of neck muscles also affect the repositioning acuity of the elbow joint (Knox et al. 2006a).

It is not clear whether the observed abnormalities occur as a result of pain or whether disturbed sensorimotor control strategies/systems lead to wear and tear, repeated microtrauma and subsequent nociceptor stimulation and pain as proposed in the Cinderella hypothesis (Hägg, 1991 #1695, see also Janda 1978; Panjabi 1992). Both possibilities are likely. For some individuals inappropriate working techniques (Kilbom and Persson 1987) or minor coordination difficulties (Janda 1978) may lead to pain onset but, considering the recurrent and episodic nature of spinal pain, sensorimotor deficits may also be the outcome of (adaptation to) a previous period of spinal pain. Along these lines, persistent altered sensorimotor function, even after the patient is reporting recovery, is considered to be one factor involved in the high rate of symptom-recurrence in spinal pain condition (Hides et al. 1996).

2.1.7.2 Models of pain and sensorimotor control

Based on both experimental and clinical research different models have been proposed to explain the effect of pain on motor control. In short, the involved mechanisms include (1) changes in proprioception or afferent mediated control, (2) changes in excitability at both spinal and cortical levels and (3) central effects related to stress, fear and strain on attentional recourses (Hodges and Moseley 2003).

2.1.7.2.1 The muscle spindle model

Two models published in the early nineties were “the muscle spindle” or “vicious circle” model (Johansson and Sojka 1991) and the “pain adaptation model” (Lund et al. 1991). Muscle spindles are muscle receptors conveying information of muscle length and length changes which makes them fundamentally important for proprioception, that is the sense of position and movement, described in detail below. Proprioception is necessary for motor control, providing the basis for both intra and inter-muscular coordination (see; Proprioception, later in this text). In brief the muscle spindle model stipulates that pain, muscle fatigue or inflammation activate chemosensitive receptors in the tissues, which may disturb the function of the muscle spindles via spinal reflexes. In the initial version of the model this activation was presumed to emit an increase in the reflex mediated muscle stiffness that in turn would increase muscle activity and thereby initiate a vicious circle of increasing metabolite concentration, further increased pain and so on. The model has recently been
revised so that its focus primarily concerns the negative consequences that disturbed muscle spindle function has on proprioception (Johansson et al. 2003b).

Support for this idea comes from studies demonstrating that close intra-muscular injection of algesic and inflammatory substances profoundly modulates the sensitivity of muscle spindles (Wennergren et al. 1998a; Ro and Capra 2001) which has been shown to have a negative effect on the information content from groups of muscle spindles (Pedersen et al. 1998), subsequently on proprioception and, thus, on motor control (Johansson et al. 2003b). This model provides a possible explanation of impaired proprioceptive function that has been demonstrated in individuals of acute and persistent neck pain (e.g. Revel et al. 1991; Heikkila and Aström 1996; Kristjansson et al. 2003). An interesting aspect is that experiments in animal models have shown that activation of chemosensitive receptors modulate muscle spindles also in other body regions (Thunberg et al. 2001; Johansson et al. 2003b). The “spreading effect” was attributed to reflex effects from chemoreceptors onto heteronymous gamma-motoneurones. This mechanism has potential to impact proprioception in joints outside the painful region. In agreement with this idea, persons with chronic neck pain have been showed to have reduced proprioception also in the upper extremity (Knox et al. 2006b).

2.1.7.2.2 The pain adaptation model

The pain adaptation model (Lund et al. 1991) presents a somewhat different picture of how pain may affect motor control. This model predicts that pain causes an adaptation of muscle activation characterized by an inhibited activation of agonistic muscles but increased activation of antagonistic muscles. These changes in motor output were suggested to originate from an effect on spinal motor networks (i.e., alterations in the firing pattern of segmental interneurones in the spinal cord or brainstem) from nociceptive inflow (Lund et al. 1991; Stohler et al. 1996). The consequence is a reduction of both amplitude and velocity of movements (Westberg et al. 1997) that has been interpreted as a defence reaction; movement is restricted to avoid further injury, minimizing the probability of pain and, at the same time, enabling healing of the damaged tissues (Graven-Nielsen et al. 2002). Moreover, during dynamic activity, pain seems to modulate voluntary activation by either increasing EMG activity in phases where it is normally silent and decreasing it in phases where it is normally active (Arendt-Nielsen et al. 1996; Graven-Nielsen et al. 1997; Zedka et al. 1999). Such functional reorganization of muscle activity appears, however, to depend on the motor task (Arendt-Nielsen et al. 1996; Madeleine et al. 1999). Nevertheless, the effect will be an impaired ability of the muscle system to completely relax.

Deficits of this type have been demonstrated in some clinical studies of patients with spinal pain and in a number of experimental studies of normal subjects after injections of hypertonic saline. For example, the contraction-relaxation pattern of the trapezius and infraspinatus muscles in chronic neck pain patients seem to follow the predictions of the pain adaptation model with decreased ability to relax between repetitive muscle contractions and decreased shoulder flexion peak torques (Elert et al. 1992; Fredin et al. 1997; Larsson et al. 2000). Maximum voluntary contraction of painful muscles is also reduced in a number of disorders like fibromyalgia (Jacobsen and Danneskiold-Samsoe 1987; Backman et al. 1988), low back pain (Thorstensson and Arvidson 1982; Suzuki and Endo 1983) and neck pain (Silverman et al. 1991). However, reduced maximum voluntary contraction may, as pointed out by some authors, be a result of muscle deconditioning rather than a direct effect of pain.
(e.g., Thorstensson and Arvidson 1982). Still, the general picture from experimental studies is a decrease of EMG activity from induced muscle pain (although some studies have been reported no changes (Birch et al. 2000) and even increased muscle activation during experimental pain (Farina et al. 2004; Madeleine and Arendt-Nielsen 2005)). This decrease has been described following experimentally induced muscle pain both during static and dynamic muscle contractions (Lund et al. 1991; Arendt-Nielsen et al. 1996; Graven-Nielsen et al. 1997; Svensson et al. 1998; Madeleine and Arendt 1999). Zedka and coworkers (1999) also showed that injections of hypertonic saline into the erector spinae resulted in, not only reduced amplitude in EMG activity in the muscle, but also in a reduction of velocity and movement range of trunk motion.

The pain adaptation model has been relatively influential and presents a good explanation of some of the effects on movement control that occurs in acute muscle pain. It appears however that motor dysfunction in chronic pain states may be a more complex phenomenon. Since the model was developed mainly from studies of experimentally induced muscle pain, it has been argued that it may have limited application in patients with chronic pain and for pain originating from other tissues than muscles, such as joints or nerves, or for that matter, pain from undetermined (nonspecific) source (Sterling et al. 2001a).

2.1.7.2.3 The fear-avoidance model

It was recently proposed that pain adaptation may be a learned protective behaviour and thus a central effect rather than, as was first suggested, an effect originating from peripheral reflexive circuits triggered by nociceptive stimulation (Graven-Nielsen et al. 2002; Asmundsen et al. 2004). Hence, the pain adaptation model is today very much congruent with, and often mentioned along with, the “fear-avoidance model” that suggests that a cognitive appraisal of fear of movement and reinjury (kinesiophobia) underlie the protective movement behaviour (Lethem et al. 1983; Vlaeyen and Linton 2000; Graven-Nielsen et al. 2002; Asmundsen et al. 2004). This later model has in fact been described as a cognitive behavioural formulation of the pain adaptation model (Passatore and Roatta 2006). Nonetheless, Nederhand et al (2006) showed that fear of movement can affect the activation of the trapezius muscle in WAD. They also demonstrated that pain and fear of movement influenced muscle activation independently suggesting a rather complex interaction of these two factors (Nederhand et al. 2006). This disassociation implies that fear of movement is important but also that reduced muscle activation is not only an effect of kinesiophobia and that pain influence muscle activation through other mechanisms as well. Pain-related fear has been suggested to be a factor that maintains “pain avoidance movement patterns and behaviours”. In a number of injured subjects, abnormal movement patterns persist after the initial injury has apparently healed, which may lead to a “disuse syndrome” with further aggravation of old and maybe producing new symptoms (Moseley and Hodges 2005). This is in notable agreement with the idea of the muscle spindle (Johansson et al. 2003b) model.

2.1.7.2.4 The neuromuscular adaptation model

Yet another model, resembling the pain adaptation model, is the “neuromuscular adaptation model” (Sterling et al. 2001a). Even though it does not include an explicit theory on the neurophysiologic mechanism, it provided a more complex picture on how muscle coordination can be affected by pain. It states that pain leads to inhibition or delayed
recruitment of specific muscle groups that perform key synergetic functions to limit unwanted motion (Sterling et al. 2001a). It has been suggested that this phenomenon usually occurs in the deep inter-segmental muscles which primary function is to provide joint stability (Hides et al. 1996; Hodges and Richardson 1999; Falla et al. 2004b).

In clinical neck pain, a reduction in the activity of the deep cervical muscles (i.e., m.m. longus colli and longus capitis) has been demonstrated to be linked to an increased activity of the superficial flexor muscles during craniocervical flexion (Falla et al. 2004c). Delayed activation of the cervical flexors, most evident in the deep flexors, was also observed in neck pain patients when performing rapid arm movements (Falla et al. 2004b). It was proposed that the most likely explanation for the reorganization of activity from deep to superficial muscles is a motor strategy developed to compensate for dysfunctional deep flexor muscles (Jull and Moore 2000). The logic of a compensatory mechanism can also be applied to explain recent findings from studies involving hypertonic saline evoked upper trapezius pain. Thus, reorganization of the coordinated spatial distribution of muscle activity has been demonstrated both between muscles (Madeleine et al. 1999), between muscle parts (Falla and Farina 2008) as well as within the same part of the trapezius muscle (Madeleine et al. 2006), which, notably, occur with unchanged force output (Falla and Farina 2008).

2.1.7.2.5 Differences & similarities

Although sharing many key features, the described models have in the literature often been portrayed as distinct and sometimes as contradictory. For example, the issue whether pain inhibits or facilitates muscle activation has been widely debated with respect to the clearly divergent initial proposals made in the muscle spindle model and the pain adaptation model (Graven-Nielsen et al. 1997). Still, all models are supported by clinical and experimental studies. It is likely that they operate in parallel or in different stages of the pain process from acute to chronic (Johansson et al. 2003a). In any case, both peripheral and central mechanisms are most certainly involved, as well as complex interactions between pain and sensorimotor function. Although the picture is far from complete, the different models have been instrumental in producing ideas for important studies.

2.1.7.2.6 Proprioception a key factor

With that said, a special focus on proprioceptive deficits in musculoskeletal pain may be warranted since it may produce similar modification of motor control and give rise to similar possible consequences as described in all of the depicted models (Passatore and Roatta 2006). Because proprioception, besides being critical for sensing head or limb position, is important for both intra- and inter-muscular coordination since proprioceptive deficits can potentially shape spatiotemporal organization of muscle activity within and between muscles. To overcome a loss of movement accuracy and precision, the system may adopt a different motor strategy in performing a given movement, with regard to muscles, groups of muscles or motor units activated, the time of onset and the sequence of their individual activation and relaxation patterns and also in the co-activation of antagonist muscles (co-contraction) (Ghez and Sainburg 1995; Gribble et al. 2003). Furthermore, uncertainty of the spatial location of the body and body parts can result in smaller, slower or hesitant movements, which could be interpreted as functional adaptations to pain or fear of pain.
2.1.8 Rehabilitation and treatment

Due to the lack of knowledge of the mechanism underlying most cervical pain conditions, science-based knowledge of what treatment methods to use for the individual patient is very limited. This means that treatment based on causal mechanism is not achievable for most cases of chronic nonspecific neck pain. This absence of knowledge leaves intervention and rehabilitation to symptom reduction and functional improvements.

2.1.8.1 Efficiency of multimodal rehabilitation

Despite the rather negative prospect of finding a genuine cure, there are today scientifically based guidelines for efficient rehabilitation of people with persistent non-specific musculoskeletal disorders. In a recent review of treatments of long lasting musculoskeletal pain it was concluded that multimodal rehabilitation, (i.e., well-planned synchronized interventions of at least two modalities) including cognitive behavioural therapy in combination with structured physical activity/training or physical therapy, is much more likely to be successful compared with single treatments that do not activate the patient (2006; SBU 2006b). The positive effects include, for example, reduced pain and time on sick-leave. Provinciali et al (1996) found mulidiciplinary treatment to be the most effective approach for WAD and Meijer et al. (2005) came to similar conclusions in their review on rehabilitation programs for non-specific pain. Efficient programs mostly included education on pain, anatomy and psychology as well as physical training and occupational retraining.

It has been recommended that all individuals with persistent or frequent symptoms for more than three months should be evaluate d for multimodal rehabilitation (e.g., Sterner and Gerdle 2004). However, most people suffering from non-specific neck pain are not offered multimodal rehabilitation. Instead they are referred to less structured, and often unimodal, intervention programs in outpatient settings.

2.1.8.2 Efficiency of unimodal rehabilitation

For such single treatment (modality) approaches it appears as if manual therapy, mobilization, exercises, educational videos, low-laser therapy and perhaps acupuncture are beneficial, compared to care as usual or sham treatment. However, no convincing evidence (i.e., from randomized controlled trials; RCTs) has been found that indicate a superiority of any method over the other in the short and long term (see reviews by SBU 2006; and Hurwitz et al. 2008). Still, the most consistent finding from a number of studies and reviews is that, for persistent neck pain (as well as for low back pain), structured supervised training lead by a therapist reduce pain and activity limitation and improve health and return to work, compared to more passive methods like advice on training or stress management (2006; Hurwitz et al. 2008). In these studies, many different types of exercise and training regimes were used. Moreover, in individual studies the interventions are often complex and sometimes mixtures of several training forms or treatments, even though defined as unimodal, which makes it difficult to determine which components of a treatment package might be effective. Notably, in many of the studies showing positive treatment effects, components of proprioceptive or coordination training have been included (e.g. Revel et al. 1994; Fitz-Ritson 1995; Lundblad et al. 1999; Taimela et al. 2000; Jull 2001). This observation – that training of sensorimotor functions may be a key component in rehabilitation of neck-shoulder pain conditions – is consistent
with the emerging knowledge from both clinical research and research on the pathophysiological mechanisms of musculoskeletal pain (see review by O'Leary et al. 2003).

2.1.8.3 The shortcoming of RCTs

Reviews investigating the efficiency of different treatment approaches rely heavily on results from RCT-studies. However, with respect to nonspecific syndromes the RCT methodology has some underlying difficulties when it is used to evaluate the relative effectiveness of one treatment package against another. As emphasized by McCarthy and Cairns (2005), the heterogeneity of nonspecific groups may well be “washing out” larger, positive effects observed in some individuals by smaller or negative effects seen in others. Today the relationship between a specific patient profile and the type of intervention suited for that profile is unclear. Specific treatments directed to unspecified injuries will have limited chances of succeeding (as observed in the small effect sizes for unimodal treatments described above) and it is important not to discount treatments that may be beneficial to some patients merely because we have failed to identify who they are. Hence, the clinical implications and conclusions draw from pragmatic RCTs of nonspecific neck pain must be interpreted with care since the RCT methodology, at that early stage, clearly lack the discriminatory ability necessary to evaluate such complex interactions. Better effects of multimodal rehabilitation approaches is not surprising accepting the fact that chronic neck-shoulder pain, in most cases, is a multifaceted disorder that demands intervention on many levels. If the pathomechanism is unclear a broad scope of interventions, including methods that affect both organic and non-organic problems, is obviously more likely to succeed than one single method. Evidently, this implies that there is a considerable potential for improvement of rehabilitation efforts by improving the assessment methods for neck pain patients.

Non-specific neck pain definitely contains more specific homogeneous sub-groups of patient profiles who would be more suited than others for a specific treatment approach. But, and this is a key motive for my research – since the link between our measurements and the diagnostic profile of our patients is unclear, such subgroups are yet to be identified. Owing much to the lack of knowledge of pathomechanisms, there is no agreement today on how sub-classifications on nonspecific neck pain should be conducted, i.e. what parameters or entities that should be addressed, what tests that should be used or what the subsequent findings of the tests might indicate. Hence, it is critical to identify such key features of nonspecific pain disorders (e.g. sensorimotor function) and to establish the clinical validity of outcome measures reflecting these parameters.

2.1.8.4 Measurements, characterization and profiling

"Physiotherapy, like medicine and law, will always remain partially an art, but without measurement it can be nothing more than art" (Rothstein 1985, p.1).

Despite the obvious value of using outcome measures and instruments such as questionnaires or performance tests, they have traditionally been used to a limited extent by health care professionals in the management of neck pain. Although this may be about to change, the fact remains that the validity, reliability and utility of almost all commonly used clinical musculoskeletal neck examination tests have been questioned (Viikari-Juntura 1987;
Bertilson et al. 2003; van Trijffel et al. 2005; Nordin et al. 2008). Moreover, classical diagnostic criteria used in clinical examinations might not provide sufficiently objective measures of neck pain disorders (Punnett and Wegman 2004). The lack of methods for objective measures of relevant outcome parameters emphasizes the importance of developing such methods.

There is a vast amount of literature on tools and techniques used to assess different dimensions of pain. Both self-assessments and tests administered by clinicians may, for example, be used to characterize the patient’s clinical profile. As already mentioned, the ICF structure may provide a conceptual framework that will eventually be useful in such profiling. Moreover, another ambitious project; the Initiative on Methods, Measurement, and Pain Assessment in Clinical Trials (IMMPACT) has recommended six core outcome domains that should be considered in clinical trials of chronic pain: pain, physical functioning, emotional functioning, participant ratings of improvement and satisfaction with treatment, symptoms and adverse events and participant disposition (Turk et al. 2003). Such initiatives will be valuable to systemize and guide both research and management of musculoskeletal pain in the future. However, hitherto no consensus has been established on what assessments and measures that should be preferred in neck pain conditions. Relevant and discriminative assessments are a prerequisite for individualized rehabilitation interventions (McCarthy and Cairns 2005). The model presented in Figure 2 by McCarthy and Cairns (2005) is an example that points out the importance of valid measures in order to characterize patients in a biopsychosocial profile. Such profiling is a crucial step towards finding the specific needs and barriers to recovery of patient. To establish which patients have the greatest chance of success with a specific intervention approach would indeed be a major breakthrough in rehabilitation of musculoskeletal pain.

2.1.9 A multivariate problem approach

It is not the ambition of the present thesis to cover the various domains of chronic pain. However, it is important to appreciate that chronic neck pain constitutes a complex

Figure 2. A model of management for pain syndromes. From McCarthy & Cairns (2005). Re-printed with permission from Elsevier Limited.
multidimensional problem and that studying any aspect in isolation implies a risk of overlooking important associations to other, not studied aspects. When exploring novel fields of clinical assessments, like sensorimotor functions, with the intention to elucidate presumably important components in patient profiles, it is important to investigate how such assessments relate to other clinical features. A lack of association with subjective symptoms, functional deficits and other personal characteristics imply that the phenomenon under study may not be meaningful for the individual. Thus, any novel assessment or outcome measure would benefit from being validated against self-assessed health for the purpose of clinical relevance. In this thesis the multivariate nature of chronic neck pain is acknowledged by the use of multivariate projection methods for exploring associations between movement precision and self-ratings of various health domains.

Sensorimotor functions, like proprioception, coordination or balance, are important features of neck-shoulder pain. Objective assessments of such functions should therefore be included when people with neck-shoulder disorders are clinically examined and evaluated. Theoretically, numerous sensorimotor functions may be addressed that together could constitute a comprehensive individual sensorimotor profile. Attempts along these lines have been done (Sjölander et al. 2008). In this thesis, however, the focus will be on assessments of a specific set of sensorimotor functions concerned with precision of goal-directed movements of the upper limbs – assessments that might be objective measures and of use to describe sensorimotor dysfunction in neck pain.

2.2 Proprioception

2.2.1 Kinaesthesia and proprioception

In all situations we, consciously or unconsciously, sense our body parts, their positions and movements. To describe these sensations the term proprioception, derived from the Latin proprius (one’s own) and receptus (to receive), was coined by the British neuroscientist Sherrington (1906) and has since its introduction been extensively used in the scientific literature.

Proprioception comprises of two main modalities— the sense of position and the sense of movement (McCloskey 1973; Roll and Vedel 1982; Sittig et al. 1985). The latter is sometimes referred to as kinaesthesia or kinaesthesis. This term was originally formulated by Bastian in 1880 (1880) from the Greek kinein (to move) and aisthesis (to perceive). Quite confusingly, proprioception and kinaesthesia are sometimes used interchangeably and sometimes as separate concepts in the literature. Proprioception has sometimes been limited to only unconscious sensation and kinaesthesia to conscious perception of the body or, alternatively, proprioception has been referred to the sensing of the body's own movements, with kinaesthesia composing a subset concerned only with movement of the extremities.

In this thesis proprioception is defined as the conscious and unconscious sensation of positions and movements of the body segments in relation to each other, without the aid of vision, touch or the organs of equilibrium.
2.2.1.1 Joint-position sense

Lately, in clinical research the term joint-position sense has become popular; perhaps to avoid the confusion afflicted with the use of proprioception and kinaesthesia, but nevertheless unfortunate since it incorrectly implies that the receptors responsible for the sensations of position and movement are mainly located in the joints. On the contrary, which is described in the next section, the most vital receptors reside outside the joint; particularly in the surrounding muscles. Moreover, although proprioceptive assessments usually involve joint position estimates, the term joint-position sense is misleading since it implies that the control of movement and positions are explicitly based on joint angulations and that there is a specific sense allocated to regulate this particular parameter, an assumption that is dubious with respect to contemporary models of motor control (Desmurget and Prablanc 1997; Brown and Rosenbaum 2002). As argued by van Beers et al. (1998), joint angles are rarely meaningful in everyday life and can therefore not be readily perceived. Instead, in for example manual reaching, the position and orientation of the hand (end-effector) is functionally more relevant, although joint position estimates can be useful parameter in tests of proprioception because of the obvious geometric relationship between joint coordinates and spatial coordinates.

The division of proprioception into a static position sense component and a dynamic movement sense component has gained strong experimental support. It has been shown that extremely slow passive movements are perceived as changes in position without any perception of movement (Horch et al. 1975; Clark et al. 1985). From experimental studies of movement illusions induced by muscle vibration it was suggested that these submodalities are using partly different neural pathways (McCloskey 1973). Also, with reference to the sense of movement, more recent findings argue for a further subdivision into direction and velocity components (for review, see Sjölander and Johansson 1997), which may be used separately in the control of movements and contribute to the perception of different movement qualities (Sittig et al. 1985; Clark 1986). The specific effect of different proprioceptive modalities remains still to be clarified but the crucial effect of proprioception for optimal control of movements is beyond question.

2.2.2 Afferent sources of information for proprioception

The sensory input from which proprioception is formed originates from mechanoreceptors in the muscles, skin and joints (Grigg 1994), collectively often denoted proprioceptors. Sherrington (1906) proposed in his classical treatise *The integrative action of the nervous system*, a classification system of all sensory receptors according to the source of the stimulation which they respond to. Proprioceptors which provide information about ones movements and postures, through internal stimuli, were distinguished from exteroceptors that respond to stimuli in the immediate external environment. To a major extent his classification holds still today although questions of which receptors subserve proprioception, and their relative contribution, have been debated.

In the mid seventies, the at the time, prevailing idea of the joints as the most critical structures for proprioception were more or less abandoned after findings showing that joint receptor afferents only are active when the joint are in extreme positions (Clark and Burgess 1975). Today it is clear that proprioception depends on information from receptors in both muscles and skin as well as in joints, with muscle receptors, or more specifically – the muscle spindle – ranked as the principal proprioceptor (for review see Gandevia and Burke 1992).
Muscle spindles are fusiform (cigar-formed) structures located in muscle bellies in parallel to the surrounding extrafusal muscle fibres (for reviews see Matthews 1972; Hulliger 1984). Muscle spindles are very powerful for sensing positions and movements owing to their refined sensory ability to signal muscle lengths and length changes and because of a, for sensory receptors, unique ability to adapt its own sensitivity via the gamma-motor drive. However, it is important here to note the general principle that the CNS, in order to extract meaningful information on positions and movement, need the combined signalling of many receptors (i.e., assemble coding), and that any receptor in isolation from others is generally ineffective in providing such information (Bergenheim et al. 1996; Wallace and Kerr 1996). Convincing evidence for the importance of muscle spindles were provided in studies where proprioceptive acuity was found to be only marginally reduced when other sources of proprioceptive inflow (i.e., from joint and skin mechanoreceptors) were removed (Clark et al. 1979; Ferrell and Craske 1992). Earlier Goodwin et al. (1972) had showed that vibration, which is known to excite muscle spindles, induce illusions of limb movement (Goodwin et al. 1972). A finding that strongly implied that muscle spindle information is related to the perception of position and movement, which had previously been questioned (Goodwin et al. 1972).

As mentioned, the significant role of the muscle spindle system for proprioception does, however, not exclude the influence of receptors in other structures. Rather, the relative importance of muscle, skin and joint receptors seems to depend on which body part, joint position and type of movement that is involved. Mechanoreceptors of the human hairy skin, adjacent to or covering joints may play an important role of limb position and movement, especially in the hand and fingers (Ferrell and Milne 1989; Ferrell and Craske 1992; Edin and Johansson 1995; Collins and Prochazka 1996; Collins et al. 2005), and joint mechanoreceptors may, as mentioned above, be important in the control of more extreme joint positions and joint ranges (Clark and Burgess 1975). In this context and in the framework of this thesis, it is also worth noting the high number of spindles subserving joints in proximal muscles, particularly in the neck and shoulder region, compared to distal joints (Bakker and Richmond 1982). Strikingly, this observation corresponds to numerous findings of higher proprioceptive acuity in proximal compared to distal joints (Hall and McCloskey 1983; Clark 1992; Scott and Loeb 1994; Refshauge et al. 1995) and may indicate a relative importance of muscle spindles in different anatomical regions.

2.2.3 The body in the brain

2.2.3.1 Proprioception and the body schema

Tightly linked to proprioception is the concept body schema (or body schemata) – a representation of one’s own body that provides a standard against which postures and movements are judged (Head 1920). Evidence from psychological and neuropsychological studies suggests the existence of such internal mental representations of the body, in parallel to (and not to be mixed up with) the topological maps of body parts in the brains cortex (i.e., somatotopic representations) (Schwartz et al. 2004; Schwoebel and Coslett 2005). Today there is no consensus on the definition of body schema and related concepts like body image, virtual body or corporeal awareness, and there are several proposed models regarding the structure of these internal body representations (e.g Paillard 1999; Vallar et al. 1999). Common for these models is the idea of a body schema that is retained and modified
throughout life experience as a result of past sensory experiences, primarily proprioceptive but also tactile and vestibular as well as of motor output signals (Maravita et al. 2003; Schwobel and Coslett 2005; Giummarra et al. 2008). According to Melzack (Melzack 1990) the body schema is subserved by a distributional neural network or neuromatrix, largely pre-wired by genetics but open to continuous shaping. 

Gallagher (1986; 2005) proposed an idea that has been quite influential where he made a conceptual distinction between an unconscious body schema and a conscious body image. Body schema, in his view, relates to an unconscious sense of one’s body and actions that governs automatic control of posture and motor action. Body image on the other hand is defined as a more conscious, top-down, idea or mental representation including body-specific perceptions, intentional states, attitudes, beliefs and emotions, which is mostly used for conscious perceptual judgements. Thus, body schema is unconscious, automatic and used for motor action while body image is used for conscious perceptual judgements. While the body schema mainly relies on proprioception and thus view the body and actions ‘from inside’, an important component of the body image is the appearance of the body ‘from the outside’. Consequently the body image may also depend on visual information of the body (for a review, see Giummarra et al. 2008). A fascinating aspect is that tools and attachments to the body, such as a prosthesis or a screwdriver, can become incorporated into the body schema, affecting one’s automatic approach to the environment, as well as into the body image with effects on one’s conscious projection and movement (Gallagher 1995). Furthermore, evidence from behavioural studies indicate that the body schema and image rely on distinct bottom up and top down processes, respectively (Tsakiris and Haggard 2005; Kammers et al. 2006). For instance, Kammers et al 2006 used vibration to create illusive lengthening of muscles of the limbs and concluded that perceptually based position matching was associated with the body image while action based reaching was associated with representations of body schema. Furthermore, in cases of deafferentation (i.e. individuals without proprioceptive input from the body) described below, an enhanced body image achieved through constant visual contact with the body, could explain their ability to move and function despite a lost or reduced body schema.

2.3 The role of proprioception in sensorimotor control

Proprioceptive afferent information is used for conscious and unconscious control of movement. It allows for detection and correction of errors in the ongoing movements via feedback (closed-loop control) and reflex mechanisms and provides the basis for coordinated (intra- and inter muscular coordination) and smooth movements as well as stabilization and balance control. It also provides information used in planning of motor commands and it is crucial for learning motor skills (Schmidt and Lee 1999). Proprioceptive information is, thus, essential for deciding which movements to make, for observing the consequences of these movements and for learning by experience.

A major argument for such an important role in motor control is the observation that movement accuracy decreases in the absence of proprioceptive information from a moving limb (Rothwell et al. 1982; Sainburg et al. 1993; Ghez et al. 1995). For example, Sainburg and coworkers (1993) showed that patients with a loss of proprioception due to large-fiber sensory neuropathy could not compensate for interaction torques in a movement similar to
slicing a loaf of bread, which resulted in severe impairments of interjoint coordination. Similarly, Rothwell et al. (1982) demonstrated this category of patients incapable of making reflex corrections to upper limb movements, to sustain constant levels of muscular contractions or maintain long action sequences in the absence of visual feedback.

The limitations of conscious experience make us selective – we are not aware of everything we lay our eyes on. Similarly, we can quite happily function without ever paying too much attention to our movements although the brain all the while, unconsciously, is sensing movement. In everyday situations, conscious awareness of our movements and their sensory consequences is only called upon when movements start to deviate from what we expect. Fourneret and Jeannerod (1998) showed that even quite large deviations can remain undetected as long as subjects get the impression that their intentions have been achieved. Thus, proprioception in everyday life is an unconscious aspect of the sensory system but, nonetheless, crucial for our ability to move. Striking examples of how important proprioception is comes from observations of individuals with a loss of proprioception as has been mentioned above. If, for instance, the lights are switched off so that these individuals are prevented to use vision to guide movements, their movements freeze or they simply fall in a heap on the floor unable to make successful voluntary movements (Cole 1991).

Notably, for a period in the history of motor control (from the late nineteen-sixties until the early nineteen-nineties) sensory information was suggested to be of only marginal importance. This belief grew from findings showing that the time delays associated to the transduction and processing of afferent signals is generally too long to be implemented and used for movement corrections. Estimates of the time for proprioceptive feedback to influence ongoing hand movements are between 80 and 250 ms (Cordo et al. 1994; Paillard 1999; van Beers et al. 2004), which could appear to be quite fast with respect to many everyday tasks but, nonetheless, insufficient for online control of very fast movements. It was concluded that such movements must be preplanned, i.e., under feedforward (or open-loop) control (see Desmurget and Grafton 2000 for a review). The idea of motor programs (Keele and Posner 1968) that evolved during the same period was considered to involve a set of muscle commands which was structured before a movement sequence begins and allowed the whole sequence to be carried out unaffected by peripheral feedback. However, also in such pre-programmed movements, the initial movement conditions, obviously, have to be known in order to carry out an accurate movement, which requires estimates based on sensory feedback (e.g., Vindras et al. 1998). Nevertheless, the idea of a feedforward control mechanism still applies although the picture today has become more nuanced. Most authors agree on the importance of both feedback and feedforward control of movement even though the details about how sensory feedback influences motor commands are still not fully understood (Wolpert et al. 1995; Desmurget and Grafton 2000).

In modern theory of motor control, the concept internal models have been included alongside the notion of feedback and feedforward control. An internal model is a hypothetical central neural representation of the laws of physics (i.e. of the dynamics and kinematics of movement and the behaviour of objects in the external environment) that enables the CNS to predict the consequences of motor commands and to determine the motor commands required to perform specific tasks.. There is today compelling evidence of the employment of such internal models or transformations within the CNS which can mimic the input/output characteristics (forward models), and their inverse (inverse models), of the movement.
apparatus (for a review see Wolpert and Kawato 1998). Just like feedback and feedforward this idea has its root in engineering theory of adaptive control and state estimation. By integrating information of the current, desired, and predicted state of the motor system (its sensory inflow and motor outflow) in internal feedback loops, the probable new location of the effector, such as the hand in a reaching movement, can be predicted. Hence, since both a copy of the motor command, called efference copy or corollary discharge (Sperry 1950; Von Holst and Mittelstaedt 1950) and the predicted sensory consequences of the movement is available instantaneously or with negligible delay, forward modelling entail that the time delay associated to ‘regular’ sensory feedback can be avoided. An important implication of this idea is that the preplanned motor plan assembled prior to the onset of a movement does not unfold unaltered but is updated continuously. The today established theory of internal models clearly argues against the traditional view that rapid reaching movements only operate through open-loop strategies and that feedback only is used in slower movements or in the end phase of faster movements (Desmurget and Grafton 2000). Furthermore, sensory information is critical to set parameters for and update internal models. In other words, sensory information is needed for the nervous system to progressively ‘learn’ to estimate the behaviour of a motor plan (Sainburg et al. 1993).

2.4 Testing proprioception

Because proprioceptive deficits appears to accompany a number of injuries and diseases as described earlier in this text and since a major part of the studies of this thesis concerns tests of proprioception, a review on this subject is briefly outlined with focus on the procedures of relevance in my research. Although tests of proprioception are often used both in clinical and more fundamental research, it should be said that the interpretations of the results is not straightforward.

Assessments of proprioceptive function are conducted using methods based on psychophysics – the relation between stimulus and sensation (see e.g., Gescheider 1997). This research field includes a variety of methods that are affected by a number of factors depending on certain aspects of the test design. What most commonly has been assessed is the awareness of limb position in space and thresholds to detect passive movements (Clark 1986). Depending on the procedure used for testing, the tests are often named as “position sense tests” and “movement sense tests” even though it has not been established whether such tests selectively measure these submodalities of proprioception.

In psychophysics there are three standard methods for assessing sensory thresholds: the method of limits, the method of constant stimuli, and the method of adjustment (Gescheider 1997). In the method of limits a series of stimuli is presented in either ascending or descending series, that is, the level is gradually increased or decreased until the participant reports that they are aware of it. In the method of constant stimuli the level of the stimulus under study is instead presented randomly preventing the test subject to predict the next stimulus. In the method of adjustment the subject is to adjust the level of the stimulus until it, for example, is equal to the level of another stimulus (Gescheider 1997).

While movement detection and velocity discrimination normally is assessed using the two first methods, position sense tests usually involves the method of adjustment (e.g., Lönn
et al. 2000b). The method of limits has also been used, although much less frequently (Waddington and Adams 1999). For the framework of this thesis a closer description of position-matching tests will follow.

2.4.1 Position-matching

In position matching tests, subjects are usually blind-folded throughout the whole procedure to prevent visual information from affecting the result. Such tests can be conducted in many different ways and from the literature it stands clear that a large number of designs have indeed been used (see Clark 1986). Typically, a limb or joint position (i.e., criterion or standard stimulus) is to be matched, either with the contralateral limb or in a replication with the same (ipsilateral) limb after moving it back to the original, or another, starting position. Usually the movement is restricted to one degree of freedom (DOF). Different body regions and joints have been studied including for example the Shoulder (Lönn et al. 2000b; Björklund et al. 2003), knee (Stillman 2000), elbow (Knox and Hodges 2005), cervical (Revel et al. 1991; Heikkila and Astrom 1996) and lumbar spine (Brumagne et al. 2000; Åsell et al. 2006). Studies have been using both passive and active movement modes (Lönn et al. 2000a; Janwantanakul et al. 2002; Djupsjöbacka and Domkin 2005), ipsilateral and contralateral tests (Grob et al. 2002) and both visual and proprioceptive targets (van Beers et al. 1999). Studies have also included different starting and target positions (Lönn et al. 2000b), target selection modes (self selected or experimenter selected) (Walsh 1981), movement extents (Janwantanakul et al. 2001) or memory cues (limb positions or joint angles) (Soechting 1982) to mention some variations. This variety of designs and methods makes comparisons between studies quite difficult. It is also important to ponder that the design has consequences for what perceptual cues subjects will attend to and what parameters they choose to control. Consequently, differences in test design may have influence on the results in various ways and likely also to a higher degree than is generally recognized. (Lönn et al. 2000b; Gunzelmann and Anderson 2006).

2.4.1.1 Cognitive influence

An inherent problem of psychophysical methods in general is that proprioception can only be assessed indirectly. The proprioceptive function one is trying to estimate may be obscured by mental states and central processes involved in the response adjustment phase. For example this method is susceptible to fatiguing effects and attention lapses during testing, which may confound the results. Moreover, in tests of limb position-matching, ipsilateral matching – matching with the same limb to a previously performed and memorized position – is usually preferred to avoid the problem of possible proprioception differences between different limbs, due to differences in body image or body schema across sides or laterality issues (dominant vs. non-dominant limbs). However, this procedure will inevitably involve a memorization component where the position of the criterion movement has to be stored in short-time memory and used for comparison of the upcoming matching movement. Thus, it should be noted that position sense testing, in part, reflects also such central processes rather than ‘pure’ proprioceptive sensation and the test design should, therefore, be selected with care.
2.4.1.2 Position vs. movement cues

When studying the underlying sensory mechanisms of proprioception the influence of limb position and limb movement is important. Opinions differ as to the preference which healthy subjects have for accessing movement cues (i.e. dynamic information of velocity, amplitude, duration or direction derived during movement) and position cues derived during maintenance of the test position. For position-matching these aspects have classically been addressed by simply asking the subjects to attend to and recall either the end location or the movement extent while alternating starting and/or target positions as well as movement extents. Imanaka et al. (1993) noted however that subjects’ responses may be influenced also by the unattended cues, suggesting complex interactions between position and distance cues (Imanaka et al. 1993). Thus, these findings could partly be explained by the fact that it is difficult to control whether subjects actually attend to the cues that they are instructed to during the test (Semler and Simmons 1979; Imanaka et al. 1993).

2.4.1.3 Passive vs. active tests

Further, a general problem when trying to differentiate between position and movement sense is that any changes in position inevitably leads to a movement and vice versa (Clark 1986). It has been suggested that “pure” position sense could be assessed if some kind of distraction is implemented during the movement phase that makes movement cues unreliable or useless (e.g., Stillman 2000). Such distractions could ensue if a passive criterion position is presented via an indirect movement path (Remedios et al. 1998), or by having the subject count backwards aloud during the movement (Lee and Kelso 1979; Wells et al. 1994). These procedures would, however, seriously risk confusing the subjects and distract also the process of attending to the position cues. Still, by using very slow passive movements, below the threshold of movement detection, it may be possible to achieve isolated assessments of “static” limb position sense (Clark 1986; Cordo et al. 2000). Conversely, by using a passive velocity discrimination method, Lönn et al (2001) showed that subjects base their estimations on velocity differences and not on limb position or movement time, indicating that such a test, indeed, addressed limb velocity sense. A drawback of both these latter methods is, however, that they are quite time consuming reducing the applicability especially in clinical studies. For upper limb position matching it has been suggested that position cues are more important for the control of longer movements (Roy 1977; Roy and Kelso 1977; Semler and Simmons 1979) while distance (or movement) cues appears to be more influential in shorter movements (i.e., less than approximately 15-20 cm) (Walsh 1981).

2.4.1.4 Efferent vs. afferent information

Another suggestion that could explain the differences in the control of movements to targets at long and short distances, is that matching of longer movements may rely more on afferent proprioceptive information whereas shorter movements is controlled more by efferent mechanisms (Wolpert et al. 1995), that is predictions based on the motor commands involved in the generation of the criterion movement. Since there is no memory of the motor commands involved in passive tests it might seem reasonable that passive position matching should be used if the purpose is to estimate the “pure” afferent processes of proprioception involved. However, passive position matching tests have repeatedly been showed to be more unreliable than active tests (e.g., Lönn et al. 2000b; Janwantanakul et al. 2002). Moreover,
since the proprioceptive system normally functions under circumstances where the muscles are activated the generation of positions and movements sensation is, in everyday life, not a passive process, which argues in favour for using active rather than passive tests (Matthews 1972; Gandevia et al. 1992; Kalaska 1994).

2.4.1.5 Outcome measures

The outcome measures used in position-matching can be separated into systematic errors or random errors. Importantly, these two types of error reflect fundamentally different sensorimotor aspects which must be recognized (Schmidt and Lee 1999). In a typical position-matching procedure the standard stimulus (i.e., limb position) is matched either with the contralateral limb or in a replication with the ipsilateral limb. The difference between the standard and replicated (adjusted) position is usually denoted Algebraic Error (AlgE) and is used as the outcome for the individual trials. However, it is obvious that a single trial will not be sufficient for describing a subject’s behaviour or performance and that including many trials in the estimate will provide a more stable measure (Allison and Fukushima 2003; Swait et al. 2007). The mean of several algebraic errors is usually denoted Constant Error (CE), which represents the response bias or the systematic tendency to over- or underestimate the stimuli. As mentioned, what is often the primary objective in many clinical studies is, however, to establish the proprioceptive acuity or precision, which is measured in the dispersion (i.e., variability the inverse of acuity) of the stimulus responses around the CE. Variability is normally calculated as the standard deviation of the AlgE over several trials and denoted Variable Error (VE). As such, VE indicates the difference threshold to discriminate between two stimuli and is considered to reflect the noise in sensory signals (signal to noise ratio) and in the processing of the sensory signals. This means that any proprioceptive impairment reveals itself in unreliable responses which in position-matching are captured by increases in a variance measure (i.e. VE).

Still, in clinical studies the mean of the absolute (signless) algebraic errors over several trials; Absolute Error (AE) is frequently used. This has been criticized (e.g. Clark et al. 1995) since AE is a composite measure of VE and CE (Schutz and Roy 1973; Schmidt and Lee 1999) and, hence, difficult to interpret. AE may be viewed more as a global performance measure and its use probably follow a task-oriented tradition in motor control research where the underlying processes of the performance have not always been a concern (Schmidt and Lee 1999). Previous studies however show considerable inconsistency in the manner of reporting position sense estimates, even in studies that express the same aim of trying to estimate, for instance, proprioceptive precision. A disappointing observation is that clinical studies recurrently show insufficient care and effort in describing what is measured and why. Both systematic and random errors may have clinical relevance but, as argued, only random errors can be considered to reflect the quality of proprioceptive information (Clark et al. 1995; Gescheider 1997; van Beers et al. 1998).

Evidently, VE and CE provide better measures than AE to interpret and understand the processes underlying the sense of positions and movements. It is important, however, to include enough trials in a test series in order to get stable measures, especially for VE calculations (Allison and Fukushima 2003; Swait et al. 2007). For example, one odd trial, maybe by mistake, will have a large effect on variability estimates if there are few trials compared to if they are many, which will make the VE reflect the one mistake and not
genuine acuity. Recently, Swait et al (2007) elegantly demonstrated that a minimum of six trials is needed to achieve stable estimates of CE and VE in a cervical repositioning test. This result is also in accordance with results reported for the thoracic and lumbar spine (Allison and Fukushima 2003). Rather frequently in clinical studies however, not more than three trials are used, which may have confounded the results in some studies (e.g., Voight et al. 1996; Sterling et al. 2003; Treleaven et al. 2003) and provided for impetuous conclusions of poor reliability of position sense estimates (Strimpakos et al. 2006).

2.4.1.6 Systematic and variable (random) error

As already mentioned, a systematic error (CE) cannot, directly, be interpreted as a sign of reduced proprioception since a strong tendency to over- or undershooting, still, can be very reliable. This situation is often compared to that of aimed shooting or archery, where arrows can be shot very close to each other but, systematically, off the target to one side. Without feedback and a possibility to reset the sites this performance, still, imply high acuity (low VE) but will obviously result in low scores. With this logic it was suggested that CE rather should be regarded as reflecting the current calibration status of the system (van Beers et al. 1998). Typically, in everyday movements vision is used to calibrate proprioception and our internal (egocentric) reference frame to the outside world. Without visual (or haptic) feedback however, the calibration may be offset and may also, as is discussed below, have a tendency to drift with time (Schutz and Roy 1973; van Beers et al. 1998). Large intra- and inter-individual differences in the calibration status and in the tendency to drift may be present (Smeets et al. 2006) and is likely one reason for why CE has been shown to be quite unreliable when compared between test occasions (Lönn 2001; Janwantanakul et al. 2002).

In studies of spinal pain there are inconsistent findings of position-matching CE; sometimes reporting overshooting (e.g., Heikkila and Astrom 1996; Treleaven et al. 2003), undershooting (e.g, Brumagne et al. 1999) or no difference to healthy control subjects (e.g. Newcomer et al. 2000). The divergent findings are likely related to characteristics of the group under study as well as to differences in methodology and study design. For example, in spinal pain the influence of inertia and gravity in combination with pain provocation in different movement directions are likely important for under- and overshooting biases. It has been shown that the magnitude of undershooting depends largely on the degree to which the movements are performed in the direction against gravity (Lyons et al. 2006). Undershooting in downward movements (e.g. in spinal flexion in upright positions) is proposed to be due to a higher ‘cost’ of a target overshooting compared to an undershooting since a complete reversal would have to work against gravity (Elliott et al. 2004). Moreover, a more general principle proposed for goal-directed movements predicts that increasing levels of uncertainty (noise) in the sensory inflow cause subjects to undershoot the target “to be safe” (Engelbrecht et al. 2003). Nevertheless, since the interpretation of systematic errors, as the above examples illustrate, is rather complex, CE is not suited to assess acuity or reliability of a system and should not be used in isolation to make inferences of the quality of proprioceptive information. In the studies included in this thesis, mainly precision and uncertainty of movement which refers to VE is addressed because these are a direct consequence of noise in the sensory system (Gescheider 1997). In any case, some aspects of systematic errors may be related to uncertainty and precision and yet others deserve further attention since they have direct consequences for how the VE should be analysed.
2.4.1.7 Bias drift and detrending

A number of research studies have demonstrated that movements increasingly drift from targeted locations as visual feedback information is removed (Wann and Ibrahim 1992; Wickelgren et al. 2000; Brown et al. 2003; Smeets et al. 2006; Mon-Williams and Bingham 2007). In position-matching tests, a common observation is that a subject in the beginning of a test series undershoots the target but, as the test progress (and maybe as confidence gains), starts producing longer and longer movements. This means a CE-drift (drifting average) from negative to positive values within the same session. Why this is mentioned is because the presence of a CE-drift has crucial importance on the variance and how the VE should be evaluated (van Beers et al. 1998). The individual AlgE may in such cases be spread over a quite large range resulting in a large standard deviation (VE) which is deceiving. The magnitude of the CE drift is highly subject-specific both in amplitude and direction, and the mechanisms behind it have been explained in terms of execution errors, sensory adaptation and drifting sensory maps (Smeets et al. 2006). Regardless of mechanism, the drift obviously presents a problem since the summary measures (average; CE and standard deviations; VE) are unable to reveal if the data includes a systematic drift or not. Importantly, it was demonstrated that the drift in performance occurs without any drift in sensory information (Smeets et al. 2006). This concord with the suggestion that proprioceptive information required for controlling movement is not affected by movement drift (Brown et al. 2003).

Smeets (and van Beers 1998; 2006) have highlighted this phenomenon and also described a way to handle drifting means so that it does not affect the calculation of VE. The approach is based on a linear regression were the CE as a function of trial number is normalized or detrended. That is, the drift, represented by the inclined regression line through the AlgE, is transformed (‘flattened’) to represent the average (CE) and the residuals of the individual errors around that line are the ‘new’ AlgE which are used to calculate the VE. An important notion is that this procedure does not remove ‘true’ variance of a data set (van Beers et al. 1998), although the drift or trend itself can provide important information about the processes under study that might deserve further evaluation (Smeets et al. 2006). It stands clear however, that the problem of bias drifts, with a few exceptions, has not been properly acknowledged with respect to proprioception testing in the scientific literature.

2.4.1.8 Summary of tests of proprioception

To summarize, the choice of test design involves a trade-off between a number of strengths and weaknesses of the different methods. Active tests may be preferred due to the reliability and validity issues described and ipsilateral tests to avoid the issue of laterality differences and combination errors across limbs. However, repositioning of the same limb will inevitable tax short-time memory (i.e. during the retention time between target presentation and repositioning), which could affect the results and might necessitate some control of the memory component in the test. Thus, the design of repositioning tests for clinical use could for example include variations in the retention time to enable testing of individual and group differences of the potentially confounding effect of short-time memory. Other possible cognitive influences, like lack of concentration due to fatigue or boredom should be recognized in lengthy tests, which might benefit from including pauses in the test series. Furthermore, to be able to address the contribution of position vs. movement sense, targets at different locations could be included since long and short locations appears to be controlled
differently with respect to those parameters. This latter aspect has not been definitely clarified though and needs to be elucidated further. Also, as far as possible the test procedure and instructions to the subjects should be automated, since these factors may influence what cues subjects us to control the movement. Furthermore, from the review above it stands clear that tests of proprioception using position-matching should be addressed by using VE as outcome measure and it is important to include at least six trials to obtain reliable results. Finally, bias drift usually associated with unsighted test affects VE and risks spoiling the usefulness of VE unless the drift is detrended. The designs of the proprioception tests used in the present thesis are based on these conclusions. Hence, in clinical studies, the method of adjustment including ipsilateral movements to targets at different locations and an active test procedure is a reasonable design to assess proprioceptive functioning.

However, since proprioception in everyday life is mostly an unconscious aspect of the sensory system, the described procedures which stress conscious awareness of the movements, can be criticized. In an ecological perspective, tests that address more direct or unconscious aspects of proprioception should be encouraged. In everyday behaviour many motor functions normally operate without conscious attention, and in many cases operates best when the object of perception is something other than one’s own body (Crook 1987).

2.5 Goal-directed reaching

2.5.1 Control of arm movements

In contrast to the sightless single joint movements described above, natural pointing or reaching movements demand interaction with the environment and involve control of multi-joint movements in 3D-space. Numerous everyday activities require individuals to make rapid movements to specific locations in space such as pointing, reaching, grasping and catching. In this sense pointing and reaching to visible targets clearly provide a more ecological approach to study motor control. Such movements may be regarded as subcomponents or building blocks for more complex actions like painting or eating and have as such been extensively studied (Meyer et al. 1988). The apparently simple task of pointing to a target has, in fact, proved to be an exceptionally powerful paradigm to study processes of sensorimotor interaction and control. More than a century ago Woodworth (1899), in a now classical monograph, proposed a model for how simple target aimed movements are controlled, which still is very influential today. For example he addressed the issue of the time required for the nervous system to process and use sensory feedback, and mechanisms responsible for the relation between the speed of the movement and the accuracy of goal-directed movements. Since Woodworth’s days goal-directed pointing has been used to study topics such as feedback and feedforward control (Beaubaton and Hay 1986), impulse variability (Schmidt et al. 1979), the speed of feedback processing (Keele and Posner 1968; Carlton 1980), the relative importance of visual versus proprioceptive feedback (Adams et al. 1977), and speed-accuracy trade-off functions (Fitts 1954; Wright and Meyer 1983). Some of these issues have already been covered in this review and I will here briefly discuss the two last aspects which are of relevance for the studies in this thesis.
2.5.2 Speed-accuracy trade-off

As indicated above, Woodworth was one of the first to describe and study the rather intuitive trade-off in human movement: the faster we move, the less precise are our movements, or vice versa: the more severe the constraints are, the slower we move. This relationship is for many known as Fitts’ Law, named after the scientist Paul Fitts who formulated this well known empirical model for rapid aimed movements (Fitts 1954). The principles of Fitts’ law have with remarkable success been extended into various research domains but have, naturally enough, also been subject to modifications over the years. Later developments of Fitts’ Law, include for example the linear speed-accuracy trade-off, formally the impulse variability model (Schmidt et al. 1979), which predicts that the standard deviation of endpoint errors (i.e., precision) is a linear function of velocity, calculated as distance over time. Of relevance for this thesis, this version of the speed-accuracy trade-off has been shown to be superior to Fitts' logarithmic model for temporally constrained tasks (Meyer et al. 1990). Various ideas on the mechanism behind the speed-accuracy trade-off have been suggested, and are still debated. The original proposal concerned the obvious fact that slower movements provide more time to process sensory feedback and to correct movements. However, motor output is an inherently noisy process and recent research has demonstrated that also noise arising in the output phase of movement contribute to the speed-accuracy trade-off (Schmidt et al. 1979; Meyer et al. 1990; Van Galen 1995; van Beers et al. 2004). Moreover, motor noise has been shown to be velocity dependent (van Beers et al. 2004) which is a consequence of increased noise with increasing levels of muscle activation (Van Galen 1995). The implication of the close relationship between movement speed and precision is that movement speed should be considered when assessing the acuity of goal-directed reaching movements.

2.5.3 Sensorimotor integration

2.5.3.1 Sensory noise, multisensory integration and optimal feedback control

Goal-directed reaching movements entail several different processing steps. First, the spatial positions of the target and hand have to be identified. Second, the motor commands that can bring the hand to the target have to be determined. Third, the motor commands have to be sent to the arm muscles that result in a movement. Neural noise is present in all of these steps and will risk distorting the movement preventing a precise target reach. For instance, in the first step above, all sensory organs that provide information of the state of the system (positions and velocities of limbs and joints) have a limited resolution and the signals they transmit are contaminated with noise (Bays and Wolpert 2007). On a perceptual level sensory noise transforms into uncertainty (van Beers et al. 2002a).

Furthermore, state information is normally provided in more than one sensory modality. A combination of different sources of information results in more precise estimates of the hand than any of the sources alone (van Beers et al. 1999). However, a central question in movement control is how noisy sensory inflow from different sensory modalities is combined into a single percept (i.e. multisensory integration). When reaching for an object vision provides information of the location of the target, hand and arm in an eye- or head-centred coordinate system, while proprioception provides information on the location of the arm and hand in an intrinsic body- or body part-centred coordinate system. It has been demonstrated that integration of the two modalities is conducted according to optimization principles. By
using both sources of information and weighting each source according to its reliability reduces the uncertainty of the estimate of hand position (Wolpert et al. 1995; van Beers et al. 2002b). In this way the brain behaves like an optimal feedback controller that weight feedback signals and modifies their importance selectively to optimize an index of performance – in this example precise location of the hand. Optimal sensory integration has also been demonstrated, in for example, combining visual and haptic information for estimation of size (Ernst and Banks 2002) and inclination of objects (Ernst and Bulthoff 2004).

2.5.3.2 Direction specific sensory efficiency

Although both vision and proprioception provide information about hand location, it is generally held that vision dominates and that proprioception has an inferior role in typical everyday movements (e.g., Welch and Warren 1986; Land et al. 1999). This assumption is based on findings from classical prism adaptation studies where proprioception has been found to adapt more than vision (Welch and Warren 1986). Since the dominant modality should be less prone to adaptation it has been concluded that vision dominate proprioception. However, this traditional view has been questioned (van Beers et al. 2002b). In experiments where subjects were asked to align their left hand either with a visual target or a proprioceptive target (their unseen right hand) it was shown that visual localization was better in azimuth (left-right direction) while proprioceptive localization was better in depth (van Beers et al. 1998). According to the optimal sensory integration model this imply that depth estimates rely more on proprioception and left-right estimates rely more on vision. These findings have been confirmed in studies of pointing to combined visual and proprioceptive targets (van Beers et al. 1999; van Beers et al. 2002b). The mechanism behind this direction specific sensory efficiency can be explained by the physiology of the visual system: While localization in left-right (as well as up-down) direction is determined by the objects representation on the retina, target depth has to be derived from relatively less precise estimates like gaze vergence and disparity (Foley and Held 1972). The advantage of the proprioceptive system in depth may also, partly, be due to a geometric effect. This can be shown by transforming proprioceptive uncertainty of hand position into joint angles (i.e. the kinematic transformation) where the uncertainty in both shoulder and elbow angles will convert into uncertainty of hand position primarily in azimuth direction (van Beers et al. 1998).

To summarize this section, goal-directed reaching and pointing movements to visible targets has been used extensively in studies of sensorimotor control because of their involvement as subcomponents in more complex actions seen in everyday life. Both vision and proprioception are important for precise reaching and have, interestingly, been found to contribute to different extents to movement control in different directions. This observation opens up for a possibility to address the contribution of vision and proprioception by estimating the spatial distribution of movement errors. Surprisingly, goal-directed reaching/pointing has not been studied before in neck pain subjects in spite of the importance of neck control in order to direct vision and despite the close functional relationship between the neck and upper limbs. Clinical studies of movements that are relevant for normal movement behaviour are important and need to include vision since this is a crucial component for interaction with the environment.
The terms reaching and pointing is in this thesis used interchangeably in the sense that they both represent acts that include goal-directed arm movements. The term acuity is used in this thesis for describing the precision in pointing tasks, although acuity most commonly refers to a perceptual level.
3 AIMS

The general aim of this thesis was to evaluate whether arm movement acuity (i.e., sightless, single-joint repositioning acuity and reaching acuity to visual targets) is reduced in people with chronic neck pain compared to healthy individuals and to investigate associations between arm movement acuity and experienced symptoms, functioning and pain. Other main aims were to study the influence of short-term memory on differences in repositioning acuity and to investigate associations between different tests of proprioceptive acuity for the upper extremity involving different movement types (passive vs. active), target locations and target modes.

3.1 Specific aims of the thesis

Paper I
To test the hypothesis that patients with WAD have an impaired shoulder proprioception and to study whether the degree of proprioceptive impairment is reflected by the patients’ symptoms and self-rated function.

Paper II
To evaluate (1) whether people with chronic neck pain of non-specific as well as traumatic (WAD) aetiology have an impaired shoulder proprioception; (2) the potentially confounding effect of short-term memory on group differences in repositioning acuity and (3) whether the degree of proprioceptive impairment is reflected by the patients’ symptoms and self-rated function.

Paper III
To investigate relationships between outcomes of different tests for assessment of proprioceptive acuity in the shoulder joint by analysing: (1) associations between outcomes of velocity-discrimination and position-matching tests, (2) associations between position-matching test outcomes during shorter and longer movements and (3) the effect of different testing conditions (i.e., different modes of target presentation and active vs. passive searching in target presentation) of ipsilateral upper extremity position-matching on proprioceptive acuity.

Paper IV
To evaluate whether the acuity of goal-directed reaching movements is reduced in people with chronic neck pain of both non-specific and traumatic aetiology (WAD) compared to asymptotic subjects and to investigate associations between pointing acuity and symptoms and self-rated health, function and pain in subjects with chronic neck pain. An additional aim was to test whether possible group differences in end-point variability is greater in the near-far direction than in other directions.
4 METHODS

This thesis includes four studies based on data from three study samples. An overview of the papers, samples, design and primary outcome measures is presented in Table 1. In study I-III upper extremity (u.e.) position matching were investigated and in study IV end-position pointing acuity. Study I, II and IV were cross-sectional comparative case-control group studies of people suffering from chronic neck pain and healthy controls and included also correlation and multivariate analyses of the sensorimotor measures and self-rated symptoms and functioning. In study III relationships between different testing conditions of upper limb position matching and velocity discrimination were investigated in a mixed group of subjects.

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Table 1. Overview of the samples, design and primary outcome measures in the studies.
CON: Healthy control group; NS: Nonspecific (non-traumatic) neck pain group; WAD: Whiplash Associated disorders; VAS: Visual analogue scale; SF-36: The Short form-36 Item health survey; PDI: The Pain disability index; NDI: The Neck disability index; DASH: Disability of arm shoulder and hand questionnaire; SES: The Self-efficacy scale; TSK: The TAMPA scale of kinesiophobia

4.1 Subjects

4.1.1 Study I

In study I, 37 consecutive subjects (17 men and 20 women, mean age 39.9 ± 9.7 years), referred to a vocational rehabilitation center (Alfta Rehab Center, Alfta, Sweden) for
rehabilitation due to WAD participated along with a control group consisting of 41 healthy subjects (15 men and 26 women, mean age 39.0 ± 9.6 years). The groups were matched for gender and age.

The inclusion criteria for the WAD group were; i) neck pain of at least six months duration; ii) onset of symptoms related to a whiplash trauma; iii) classified as grade II (neck complaint and musculoskeletal signs) and III (neck complaint and neurological signs) according to the Quebec Task Force criteria (Spitzer et al. 1995); iv) 20-60 years of age; v) right-handed. The time since the trauma (in the majority of cases a rear-end car collision) varied between 6 months and 13 years (median 2.5 years). Pain in the neck-shoulder area was their major complaint. Diagnosed fractures or rhizopathia disqualified the subject for participation.

Control subjects were recruited through advertising in the local community and from the rehabilitation centre staff. They were included if they were right-handed, had no history of head, neck or shoulder trauma, no current shoulder or arm problems or longer periods of constant or intermittent neck-shoulder pain as reported when enrolled. Patients and controls were excluded if they reported recent injuries to their right arm or shoulder (fractures, joint sprains or luxations less than 2 years ago), conditions of neurological or rheumatic (rheumatoid arthritis, pelvospondylitis) disease, diabetes or fibromyalgia.

4.1.2 Study II and IV

In study II and IV, a sample of 45 subjects with chronic neck pain of both traumatic and non-traumatic aetiology was studied. There were 24 subjects with neck pain without traumatic association, referred to as non-specific (NS), and 21 subjects with WAD. The research subjects were a convenience sample obtained from Alfta Rehab Center, from general practitioners and physiotherapists from the immediate surroundings and by advertising in local papers. An age and sex-matched group of control subjects (n=22) was obtained by advertising in local papers.

The inclusion criteria for the chronic neck pain groups were; i) pain in the neck, validated by pain drawings; ii) at least three months duration of neck pain; iii) Neck Disability Index > 10; iv) 20-60 years of age; v) right handed. To be included in the WAD group the subject should relate the onset of symptoms to an accident, and the symptoms should have presented within two weeks after this accident.

To be included the control subjects had to; have no history of head, neck or shoulder trauma; no current neck or shoulder pain or longer periods of constant or intermittent neck-shoulder pain, assessed by the Nordic Council of Ministers questionnaire (Kuorinka et al. 1987); be right handed.

Exclusion criteria for all groups were; surgery of the neck, shoulder or back; reported injuries with fractures or luxations of the neck or shoulders; conditions of neurological or rheumatic disease (rheumatoid arthritis, pelvospondylitis), fibromyalgia or diabetes.

4.1.3 Study III

Fifty-two right-handed subjects (16 males and 36 females) participated in study III. Since a large inter-individual variance in performance provide for better conditions for correlation analysis of the different proprioception tests, subjects were selected to compose a
heterogeneous group with respect primarily to age but also to physical fitness and musculoskeletal pain – factors that have been suggested to influence proprioception (e.g., Skinner et al. 1984; Brumagne et al. 2000). Thus, 24 healthy university students (age 24 ± 3 years, mean ± SD), 13 healthy elderly (60 ± 5 yrs), seven healthy middle-aged subjects (42 ± 4 years), three tai-chi athletes (46 ± 7 yrs) and five subjects with chronic neck-shoulder pain (36 ± 7 yrs) were included in the study.

4.1.4 Ethical considerations

All studies were approved by the Regional Ethical Review Boards in Umeå (study I and III) and Uppsala (study II and IV) and in all studies the participants gave their informed consent before entering the study.

4.2 Assessment of upper extremity repositioning acuity (Study I-III)

4.2.1 Apparatus and data collection

In study I-III the same apparatus was used for all position-matching tests. It is depicted in figure 3 and consisted of a comfortable chair and a motorized computer-controlled arm rig (see also Lönn et al. 2000a). An electromagnetic tracking system (FASTRAK, Polhemus Inc., USA) was used to monitor the position and movement of the arm rig.

![Fig. 3 Illustration of apparatus for shoulder proprioception testing in (a) and start and target positions for shoulder repositioning tests (b). From (Sandlund et al. 2006), re-printed with permission from Journal of Rehabilitation Medicine.](image)

4.2.2 Testing procedures

4.2.2.1 Active-active position-matching (Study I-III)

Subjects were seated in the testing apparatus wearing blindfolds and headphones in order to minimize visual and auditory cues. The headphones were also used to provide pre-recorded verbal instructions. From a starting position of 50° to the sagittal plane, horizontal shoulder adductions to target positions at 20° (short target) and 32° (long target) relative to the starting
position were conducted (Fig. 3b). The task was to match a previously reached target position and was performed as follows: From the starting position, the subject actively moved the arm until a command to “Stop” was given. The rig was then locked and the subject instructed to “Memorize the position” while the rig remained locked for five seconds (paper I and III). When the rig was unlocked the subject actively moved their arm back to the starting position. The subject was thereafter instructed to “try to find the position”. After moving the arm to match the memorized target, the subject pressed a switch in their left hand to indicate target recognition.

All repositioning tests described in this thesis used the same starting position and the same target positions presented in a randomized order. However, the number of trials differed between the studies. Six trials were performed to each target in study I, 8 in study II and 12 in study III. In order to prevent tiring effects in study II and III, the test was performed in two blocks with a one-minute break half-way through the testing session, during which the subjects were relieved of blindfolds and headphones. A short training session was given prior to all test occasions. By presenting a passive movement at a speed of 10 degrees per second during this training session, subjects were advised to perform the movements consistently at the same speed.

In order to allow for analysis of the effect of retention time (RT) on position-matching acuity in paper II, the time between the target presentation and the start of the repositioning movement was varied between 0.2 to 6.2 seconds in steps of 1 second by an algorithm limiting the variation in this delay to exceed three seconds between two consecutive trials.

4.2.2.2 Active-audio position-matching (Study III)

The active-audio test differed from the described active-active condition in the target presentation procedure. When moving in the direction of the target position the subject was instructed to continue until a continuous tone appeared in the headphones. The tone could be heard when the hand was inside an angular sector of ± 1.5 degrees around the target position. When the hand had remained within the sector for 1.5 s the rig was locked and the subject instructed to memorize the target position of the hand.

4.2.2.3 Active-haptic position-matching (Study III)

Here the subject actively moved the arm from the starting position in the direction of the target with the instruction to find a doorbell button by feeling it with the tip of the right index finger. When it was found, the subject pressed the doorbell button, which provided a typical sound heard by the subject in the headphones. The position of the rig was locked and the subject instructed to memorize the location of the doorbell button.

4.2.2.4 Passive-standard, passive-audio and passive-haptic (Study III)

In the passive tests the procedure was similar to the corresponding active test variants, except that the arm in the rig was moved passively by the motor during both target presentation and matching. The subject controlled the motion of the rig by operating the joystick with the fingers of the left hand. When satisfied with the match, the subject pressed a button on the joystick.
4.2.2.5 Velocity-discrimination test (Study III)

In this test the discrimination threshold for angular movement velocities was assessed. Starting aligned with the sagittal plane the arm was passively moved in horizontal abduction by the motor (Fig. 3b). The subjects task was to judge and verbally respond in a forced-choice manner whether a later comparison movement was faster or slower than a previous criterion movement. The criterion movement velocity was always 30 deg/s. To prevent the use of cues based on movement time and extent, half of all comparison movements had a movement extent of 60 degrees (equal to the criterion movement), while for the other half, the movement times in the comparison movements were equal to the movement times of the criterion movement. To achieve an optimal stimulus distribution for determination of the discrimination threshold (Treutwein 1995) a real-time adaptive algorithm (accelerated stochastic approximation) was applied for calculation of the comparison velocities.

4.2.3 Data processing and outcome measures

4.2.3.1 Repositioning acuity (Study I-III)

The Variable Error (VE) was used as the outcome measure of shoulder repositioning acuity. VE represents the variability of errors in several trials and, according to the general psychophysical definition of the sensory discrimination threshold (Gescheider 1997), it is considered to reflect the acuity of sensorimotor processes (Clark et al. 1995). VE is calculated as the standard deviation of the differences between the produced position and the target positions (i.e., the algebraic errors) for a number of trials. The algebraic errors for each subject’s test series were also detrended by computing the residuals from the best straight-line fit linear trend. The detrending procedure was performed in order to eliminate possible systematic drift in errors over time (e.g. a drift from undershooting the target in the first trials to overshooting in the last trials) which is not related to movement acuity but can cause an increase in the VE (van Beers et al. 1996). VE was determined separately for each target.

4.2.3.2 Velocity discrimination (Study III)

A binary logistic regression (Johnson 1998) model was fitted to the subjects' responses (“Faster” and “Slower”) and the difference between the criterion and comparison velocities. From this model the Just Noticeable Difference (JND) in degrees per second was calculated for each subject. JND is the smallest difference in sensory input that is detectable by the subject and thus represents the sensory discrimination threshold in forced choice tests analogous to the VE measure that represents the sensory discrimination threshold in position-matching.

4.3 End-point acuity of goal-directed pointing (Study IV)

4.3.1 Test set-up

The subjects sat in a rigid chair with their torso harnessed to the back of the chair in order to restrict movements of the torso but allowing free movements of the shoulders. The used test set-up was similar to the set-up used by Domkin et al (2005) although slightly modified. An arm support was placed at waist height to the subject’s right. Parallel to the frontal plane on the arm rest, an adjustable rim was placed to mark the start position for the hand. A pointer
attached to a rectangular plastic plate was fixed to the hand in line with the third digit, extending 20 cm from the fingertip. The plate was attached to the palm and fingers in order to keep the fingers extended and prevent movements of the joints distal to the wrist. The target was a soft foam-rubber stick, one cm in diameter, placed at eye level in front (one arm-length minus the hand) of the subject 20 cm to the left of the subject's left acromion, pointing medially to the right (i.e. parallel to the frontal plane). The start and target positions are depicted in figure 4.

4.3.2 Testing procedure

On a command to “go”, the subject was to perform a pointing movement as fast and accurate as possible without corrections, matching the pointer tip with the tip of the target. After holding the arm still for a second at the target, they were instructed to “go to the starting position”. The movement was repeated 15 times with full vision starting each movement from the same predetermined starting position. The starting position at the arm support was achieved through placing the hand with the plastic plate against the rim and the lower arm resting, ulnar side facing down, on the arm support and the wrist in near full dorsal extension. Before the test 3-5 practice trials were performed to familiarize with the task.

4.3.3 Data collection and processing

Kinematic data were recorded with an electromagnetic tracking system (FASTRAK, Polhemus Inc., USA) at a sampling rate of 30 Hz. Pointer coordinates (3D position and orientation) were derived from the movement profile of the sensor attached to the plastic hand plate approximately at the level of the proximal end of the metacarpus. The data were
represented in a common global coordinate system with coordinate axes X, Y and Z oriented to correspond to the horizontal, near-far (depth) and vertical directions respectively as illustrated in figure 4.

Movement initiation and termination were assessed from the velocity profiles of the pointer tip. Movement initiation was defined as the moment when the velocity of the pointer tip exceeded 10% of its maximal value and, similarly, termination was defined as the moment when the velocity dropped below this value. Analysis of pilot data had previously showed that the 10% limit of the maximum velocity optimally separated the dynamic phase of the pointing movement trajectory from its terminal phase. Pilot data also indicated that the pointer tip remained as good as stationary approximately 500 ms after the end of the movement time (Domkin et al. 2005). Therefore, the end-position accuracy was assessed at that instant, denoted “movement termination”. The testing procedure and data collection was controlled by a computer to allow for automated delivery of prerecorded instructions to the subject.

4.3.4 Outcome measures

Similar to the position-matching studies VE was used as outcome measure for end-point variability (i.e., the inverse of acuity or precision). VE was determined separately for each direction (X, Y and Z) as the population standard deviation of the detrended algebraic errors.

In fast aimed reaching the speed-accuracy trade-off (Woodworth 1899; Fitts 1954) can influence the movement precision. Therefore, the peak velocity of the movement was calculated and used as a covariate in the analysis. The velocity of the pointer tip was computed as the first derivative of the coordinate data with application of a low pass 4th order Butterworth filter with a cut-off frequency of 3 Hz.

4.4 Questionnaires and pain assessment (Study I, II and IV)

Before testing commenced, “pain right now” was assessed on a blank 100 mm VAS-scale, anchored at 0 mm that corresponded to “no pain at all” and 100 mm “worst imaginable pain” (Huskisson 1974).

4.4.1 SF-36

The Short Form 36 Item Health Survey (SF-36) (Ware and Sherbourne 1992) was used to assess general health and wellbeing. The SF-36 provides a measure across eight 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 (psychological distress and well-being; MH), vitality (energy and fatigue; VT) and general health perception (GH). In addition, two summary scales are provided; the physical and mental component summary scales (PCS and MCS). Higher scores reflect better health status.

4.4.2 SES

A 20-item Functional Self-Efficacy Scale (SES) (Altmaier et al. 1993) was used to assess the expectations of own capability to accomplish tasks and activities of daily living. Higher scores indicate a higher self-efficacy.
4.4.3 **PDI (Study I)**

The Pain Disability Index (PDI) (Tait et al. 1987) was used in study I to assess the degree to which chronic pain interferes with daily functioning. It addresses disabilities in the areas of responsibility of family and home, leisure, job and social activities, sexuality, personal independence and daily living. A higher score indicates greater disability.

4.4.4 **NDI (Study II and IV)**

The Neck Disability Index (NDI) (Vernon and Mior 1991) estimates the level of disability due to neck pain. It addresses functional activities and consists of 10 items including: personal care, work, lifting, reading, driving, sleeping, recreational activities, pain intensity, concentration, and headache. A higher score indicates greater pain and disability.

4.4.5 **TSK (Study II and IV)**

The Tampa Scale of Kinesophobia (TSK) (Crombez et al. 1999) estimates fear of re-injury due to movement. It consists of a 17-item questionnaire where each item is rated on a 4-grade Likert scale with scoring alternatives ranging from “strongly agree” to “strongly disagree”. Higher scores indicate more kinesophobia.

4.4.6 **DASH (Study II and IV)**

The disability of the arm, shoulder and hand (DASH) (Hudak et al. 1996) was used to measure disability and symptoms of the upper extremity. The core section of DASH is a 30-item disability and symptom scale. Each item has 5 response alternatives from “no difficulty” or “no symptoms” to “unable to perform the activity” or “very severe symptom”. A higher score indicates more disability.

4.4.7 **Additional questions (Study II and IV)**

Aspects presumed to be important for performance in the repositioning and pointing tests but not covered by the questionnaires, were addressed in additional questions. These concerned the extent to which the subjects had symptoms of; clumsiness of the hands, sensory disturbances, dizziness, and poor balance. They were also asked whether they experienced difficulties performing specific body functions or activities including: bending, tilting and rotating the head; throwing, carrying, lifting, or putting on a shirt. A 6-level scale was used for each question with the alternatives; 1) Not at all/nothing; 2) Weak/mildly; 3) Moderate; 4) Quite high/Somewhat strong; 5) High/strong; 6) Almost unbearable/maximal.

4.5 **Statistical analysis**

4.5.1 **Group differences**

4.5.1.1 **Position matching acuity (paper I and II)**

In all analyses the VE for the two different target positions were included as separate variables since position-matching acuity for different movement extents may depend on partly different mechanisms (Semler and Simmons 1979), (Passive vs. active tests). Pearson’s
correlation analyses were used to assess associations between the VEs of the two target positions, over all subjects and separately for each group.

In study I VE differences between groups were evaluated by multivariate analysis of variance (MANOVA) and analysis of variance (ANOVA) for short and long target positions respectively. Wilk’s Lambda was used for evaluation of statistic significance of the MANOVA model.

In study II differences in VE between the groups and target positions were evaluated by a two-way mixed-model repeated measure analysis of variance (ANOVA). The variable position (short and long) was used as a within-subject factor and group (NS, WAD and CON) as a between-subject factor. Post-hoc analyses were performed for pair-wise comparisons of pre-planned contrasts (Dunnett’s two-tailed t-test) of the group-pairs WAD-CON and NS-CON respectively. Differences in VE between the two neck-pain groups were not expected and were, accordingly, not analyzed.

To analyze the effect of retention time (RT) – the time between the target presentation and the repositioning movement – on VE, we calculated separately for each subject the slope (RT-slope) of a linear regression trend line of the absolute values of the detrended algebraic errors as a function of RT. The overall effect of RT on VE and differences between the groups were thereafter analyzed by one- and two-sample t-tests of RT-slope.

4.5.1.2 End-point acuity (paper IV)

Differences in VE between groups were evaluated by mixed model analysis of variance (ANOVA) and Peak velocity with univariate ANOVA. However, in fast reaching movements in full-vision conditions differences in end-point accuracy between groups may, according to the speed-accuracy trade-off described by Fitt’s law, be obscured by between-subject variance in movement speed. Therefore Peak velocity was used as covariate in a mixed-model analysis of covariance (ANCOVA) with coordinate axis (X-, Y- and Z) as within-subject factor and group (NS, WAD and CON) as between-subject factor. Univariate ANCOVAs were, thereafter, performed for specific comparison of pre-planned contrasts (Dunnet’s t-test) between the neck-pain subjects and controls for the different coordinate axes.

4.5.2 Associations between variables

For analysis of associations between variables univariate correlation analyses were used but also multivariate analysis in the form of multiple linear regression and multivariate projection methods (e.g. Partial Least Squares regression; PLS). The latter methods will be described in more detail below since these methods may not be standard analytical procedures.

In study I, Pearson and Spearman rank correlations were used to study associations between VE and the scores of the questionnaires. The VE-correlating questionnaires were then included in a linear multiple regression model to analyze how much of the repositioning VE that could be explained by the questionnaire scores (i.e., the questionnaire scores were used as predictors of VE). Moreover, in order to get an estimate of the inverse relation; how well the questionnaire scores could be explained by the repositioning test (i.e., VE as predictor of the questionnaire scores), principal component regression (PCR) was used. A PCR is the result of using the scores from a principal component analysis (PCA see below) as the basis for multiple linear regressions (Jolliffe 2002).
In studies II and IV, associations between self-ratings (i.e., questions from questionnaires and additional questions including VAS) and end-point VE were evaluated by Partial least squares projection to latent structures (PLS and O-PLS see below).

In study III, PCA was used to study relationships among the outcome variables in the different position-matching procedures (i.e. VE) and velocity discrimination test (i.e. JND).

4.5.2.1 Multivariate data analysis

In science and technology there is a steady trend towards collecting larger and larger volumes of data to be analyzed. Tools with the necessary power to extract information from massive sets of data, such as PCA, PLS or O-PLS (i.e., multivariate projection methods), have been used extensively in various biological disciplines (e.g., chemometrics, proteomics, genomics) concerned with the analysis and interpretation of complex data structures (Eriksson et al. 1999; Wold et al. 2001). Among the benefits of these methods are that they produce robust and interpretable models, they can analyze many non-independent (i.e., collinear) variables and handle incomplete and noisy data structures. Projection methods are often associated to the “omics-sciences” referring to the holistic study of an entire system, as opposed to a reductionist description of each of its parts independently. This description certainly applies also to clinical data in for example rehabilitation research and physical medicine. As already described, the pathogenesis of musculoskeletal disorders is often multifactorial and as such influenced by many, correlated variables, which may be very difficult to overview and interpret. In physical medicine and rehabilitation science projection methods other than PCA are, however, not yet custom, (but see e.g., Elert et al. 2000; Lundberg and Gerdle 2002) although the variables, entities and processes of interest also in this field are, indeed, multivariate.

4.5.2.1.1 Principal component analysis (PCA) (Study I and III)

Principal Component Analysis is a multivariate projection method usually used to compress information in a data block or matrix (X) into a few ‘principal components’ (PCs). The purpose of this manoeuvre is to explain as much of the variation in the data set as possible using the new set of latent variables (i.e. PCs). The compression reduces the dimensionality of the data and facilitates an overview of the variation so that groups, relationships and outliers can be identified. A PCA projects the data to a new coordinate system so that the greatest variance comes to lie in the first PC, the second greatest variance in the second PC, and so on. The compression is possible because the variables are correlated with each other. If they were uncorrelated (independent) PCA compression would not be possible. Often correlations between variables (e.g. self-ratings in different questionnaires) occur because they change according to some systematic underlying common factor or latent variable. PCA has the ability to detect these underlying factors.

The length of a PC is referred to as the eigenvalue of the component, which is proportional to the amount of variation described by the PC. The explained variation given by a PCA model is expressed by the parameter $R^2X$ representing the amount of explained variation that can be calculated for the entire model as well as for the individual PCs. The results of a PCA are also discussed in terms of component scores (a subject’s influence on the PC) and loadings (a variable’s influence on the PC). By plotting the score values for different PCs against each other, score plots of the inter-sample relationships can be attained. The
corresponding loading plots show the variables responsible for the patterns found in the score plots.

4.5.2.1.2 Partial least squares regression (PLS)

Partial Least Squares or Projection to Latent Structures (Eriksson et al. 1999; Wold et al. 2001) is a multivariate regression method that is often described as a regression extension of PCA. While PCA detects latent structures of variables in one block (X), PLS methods are designed to reveal latent relationships between two blocks of variables (X and Y). Hence, the objective is different when calculating latent variables in PLS since it extracts the variation in X needed to predict the variation in the response Y. The advantage of using PLS instead of traditional multivariate methods (i.e., multiple linear regression) lies in the ability to analyze many non-independent (i.e., collinear) variables. Also, PLS can handle noisy data structures, fewer observations than predictor variables and missing data and allows exploration of underlying relations and trends even when the functional form governing the relationship between predictors and response is not fully known.

4.5.2.1.3 Orthogonal-PLS (O-PLS)

Orthogonal-PLS (Trygg and Wold 2002) is a modification of PLS which disentangle the variance in the X block in two parts; one that is correlated to Y and one that is uncorrelated (orthogonal) to Y. Separation of the two sources of variation can facilitate interpretation of the models significantly, especially when only one Y variable is used since O-PLS in such cases gathers all the (Y-) correlated variance in the first component. O-PLS is also useful when there is a large amount of (Y-) unrelated variation in the data set making the interpretation of the model more straightforward and accurate than ordinary PLS analysis (Trygg and Wold 2002).

The results of a PLS as well as O-PLS model are described with the statistical parameters explained variation ($R^2$) and predicted variation ($Q^2$). Explained variation in PLS pertain to both response ($R^2_Y$) and predictors ($R^2_X$) while $Q^2$ is a cross-validation estimate calculated to test the validity of the model against over-fitting. The relative contribution of each x-variable to the PLS model can be expressed as a VIP-value (Variable Importance in the Projection). A VIP larger than 1.0 is considered as influential (significant) while values lower than 0.5 indicates unimportant variables (Eriksson et al. 1999).
5 RESULTS

5.1 Shoulder repositioning acuity (study I and II)

The MANOVA in study I revealed a significant group difference for shoulder repositioning acuity with higher VE for the WAD (2.03°) compared to the CON (1.51°) group (p = 0.003). In the subsequent univariate ANOVAs significant group differences for both VE-short (p = 0.003) and VE-long (p = 0.011) were found. Gender was not a significant factor, although approaching significance (p = 0.078) in the VE-long ANOVA. Descriptive statistics are illustrated in figure 5. Interestingly, the VEs of long and short target position were found not to correlate with each other (r = 0.28 in WAD).

![Fig. 5](image.png)

Similar to the results in study I, a significant main effect of group on VE was found in study II (p = 0.023). The mixed model ANOVA used here also showed non-significant results for the within-subject factor position as well as for the interaction effect group x position. The subsequent Post-hoc analysis for the variable group revealed that the NS group had significantly greater VE than the CON group (p=0.014), while no difference in VE was detected between the WAD and the CON groups (p=0.602). Descriptive statistics are illustrated in figure 6.

![Fig. 6](image.png)
Moreover, in accordance with the findings in study I, VE for the long and short target positions were not associated. The correlation analyses showed that no association was present over all subjects (r=0.10, p=0.40). However, an interesting observation was that for the CON group, a significant association was present (r=0.58, p<0.01) whereas associations were absent for the NS and WAD groups (r=0.04, p<0.86 and r=-0.34, p<0.13 respectively). These results support the idea that VE of the two target positions may depend on partly separate mechanisms and that the two target positions should be handled separately when analyzed.

5.2 Effect of retention time on repositioning acuity (Study II)

In study II the retention time (RT) between target presentation and target matching (median 13.8 s; range 6.7 to 36.7 s) were, for all trials, not different between the group pairs (Student’s t-test, NS-CON, p = 0.314; WAD-CON, p = 0.181). The effect that RT impose on VE, reflected in the RT-slope average, was not significantly different from zero (slope=-0.019 degrees/s, p=0.13), indicating that RT had no overall effect on VE. Notably, no significant difference was found between the RT-slopes of the CON and NS groups (p=0.61), even though these groups differed significantly with respect to VE.

5.3 Associations between position sense acuity and questionnaire scores and pain ratings (Study I)

As is shown in Table II, scores from all questionnaires used correlated significantly to VE for the short target position (VE-short). However, no significant correlations were found for the long target (VE-long).

<table>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.28</td>
<td>-0.51*</td>
<td>0.38*</td>
<td>-0.46*</td>
<td>-0.01</td>
<td>-0.00</td>
<td>-0.46*</td>
<td>-0.32</td>
<td>-0.18</td>
<td>-0.48*</td>
<td>-0.12</td>
<td>0.07</td>
</tr>
<tr>
<td>VE-long</td>
<td>-0.26</td>
<td>-0.05</td>
<td>-0.05</td>
<td>0.17</td>
<td>0.08</td>
<td>-0.26</td>
<td>-0.01</td>
<td>-0.06</td>
<td>-0.09</td>
<td>-0.15</td>
<td>-0.33</td>
</tr>
</tbody>
</table>

*p < 0.05

Table II. Correlation coefficients (r-values) for variable error (VE), questionnaire scores (Functional Self-Efficacy Scale, Pain Disability Index (PDI) and the 8 SF-36 indices; 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)) and VAS pain-ratings for the WAD group. Role limitations (SF-36 RP and RE) and VAS were calculated with Spearman’s rank correlation due to non-normal distributions. From (Sandlund et al. 2006). Re-printed with permission from Journal of Rehabilitation Medicine.

VE-short correlated with the SF-36 subscales representing limitations in physical functioning (PF), limitations in social functioning (SF) and vitality (VT). The subscale representing bodily pain approached significance (p = 0.087). Consistently, low level of functioning corresponded to a high VE for the short target position. Moreover, no correlation between the VAS pain-ratings and VE were found for any of the target positions.
5.3.1 Variance of position sense acuity explained by questionnaire scores

Since VE-long did not show any association with the self-rated questionnaire scores only VE-short was included in multiple regression analyses for investigation of how much of the variance of VE-short that could be explained by the three questionnaires together. All questionnaire indices with significant correlation coefficients (see Table II) were included as predictors in the model and were shown to explain 51% of the variance of VE-short of the position sense test (Table III).

<table>
<thead>
<tr>
<th>Model p-value</th>
<th>r²</th>
<th>r²(adj)</th>
<th>Variable</th>
<th>β</th>
<th>t</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.003</td>
<td>0.51</td>
<td>0.41</td>
<td>Self-efficacy scale</td>
<td>-0.232</td>
<td>-2.15</td>
<td>0.042</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Pain Disability Index</td>
<td>0.025</td>
<td>0.23</td>
<td>0.819</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>SF-36 (PF)</td>
<td>-0.004</td>
<td>-0.37</td>
<td>0.716</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>SF-36 (SF)</td>
<td>-0.008</td>
<td>-1.46</td>
<td>0.159</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>SF-36 (VT)</td>
<td>-0.017</td>
<td>-2.09</td>
<td>0.048</td>
</tr>
</tbody>
</table>

Table III. Multiple regression analysis predicting Variable Error-short from Self efficacy, Pain disability and VE-correlating SF-36 indices, where \( \beta \) is the regression coefficient and \( t \) the test statistic. From (Sandlund et al. 2006). Re-printed with permission from Journal of Rehabilitation Medicine.

5.3.2 Variance of questionnaire scores explained by position sense acuity

To investigate the inverse relationship we analyzed how much of the total variance of the questionnaire scores that could be explained by VE-short. This was done using Principal Component Regression (PCR) that, as a first step, involved a Principal Component Analysis (PCA) of the questionnaires correlating with VE-short (in order to reduce the dimensionality of the data), and as a second step, linear regression using the PCA-scores as predictors and VE-short as response. Parallel Analysis indicated only one significant principal component (PC 1), which accounted for 44% of the total variance. This indicated that PC 1 could alone model the major part of the non-random variance of the five different questionnaire scores entered in the PCA, This was also reflected by the fact that all indices had significant loadings for PC 1. The loadings of each variable were: SF-36 (PF) \( r = -0.506 \), PDI \( r = 0.493 \), SF-36 (SF) \( r = -0.449 \), Self-Efficacy Scale \( r = -0.408 \), SF-36 (VT) \( r = -0.363 \). The subsequent regression analysis with VE-short as predictor and the WAD-patients’ scores for PC 1 as dependent variable showed that VE-short explained 43% of the variance of PC 1.

5.3.3 Associations between repositioning acuity and questionnaires (Study II)

For both the WAD and NS groups in study II two O-PLS models were fitted, one for each target position using scores of the questionnaires and separate questions as predictors (X-variables) and VE as response (Y-variable). For the NS group, the VE-short model as well as the VE-long model was significant.

For NS the predictor variables explained 95.5% of the variation in VE-short (\( R^2_Y= 0.955 \), \( R^2_X = 0.052 \), \( Q^2 = 0.687 \)). Twelve predictors had VIP-values greater than one but only four of them were significant (lower limit of VIP CI>0.5). For VE-long 45.3% of the variation was explained by the predictors (\( R^2_Y=0.453 \), \( R^2_X = 0.203 \), \( Q^2 = 0.143 \)). Fourteen predictors had VIP-values greater than one, but only two of these were significant (lower limit of VIP CI>0.5). The significant predictors and corresponding VIP-values are shown in Table IV for
each model separately. Displayed are also the lower limit of VIP CI, univariate Pearson
correlation coefficients between the variables and VE for the purpose of simple comparisons.

<table>
<thead>
<tr>
<th>Predictor</th>
<th>VIP</th>
<th>CI</th>
<th>r</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>VE-short</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tenderness in the neck</td>
<td>1.87</td>
<td>0.85</td>
<td>-0.41*</td>
</tr>
<tr>
<td>Difficulties bending the head forward</td>
<td>1.87</td>
<td>0.67</td>
<td>0.42*</td>
</tr>
<tr>
<td>Switch a light bulb</td>
<td>1.84</td>
<td>1.20</td>
<td>0.42*</td>
</tr>
<tr>
<td>TSK</td>
<td>1.57</td>
<td>0.75</td>
<td>0.36</td>
</tr>
<tr>
<td><strong>VE-long</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SF-36 Social functioning</td>
<td>1.96</td>
<td>0.55</td>
<td>0.45*</td>
</tr>
<tr>
<td>Clumsiness of the hands</td>
<td>1.64</td>
<td>1.04</td>
<td>0.46*</td>
</tr>
</tbody>
</table>

**Table IV.** O-PLS models for the VE-short and long for the NS group using scores of the
questionnaires and separate questions as predictors. The Variable Influence on Projection (VIP), the
lower limit of the confidence interval (CI) for the VIP and Pearson’s correlation coefficients (r, * p<0.05) are shown for predictors with VIP>1 and a lower limit of VIP CI>0.5. TSK: TAMPA scale of
kinesiophobia; VIP: Variable importance in the projection.

A corresponding analysis for the WAD group provided non-significant models for both VE-
short and VE-long, which indicate a lack of associations between the predictor variables and
repositioning acuity.

**5.4 Correlation analysis of proprioceptive acuity in position-matching and
velocity-discrimination (Study III)**

Cattell’s scree test suggested two significant PCs accounting for 33.1% and 12.1% of the
total variance respectively. The loadings of these two components, representing the
relationship (i.e., correlation coefficient) between the PCs and the original variables, are
plotted to enable evaluation of the pattern of correlation between the variables in figure 7.

Close clustering of variables in a loading plot indicates that these variables are correlated
(if located with sufficient distance from the origin). If the angle between two groups of
variables and the origin is close to 90 degrees, such variables are, in general, uncorrelated.
Thus, evaluation of figure 7 suggests a tendency for separation of the variables into two
groups: One group containing mainly tests of short movement extent position-matching and
the velocity-discrimination variable, and a second group containing long movement extent
position-matching variables. The grouping of the short and long target position-matching
variables were tested, post-hoc, with a multivariate ANOVA with the position-matching
variable loadings for PC 1 and 2 as dependent variables and short or long movement extent as
a fixed factor. This revealed a significant effect of movement extent (F[1,10]=19.5; p=0.001)
lending support to the grouping apparent grouping in the variable loadings plot (Fig. 7).
5.5 End-point acuity of goal-directed pointing (Study IV)

Without controlling for effects of movement speed no significant effect of Group on VE was found in the mixed model ANOVA (p=0.170) for any of the neck pain groups (Dunnett’s t two-sided post-hoc; NS-CON, p=0.170; WAD-CON, p=0.358). Likewise was the effect of group on Peak velocity non-significant when analyzed by univariate ANOVA (p = 0.103: Dunnett’s t two-sided post-hoc; NS-CON p=0.456; WAD-CON p=0.062).

However, as argued, it may be important to account for the speed-accuracy trade-off. Hence we included movement peak velocity as a covariate in a mixed-model ANCOVA of VE with Group as a between-subject factor and Coordinate axis as within-subject factor. The analysis revealed significant main effects of Group (p = 0.017), Coordinate axis (p = 0.038) and for the covariate Peak velocity (p < 0.001). No interaction effect of Coordinate axis x Group was found (p = 0.286). These results indicate that there are differences in VE between the three coordinate axes but that the differences are similar for all the three groups. The results confirmed that peak velocity was a strong modifier of VE. Pair-wise comparisons between groups showed differences between CON – NS (Dunnett’s t two-sided post-hoc; p = 0.020) and CON – WAD (p = 0.034). Post-hoc comparisons of VE differences between the three coordinate axes (across all groups) showed that VE in the Z-direction was significantly lower than that of both X- and Y-direction (Tukey’s p = 0.002 and p < 0.001 respectively) while the VE in X-direction compared to Y-direction did not differ (p = 127).
We also tested for possible group differences in VE along the three coordinate axes with univariate ANCOVAs. For NS compared to CON, significant differences were found in both depth (Y-axis) and vertical (Z-axis) direction (Dunnett’s t two-sided post-hoc; p = 0.030 and p = 0.032 respectively) but not in the horizontal direction (X-axis) although showing a trend to significance (p = 0.086). WAD compared to CON differed only with respect to the depth direction (VE-Y; p = 0.010) but not along the horizontal and vertical axes (VE-X; p = 0.200 and VE-Z; p = 0.164). Descriptive data for end-point VE in the depth direction, controlled for movement peak velocity, is shown in figure 8.

![Fig. 8](image)

**Fig. 8.** Box plots (interquartile range) for the end-point variable error (cm) controlled for peak velocity 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 (In press). Re-printed with permission from Foundation for Rehabilitation Information.

### 5.5.1 Associations between end-point variability and questionnaire scores

We used O-PLS regression to study associations between self-rated characteristics and end-point acuity controlled for movement speed (VEr) in the neck pain groups. Separate analyses were performed for the two neck-pain groups using the self-ratings as predictors and the VEr in depth direction as response. VEr in all three directions were correlated but since the variability in depth was largest and discriminated both neck-pain groups from the controls we chose VEr in depth direction as response variable. Table V and VI show the significant predictor variables from the two PLS-models. For the NS group a PLS model was fitted that explained 67.3 % of the variation in VEr (R2Y= 0.673, R2X = 0.125, Q2 = 0.377). Table V shows that strong predictors for high end-point variability were self-rated problems to perform neck movements and problems to put on and take off a shirt. The PLS-model of WAD explained 41.9 % of the variation in VEr and is shown in Table VI. (R2Y= 0.419, R2X = 0.355, Q2 = 0.262). Like the NS-group, end-point variability was related to self-rated neck
movement problems but also to several indices representing pain as well as limitations in activities involving lifting/carrying, poor balance, and social functioning.

<table>
<thead>
<tr>
<th>Predictor</th>
<th>VIP</th>
<th>CI</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neck rotation left</td>
<td>2.18</td>
<td>1.54</td>
<td>0.59*</td>
</tr>
<tr>
<td>Neck rotation right</td>
<td>2.16</td>
<td>1.52</td>
<td>0.58*</td>
</tr>
<tr>
<td>Neck lateral flexion left</td>
<td>1.90</td>
<td>1.51</td>
<td>0.51*</td>
</tr>
<tr>
<td>Neck lateral flexion right</td>
<td>1.90</td>
<td>1.53</td>
<td>0.51*</td>
</tr>
<tr>
<td>Neck flexion</td>
<td>1.80</td>
<td>0.75</td>
<td>0.49*</td>
</tr>
<tr>
<td>Put a shirt of and on</td>
<td>1.65</td>
<td>0.94</td>
<td>0.44*</td>
</tr>
<tr>
<td>Neck extension</td>
<td>1.60</td>
<td>1.01</td>
<td>0.44*</td>
</tr>
</tbody>
</table>

* p<0.05

Table V. O-PLS model for the NS group using self-assessed characteristics as predictors of VEr. The Variable Influence on Projection (VIP), the lower limit of the confidence interval (CI) for the VIP and Pearson’s correlation coefficients (r) are shown for predictors with VIP>1 and a lower limit of VIP CI>0.5. From Sandlund (in press), re-printed with permission from Foundation for Rehabilitation Information.

<table>
<thead>
<tr>
<th>Predictor</th>
<th>VIP</th>
<th>CI</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bodily Pain (SF-36)</td>
<td>1.74</td>
<td>1.40</td>
<td>-0.67*</td>
</tr>
<tr>
<td>Balance</td>
<td>1.61</td>
<td>0.62</td>
<td>0.62*</td>
</tr>
<tr>
<td>Social Functioning (SF-36)</td>
<td>1.52</td>
<td>1.01</td>
<td>-0.54*</td>
</tr>
<tr>
<td>VAS</td>
<td>1.32</td>
<td>0.65</td>
<td>0.49*</td>
</tr>
<tr>
<td>Neck extension</td>
<td>1.28</td>
<td>0.71</td>
<td>0.50*</td>
</tr>
<tr>
<td>Carry a shopping bag (DASH)</td>
<td>1.22</td>
<td>0.83</td>
<td>0.47*</td>
</tr>
<tr>
<td>Lifting</td>
<td>1.16</td>
<td>0.50</td>
<td>0.45*</td>
</tr>
<tr>
<td>Carrying</td>
<td>1.16</td>
<td>0.54</td>
<td>0.45*</td>
</tr>
<tr>
<td>Neck lateral flexion left</td>
<td>1.07</td>
<td>0.50</td>
<td>0.41</td>
</tr>
</tbody>
</table>

* p<0.05

Table VI. O-PLS model for the NS group using self-assessed characteristics as predictors of VEr. The Variable Influence on Projection (VIP), the lower limit of the confidence interval (CI) for the VIP and Pearson’s correlation coefficients (r) are shown for predictors with VIP>1 and a lower limit of VIP CI>0.5. From Sandlund (in press), re-printed with permission from Foundation for Rehabilitation Information.

5.6 Additional analysis

An additional correlation analysis was conducted to study the possible association between shoulder position-matching acuity and goal-directed pointing acuity. Since the same subjects participated in study II and IV this analysis could be performed although not included in any of the two manuscripts. No association was detected between unsighted shoulder position-matching acuity (Variable Errors pooled over short and long targets) and full vision goal-directed 3D reaching acuity (VEr-y). Non-significant correlations was a fact for all three groups analysed together (r = 0.073, p = 0.557) as well as separately (CON r = -0.03, p = 0.896; NS r = 0.003, p = 0.99; WAD r = -0.037, p = 0.874). This finding indicates different control strategies in the performance of the two tests.
6 DISCUSSION

6.1 Main findings

The results of this thesis show that unsighted position-matching as well as acuity of goal-directed 3D movements of the upper limb under full vision can be reduced in people with chronic neck pain of both traumatic and non-traumatic onset compared to healthy people. The degree of reduced acuity was shown to be associated with symptoms, self-rated functioning, activity limitations, and general health but to different extents and with different correlation patterns for the different tests and neck pain groups. Noteworthy is the strong associations found between self-rated problems to perform neck movements and reduced end-point reaching acuity, which imply a close interaction between impairments in neck function and upper limb movement control.

It was also shown that neither repositioning acuity in general nor the differences in repositioning acuity between neck pain subjects and controls were related to short-time memory storage time of the target position. Furthermore, position-matching of long and short target positions appears to depend on partly different control mechanisms, as implied in a lack of correlation between long and short target variable errors and different correlation patterns to symptoms and self-rated characteristics. Subsequent findings in the methodological study (study III) indicate that the control of short targets was primarily based on movement velocity information whereas long targets may rely more on position-based mechanisms. In an additional post-hoc analysis of data from study II and IV, it was revealed that the variable errors of full vision goal-directed 3D reaching acuity and unsighted single joint position-matching acuity were independent in all studied samples. This finding indicates that the impairments in acuity seen for the neck pain subjects in these tasks do not depend on the same mechanism. It also highlights the complexity of sensorimotor impairments in chronic neck pain disorders.

The findings of reduced position-matching of the upper limb as well as the findings of reduced pointing acuity in nonspecific neck pain are, to my knowledge, the first reports of their kind and the results obviously need to be confirmed in future studies. A point that however strengthens the results is the approach to analyze associations between upper-limb movement acuity measures and self-rated characteristics. Moreover, this association analysis approach also provides the opportunity to encircle the likely mechanisms underlying impaired arm movement acuity. It is logical to assume that clinical characteristics that emerge as significantly correlated to impaired movement acuity are, in some way, involved in the development or preservation of the pain condition. Along these lines the results of the multivariate association analyses from all of the included studies are used in the discussion section to close in on and discuss possible underlying causes to impaired arm movement acuity. I will however start out this section by discussing the results of the comparative part of the clinical studies.
6.2 Position-matching acuity (studies I, II and III)

6.2.1 Group differences (study I and II)

Reduced position-matching ability of the upper limb was found in people with chronic neck pain of both traumatic (WAD in study I) and non-traumatic background (NS in study II). The findings generally support the hypothesis of reduced shoulder proprioception in these disorders. The results were, however, not entirely conclusive since reduced position-matching acuity found in WAD in study I was not confirmed in the WAD group of study II. The reduced position-matching acuity of the WAD group in study I and the NS group in study II was significant compared to controls although the effects in neither study were large enough to discriminate cases totally from the healthy subjects. Such clear group differences were on the other hand not expected, since non-specific neck pain is a heterogeneous group and large inter-subject variation in proprioceptive function is likely (Sjölander et al. 2008). Functionally, however, also relatively small reductions in proprioceptive acuity of the shoulder may be important due to the geometric fact that small errors in proximal joints have larger effects on the end-point effector (i.e. the hand).

The hypothesis of impaired shoulder proprioception in subjects with neck pain was based on findings from experimental studies showing altered sensitivity of muscle spindles in response to noxious stimuli (Pedersen et al. 1998; Wenngren et al. 1998a; Ro and Capra 2001; Thunberg et al. 2002), an effect shown to include spindles also in adjacent muscles (Thunberg et al. 2001). Such a “spreading effect” has the potential to affect proprioception also outside of the painful region. Moreover, a number of clinical studies have reported associations between chronic neck pain and deficits in neck proprioception (e.g., Revel et al. 1991; Kristjansson et al. 2003; Sjölander et al. 2008). The adjacent anatomical location and close functional interaction of the neck and shoulder region suggest that malfunction in either area would affect the other. For instance, the trapezius and levator scapulae muscles can exert torque directly on both the neck and upper limbs. Changes in the perception of head position or posture could affect the judgement of arm position and introducing error in proprioceptive tasks of the upper limb. For example, repositioning acuity of the elbow joint was shown to be reduced when proprioception was distorted by vibration of neck muscles (Knox et al. 2006a). Results from the same laboratory also demonstrated impaired elbow position-matching, indicating a reduced proprioceptive function in people with WAD (Knox et al. 2006b). These results are in accordance with the findings in the present thesis.

However, the above cited studies used the absolute error as outcome measure and no specified target position, which obscures the comparison to the results in the present thesis. It is well established that the response variability, usually measured in terms of variable error (VE), in position-matching tests reflects the differential sensory threshold, that is, the threshold for perceiving differences between stimuli (Gescheider 1997). An advantage of our studies was the use of VE as outcome variable since that offers a possibility to draw conclusions, or at least speculate, on the underlying mechanisms of reduced repositioning acuity. Moreover, the entire testing procedure in the studies of the present thesis was automated, including pre-recorded verbal instructions, which means that the shoulder repositioning data was collected in an objective and standardized way.
6.2.2 *Different results for WAD (study I and II)*

The difference in results for the two WAD groups in study I and II is difficult to explain. Since the repositioning test was virtually identical in these studies, the discrepancy may likely be related to differences in the study samples. The subjects in study I were recruited exclusively from patients referred to Alfita Rehab Center for rehabilitation, while the sample in study II was a mixed group also recruited through advertisement (i.e., a convenience sample). The heterogeneity in sensorimotor dysfunction found in chronic neck pain subjects (Sjölander et al. 2008) in combination with the relatively small sample sizes may also have provided for differences between the two study samples. Comparing the WAD groups with respect to the SF-36 (the only instrument in common for both studies) revealed no significant differences and comparison between WAD and NS in study II showed that WAD had greater disability (as measured by the NDI, DASH and SF-36), more pronounced kinesiophobia (TSK) and slightly higher pain ratings than the NS group. Since there was a significant difference in VE between the NS and the CON groups, the indifferent VE between WAD and CON cannot be explained simply by lower level of severity of the pain condition in the WAD group. Another difference between the two studies was that the person conducting the test in study II was blinded to the subject status (i.e., whether the subject had neck pain or not) whilst this was not the case in study I. However, the highly automated test set-up essentially makes the test procedure immune to any outside involvement making this explanation unlikely. Moreover, to address the possible effect of pain related impairment of short-time memory that theoretically could affect the results in ipsilateral position-matching, a time delay between target presentation and retention movements was introduced in study II. Even though the tests were identical in other aspects this modification may have introduced additional noise into the test making it less discriminative. As mentioned earlier, small alteration of the test design can have significant and unexpected effects on the strategies subjects use to perform the task, the cues attended to and what variables they choose to control (Gunzelmann and Anderson 2006). This aspect deserves more attention in future studies.

6.2.3 *Control of long and short movements (study I, II and III)*

A fascinating finding was the lack of correlation between shoulder repositioning acuity for the short and long target positions in both neck-pain groups in study II as well as for the neck pain group in study I. The fact that the two PLS-models for VE-short and long presented different predictors also corroborate this finding. It can thus be presumed that repositioning of the two target positions depended on, at least partly, different mechanisms. This idea was investigated in Study II where the outcomes of several different position-matching tests were compared to the outcome of a velocity discrimination test. This study revealed that the acuity (VE) of repositioning movements to short target locations was associated with the velocity discrimination threshold (JND), while this was not the case for repositioning movements to the long target. This finding imply that position-matching for the short target relies primarily on movement related sensory information.

It has been demonstrated that certain aspects of movement control covary with end-point variability. For example, Sainburg and Schaefer (2004) demonstrated that movement distance was mainly determined by either the movement’s peak acceleration (pulse-height), proposed to be associated with movement planning, or by the duration of the acceleration impulse (pulse-width), reflecting more of sensory-based corrective processes (see also Schmidt et al.
Pulse-height and pulse-width could be important parameters to consider in future studies since control mechanisms of long and short movements also have been suggested to differ with respect to movement distance so that longer movements rely more on afferent sensory information and shorter movements more on efferent mechanisms (i.e., prediction based on the movement command) (Wolpert et al. 1995). The findings in study III, that control of short but not long movements relies on movement-related sensory information, is in accordance with earlier findings by Walsh (Walsh et al. 1979; Walsh 1981) who found that movement or movement distance cues were the most influential for the control of movements located closer than 15-20 cm. Moreover, Roy (1977) and Roy and Kelso (1977) had earlier shown that position cues are more important for the control of longer movements.

6.2.4 The memory component of repositioning (study II)

In ipsilateral repositioning some time must elapse between each test movement and response movement. This time delay risks taxing the subject’s memory and confounding the results in this type of test and is, obviously, a weakness of the ipsilateral test procedure. Since subjects suffering from chronic pain frequently report memory problems (Di Stefano and Radanov 1995; Söderfjell et al. 2006; Robinson et al. 2007) the findings of reduced repositioning acuity in these subjects may partly be due to reduced memory function. However, we found no support for the hypothesis that the memory component (i.e., the effect of retention time delays between the reference and test movement – the subject’s RT-slope) of the shoulder repositioning test contributed to the group difference in VE. This was indicated by the nonexistent difference in RT-slopes between the groups. A possible explanation for this indifference is that even though subjects suffering from chronic pain can have reduced memory functions (e.g. Söderfjell et al. 2006) this may not include the memory systems used in a position-matching task. Support for this idea is found in studies showing that although explicit memory functions are affected in chronic pain, implicit memory functions, which do not rely on consciously controlled processing, are unaffected (Grisart and Van der Linden 2001; Söderfjell et al. 2006). Furthermore, in contrast to what we expected there was no overall effect of RT on VE when all subjects were pooled together. This finding implies that memory does not have any direct effect on the repositioning precision, that is, at least not for time delays in the range up to 6 seconds. In an early study of position-matching by Adams and Dijkstra (1966) they demonstrated significant effects of retention time delays in a similar time range as ours (Adams and Dijkstra 1966). However, the outcome used in that study was AE. As discussed earlier, AE depends partly on systematic errors (CE), which are prone to drift (Wann and Ibrahim 1992), a fact that could explain the difference between our studies. We addressed this possibility by analysing RT effects on AE instead of VE. The results revealed a significant retention time effect on AE in line with the findings of Adams and Dijkstra (1966). Indirectly this finding implies that the effect of delayed retention times is related to the CE and not to VE. Nevertheless, the lack of differences between the groups for the RT-slope variable increases the likelihood that the reduced shoulder repositioning acuity in the neck pain groups is due to impaired shoulder proprioception.
6.3 Pointing acuity (study IV)

Everyday tasks normally require interaction with the environment involving control of multi-joint movements in 3D-space that rely on both visual and proprioceptive feedback (van Beers et al. 1996). Because proprioceptive feedback is important in this type of movement and since reduced proprioception was found in neck pain subjects in study I and II, neck pain may also be associated with reduced precision in pointing movements. This has not been studied before although reaching movements are a key component of many everyday activities. In study IV we tested the hypothesis that subjects with chronic neck pain have higher end-point variability than healthy controls when performing fast 3D-pointing movement with full vision. Thus, study IV extended the previous research on shoulder repositioning acuity by studying end-point acuity in more natural fast pointing (multi-joint) movements.

The analysis of VE and Peak velocity separately showed no significant group differences. However, when controlling for movement speed (Peak velocity), we found higher end-point VE in both neck-pain groups compared to the controls. This fact can be interpreted as a result of a combined effect of the speed-accuracy trade-off and between-subject variability in how the task was performed. More precisely, in all groups between-subject variability in Peak velocity increased the between-subject variability in VE, because of the close relationship between these two variables (e.g., Elliott et al. 2001). By controlling VE for Peak velocity this effect was eliminated and revealed the acuity reduction. The results support the hypothesis of reduced pointing acuity in neck pain and show that the speed-accuracy trade-off should be taken into account in order to reveal deficits in the control of reaching acuity.

Because the previous studies indicated a reduction in proprioception of the upper extremity in people with chronic neck pain and since acuity in the near-far (depth) direction is suggested to depend more on proprioceptive information (van Beers et al. 1996; van Beers et al. 1999; van Beers et al. 2002b), it was hypothesized that differences in end-point acuity would show up strongest in depth direction. However, reduced end-point acuity in the neck pain subjects was not secluded to the depth direction. Even though variability differences in depth was largest for both groups compared to the control group and that the WAD group, as hypothesized, showed significantly higher VE than controls only in depth, the difference was not statistically different from the VE-differences in the horizontal and vertical directions. Thus, end-point acuity differences between cases and controls are not isolated to depth direction which, according to the direction dependent sensory efficiency hypothesis (van Beers et al. 1999), would have been indicative of a proprioceptive disturbance. Proprioceptive impairment can, however, not be excluded as an underlying cause since vision and proprioception both contribute to movement control in all directions. In this unconstrained movement task the two sensory modalities are likely very tightly integrated and it is likely that a large number of pointing trials are needed in order to capture possible group differences in end-point spatial distribution. Nonetheless, the direction dependent sensory efficiency theory deserves to be addressed more in futures studies on neck pain.
6.4 Difference between repositioning and reaching

It was assumed that reduced end-point acuity found in the neck pain groups in study IV could be related to the impaired shoulder proprioception indicated in study I and II. However, the additional correlation analysis of variable errors from the repositioning test (study II) and the pointing test (study IV) showed that this was not the case. For all groups the correlation coefficients were remarkably low (r = -0.03 – 0.003). Clearly, this finding indicates that different control strategies are used for the two tasks, even though they both include arm-movement precision. This is however not a unique finding since it is known that measurements from different movement task, although apparently very similar, like throwing a javelin and throwing a baseball, may correlate nearly zero to each other (Schmidt and Lee 1999). A number of studies have come to similar conclusions when investigating for example striking and kicking movements (Lotter 1960) and different balancing tasks (Bachman 1961). Observations such as these are, in fact, central to the idea of task specificity (Henry 1961; Schmidt and Lee 1999). Thus, the finding that precision estimates in position-matching and fast reaching acuity were shown to be uncorrelated is, with this in mind, not surprising.

Another idea that is worth recognizing that could provide and alternative explanation to dissociation between repositioning and reaching acuity is the theory advocated by Gallagher (1986; 2005) reviewed in the background (2.2.3 The body in the brain). Gallagher proposes a conceptual distinction between what he calls the body schema and body image. These concepts are related to internal mental representations of the body where body schema is unconscious, automatic and used for motor action while body image is used for conscious perceptual judgements. Kammers et al. (2006) addressed this distinction when comparing the responses in (unconscious) reaching to passive and active (conscious) matching of limb positions using vibration-induced illusive lengthening of the limb constituting the target. Larger errors in the matching task and disociation between the reaching and matching tasks were found. Further analyses showed that passive and active matching were indeed correlated but significantly different from the reaching results. The findings were interpreted as a differentiated effect of the kinaesthetic illusion on the separated underlying body representations of body schema and body image for the two tasks (Kammers et al. 2006). The tasks in this example are strikingly similar to the test used in this thesis. Following this idea the fast reaching movement in study IV is, thus, an automatic movement at a pre-reflective level dependent on the body schema for movement control, whereas repositioning in study II, clearly is a more conscious perception of the arm location that should be dependent on the body image. This hypothesis could deserve further attention in research of sensorimotor control.

Irrespective of the underlying reason for the lack of correlation between the position-matching acuity and pointing precision found in the present thesis, it indicates that the impairments of neck pain subjects in these tasks does not depend on the same mechanism. As a consequence, this finding also falsifies simplistic one-dimensional explanations behind sensorimotor impairments in chronic neck pain disorders.
6.5 Possible mechanisms of reduced movement acuity

6.5.1 Peripheral mechanisms

Several possible mechanisms may account for the reduced repositioning acuity and reaching acuity found in the neck pain groups. One of these mechanisms pertains to the muscle spindle model described earlier (Johansson et al. 2003b). From research in animal models it is known that intra-muscular injections of algesic or inflammatory substances can alter the sensitivity of muscle spindles in the trapezius muscle via reflex effects from chemosensitive muscle afferents onto the gamma motor system (Wenngren et al. 1998a; Thunberg et al. 2002). This effect can in turn lead to a reduction of the information content in the combined proprioceptive signal from the spindle afferents (Pedersen et al. 1998). As pointed out by van Beers and colleagues (2002a), sensory noise will on a perceptual level transform into uncertainty, which in precision tasks would manifest itself as increased movement variability (i.e. VE; the inverse of movement precision or acuity).

High pain ratings were, however, not associated with high VE in the tests designed to target upper limb proprioception in study I and II. In study IV pain-ratings, reflected by the variables VAS and bodily pain (SF-36), were significant predictors for high end-point (pointing) variability in the WAD group but not in the NS group according to the PLS analyses. This finding leaves the mechanism of pain effects on proprioceptors tentative as an explanation of reduced pointing precision. However, since inflammatory processes are not always reflected in pain perception it cannot be excluded. Moreover, in chronic pain the nociceptive component is assumed to decrease with time and pain ratings may therefore not reflect the sensory dimension of pain adequately.

Another afferent mechanism that could affect proprioception is the fact that injuries or mechanical strain on peripheral nerves could disturb transmission of proprioceptive afferent signals. Nerve irritation can result in both motor and sensory loss, paraesthesia and radiating pain (Greening et al. 2003). In study IV none of the predictor variables that may reflect such nerve involvement (e.g. muscle weakness, sensory loss, paraesthesia) were significant predictors of reduced precision. A fact that speaks against nerve irritation as an influential mechanism of reduced pointing acuity. However, in study II clumsiness of the hands was associated with repositioning acuity of longer movements which could fit the idea of a peripheral neural deficit as well as altered mechanoreceptor sensitivity as described in the muscle spindle model (Johansson et al. 2003b).

6.5.2 Central mechanisms

Regardless of mechanism liable for a disturbed proprioceptive inflow, vague or unreliable information of the body’s postures and movement would, eventually, result in an inaccurate or indistinct body representation, as discussed in the section on body schema (2.2.3 The body in the brain). What effects a distortion of such inner representation would have will not be speculated on though. However, according to Melzack’s pain neuromatrix theory (e.g. Melzack 2005) pain sensation is incorporated along with other sensory input to shape movement behaviour, autonomic regulation as well as awareness of the body. Interestingly, higher levels of neck pain (tenderness in the neck) in NS in study II were associated with better repositioning acuity in the short distance target. This is a result that could mean that
some aspects of pain sensation actually are used in the control of movements by the subjects with neck pain and integrated into the neuromatrix output.

Seen from another perspective, the brain will adapt to all changes that takes place in the body as signalled to the CNS. An increase in input results in an increase of cortical representations whereas reduced input results in size reduction of representational space (e.g., Pascual-Leone and Torres 1993; Nudo et al. 2001). A reduced representation of sensory and motor areas would also have profound effects on the quality of movement control. Moreover, other central mechanisms of pain might also explain the findings of impaired precision in the present thesis. In brain imaging studies of chronic pain patients, one of the areas most consistently reported to be engaged is the anterior cingulated cortex (ACC) (Devinsky et al. 1995; Vogt et al. 1996; Rainville et al. 1997). Interestingly, the ACC is also involved in events like cognitive information processing, error detection and response selection associated with sensorimotor activity as well as responses to noxious stimuli. The ACC is considered to be an important area in a matrix concerned with attention (Davis et al. 1997; Derbyshire et al. 1998) and appears to play a crucial role in initiation, motivation, and goal-directed behaviours (Devinsky et al. 1995). Thus, altered activation of the ACC and ACC-related networks in response to pain, could influence many sensorimotor functions important for the performance of the tasks under study in this thesis and provide an explanation to the findings of reduced acuity of goal-directed movements.

Pain has been found to affect cognitive functions like memory and attention (e.g., Busch et al. 2006; Söderfjell et al. 2006). It is possible that sensorimotor control deficits are related to alterations in information processing and/or motor planning. Such higher order modifications could be driven by pain-related factors such as stress, fear or attentional constraints. However, the PLS analyses of the data in study II and IV showed that none of the factors concentration deficits or sleeping disturbance were associated with the precision errors in repositioning and pointing. Thus it seems as if lack of attention to the task could not explain the group differences in our studies. This is however not to say that people with chronic neck pain do not have deficits of attention and concentration. None of the tests in study I, II and III were very lengthy and might therefore not have provoked any mental tiring or fatigue as to influence the performance. In study II a break was included half way through the test series to avoid any such effects.

From the PLS model generated in study II (Table IV) it can be seen that kinesiophobia (fear of movement or re-injury) may be one mechanism involved in poor proprioceptive acuity, as measured by the TSK questionnaire. The TSK was found to be a significant predictor of poor VE only for the short target location. That observation is logical considering the findings in study III which demonstrated short distance targets to be controlled primarily by movement sense mechanism. An alternative explanation is that kinesiophobia, as well as pain by itself, may lead some people to reduce their physical activity levels that eventually could impair sensorimotor functions (e.g., Karlberg et al. 1991). Unfortunately, the activity level of the subjects was not assessed, which is a weakness of the study, and no firm conclusions can thus be drawn. With these results from study II in mind it is surprising that kinesiophobia was not associated with impaired reaching acuity in study IV where movements was to be performed as fast and accurate as possible. A strong influence of fear of movement on the performance of fast movements would have been plausible. On the other hand, performing constrained movements deprived of visual guidance may afford
kinesiophobic individuals to become even more hesitant to move and result in imprecise movements as found in study II.

6.5.3 Integration of sensory information

In study IV a strong association between end-point reaching precision and self-rated neck function was found in both neck pain groups (Table V and IV), which indicate that some aspects of neck function directly affect the control of pointing movements. This finding is in accordance with earlier suggestions that the neck has a central role for spatially orientated movements (de Jong et al. 1977; de Jong and Bles 1986; Karlberg et al. 1991). In aimed reaching, vision provide the information of the target and hand in external coordinates while proprioception provides information on the positions and movements of the hand and arm in an internal reference frame. The position of the head and neck is used as a reference in the process of integrating these two coordinate systems (Fookson et al. 1994; Berger et al. 1998). Since sensorimotor functions of the neck in various studies have been shown to be impaired (O’leary, 2003) it may be reasonable to assume that such dysfunctions of the neck represent one mechanism behind our results of reduced reaching acuity in NS and WAD. Furthermore, people with WAD with traumatic origin have been found to have impaired oculomotor function (Gimse et al. 1996; Tjell and Rosenhall 1998; Wenngren et al. 1998b). The interaction between neck movements and oculomotor function (Karlberg et al. 1991) could mean that impaired reaching acuity is an effect of reduced ability to direct vision to the target. Moreover, WAD subjects showed a strong association between reduced self-rated balance impairments and poor reaching precision (Table IV). Impaired balance function is a frequent finding in neck pain conditions (Michaelson et al. 2003; Field et al. 2007) and the importance of the neck for balance and postural control is well known (for references see Karlberg et al. 1991). Compelling evidence on this matter was provided in a study by Karlberg and co-workers (1991) where healthy subjects restricted in neck mobility by cervical collars showed impaired postural control. The findings in study IV imply that poor reaching acuity and balance problems could be related in WAD, possibly linked by reduced neck function due to neck pain. This has also been demonstrated experimentally, in both human and animal studies where anaesthetic injections into the deep tissues of the neck produce unsteadiness, ataxia and a tendency to fall (de Jong et al. 1977; de Jong and Bles 1986).

6.6 Associations between acuity measures and self-rated characteristics

As outlined in the beginning of the discussion the association analyses provide a validation to the assessments of repositioning and goal-directed reaching but also a tool to address possible underlying mechanisms for impaired sensorimotor control. The use of multivariate projection methods like PLS to this end has many advantages compared to traditional methods like multiple linear regression (see 4.5.3.1 Multivariate data analysis). The latter method was however used in study I and revealed that the questionnaires PDI, SES and the SF-36 indices physical functioning, social functioning and vitality could explain more than half (51%) of the variation in repositioning VE-short of the WAD group. Conversely, a PCA of the same indices could be described by one principal component explaining 43% of VE-short, revealed by principal component regression. The fact that only one PC could model the questionnaire data indicates that these indices were based on the same underlying latent variable, possibly
related to general physical functioning. However, the association was only found for VE-short. An association that, according to the results in study III, could imply that movement-related (velocity) sensory information is involved. As discussed earlier, precision of shorter movements has been suggested to depend more on movement-related information (Walsh et al. 1979) and/or efferent mechanisms (Wolpert et al. 1995) while longer movements rely more on position-related information.

In studies II and IV the O-PLS method was used. Here the questionnaires, separate questions and symptom ratings were chosen with the purpose to capture, in better detail, aspects of the clinical picture of the patients that could be of relevance for sensorimotor function in the upper limb. Some of the revealed associations have already been discussed above.

For the NS group in study II it was found that different variables were important for repositioning acuity of long and short target positions respectively since the two PLS-models presented different predictor variables. The PLS model could explain a noticeable large proportion of the variance in VE-short. One advantage of the statistical tool we employed for PLS (SIMCA-P 11.0) is the cross-validation procedure (Wold 1978) which effectively evaluates the generality of the model expressed in the goodness of prediction estimate Q^2. The cross-validation procedure can be used to evaluate how many components that should be modelled to protect the model from over-fitting. Notably, the cross-validation operation showed the PLS-models for WAD to be unreliable and non-significant, indicative of large intra-subjective differences in this group. For the NS group however, the Q^2 for the model for VE-short was almost 70%, which must be considered rather high for questionnaire data. As seen in Table IV of VE-short, four significant predictors were uncovered. Significant association to the variables; difficulty bending the head forward and difficulty to change a light bulb overhead imply that position-matching of the short position may be associated with problems performing movements that involve awkward postures of the head and arms. Also, higher levels of kinesiophobia (TSK) were associated with poor repositioning acuity. Such beliefs could, as discussed, lead to physical deconditioning with subsequent negative effects on sensorimotor function. Furthermore, and quite opposite to our expectations, more tenderness in the neck was found to be associated with better matching acuity. This finding could indicate that some aspects of pain, possibly related to movement, are used as cues in the control of the short-movement matching task.

The model of VE-long generated for the NS group showed that the self-rated predictors could explain 45% of the variance in VE-long and indicated, according to our significance criteria, two significant predictors (Table IV). The association with clumsiness of the hands supports the idea that matching of the long target position may be associated to upper extremity precision. The association between better social functioning and poorer matching acuity is somewhat more difficult to interpret meaningfully. Social function may be related to personality traits like extraversion and introversion and it has been suggested that introverts are more geared toward inspection and stimulus analysis compared to extraverts that may be more geared toward motor response (Brebnor and Flavel 1978; Stahl and Rammsayer 2008). However, this notion is speculative and the issue was not studied in the present thesis.

In study IV, different clinical characteristics predicted poor reaching acuity in NS and WAD. The predictors could explain almost 68% of the variation in the pointing acuity estimate in the PLS model for the NS group and 42% for the WAD group. As pointed out in
the beginning of the discussion, the association between pointing acuity and self-rated neck function was notably strong in the NS group (Table V). Difficulties to perform head movements in all movement directions contributed significantly to the association pattern. Also in the WAD group, difficulties to perform neck movements in extension and left lateral flexion were significantly associated with pointing acuity. In the WAD group also higher levels of pain (Bodily pain SF-36 and VAS) poor balance and difficulties in lifting/carrying influenced negatively on pointing acuity (Table VI).

6.7 Methodological considerations

There are some methodological issues in this thesis that should be addressed. First, the strengths and weaknesses related to test methods and designs used for proprioception testing have to major extent already been outlined in the background (2.4 Testing proprioception) but is briefly discussed below. Other issues worth noting concerns the challenges involved in conducting clinical research. For instance, establishing the inclusion and exclusion criteria in the heterogenic group of chronic nonspecific neck pain are a delicate matter. Reliable criteria to pin-point some specific subgroup within this diverse group is usually an ideal which, in for example RCT studies, is of great importance (McCarthy and Cairns 2005). However, as discussed, no consensus on what grounds such classification should be done exists today. A classification would therefore have had to be performed according to criteria that have questionable validity (e.g., Nordin et al. 2008). Thus, the inclusion and exclusion criteria used in the present thesis were deliberately set rather relaxed. No physical examination was performed when subject were enrolled, other than rough screening so that subjects were able to perform the head and arm movements included in the tests. Instead, subject recruitment was based on the subjects’ reports in a standardised questionnaire of the established inclusion and exclusion criteria. This procedure was chosen partly due to logistic reasons related to the single blind designs used in study II and IV, which disqualified part of the available researcher staff from interacting with the subjects before testing. The procedure was also a pragmatic choice since strict criteria would have meant difficulty to get the acceptable number of participants for the projects. Furthermore, although useful for other purposes, a further sub-classification of the subjects was not searched because an important part of the research questions concerned the associations of position-matching and goal-directed reaching to self-rated clinical characteristics. A large diversity in symptom levels and functioning is in that aspect not a disadvantage.

In contrast to study II and IV, the first study in this thesis (study I) was not blinded. This is a weakness that, theoretically, could have influenced the results. Even though the highly automated set-up made direct involvement in the test situation unnecessary and thus prevented unwanted group biases in the testing situation, this fact does, however, not exclude biases that may have been induced when subjects interacted with the test leader before the test. In studies II and IV the tests was single-blinded i.e., the test leader was unknowing of what category (WAD, NS or CON) the tested individual belonged to.

Furthermore, the equipment used for position-matching in this thesis has been used in a number of research projects with different designs (e.g. Lönn 2001; Björklund et al. 2003; Djupsjöbacka and Domkin 2005). In the clinical studies I, II and IV we used tests where subjects execute movements themselves since active movements, in contrast to passive,
related to normal movement behaviour but also because active tests have been show to be more reliable than passive tests (Lönn 2001; Janwantanakul et al. 2002). However, Lönn (2001) found that the reliability of passive as well as active shoulder repositioning tests is rather poor, or at best moderate. The rather poor reliability of position-matching tests thus means that any difference between individuals or groups must penetrate a high level of noise. A larger number of subjects are needed in order for any differences to emerge (i.e., higher power). No explicit power analysis was done on any of the tests used in this thesis. This is an obvious a weakness that may explain the negative finding in study II, where no differences in repositioning acuity were found between the WAD and Control groups.

Another methodological concern of the position-matching tests relates to the selection of starting and target positions. More than one target should be used to prevent repositioning to be based mostly on predictions and less on actual sensation of the hand and arm (Wolpert et al. 1995). In this thesis two targets were used that are referred to as long and short target positions. As can be seen in Figure 3 the targets were in fact rather intermediate and not located very far apart. The reason behind the choice of targets and starting position was, primarily, that we wanted to avoid any risk of provoking pain or other symptom in the neck pain subjects when they performed the test. An intermediate starting position at 50 degrees with respect to the sagittal plane was in pilot studies found to be appropriate and feasible to perform for also individuals with quite severe symptoms. If not for avoiding symptom provocation, the targets could possibly have been set further apart, since it was suspected (and later demonstrated) that control mechanisms might differ for long and short target locations.

The presented results of reduced position-matching and pointing acuity in chronic neck pain have been interpreted as an effect of their clinical condition. Another possibility may, however, be that the neck pain subjects were physically deconditionned, as a result of their neck pain. That is, prolonged neck pain may have made the subjects reduce their engagement in physical activities with a subsequent decline of fitness level. Unfortunately, activity levels were not assessed in the present thesis. Physical fitness has profound effects on virtually all body systems, including sensorimotor control and it would have been valuable to have had some estimate of this factor, self-rated or measured with some form of activity sensor. On the other hand deconditioning can be viewed as one part of the neck pain condition and for some individuals also be a reflexion of their clinical status. Nevertheless, measures of physical fitness should be considered in future studies to allow for testing of this hypothesis.

6.8 Conclusions

The results of this thesis show, for the first time, that arm movement precision is impaired in people with chronic nonspecific neck pain of both traumatic and non-traumatic aetiology. The clinical validity of the used tests is supported by the finding that reduced precision was associated to specific symptoms and self-rated functional limitations in the neck pain patients. Further, the results also suggests that poor precision of goal-directed arm movements in people with chronic neck pain is related to difficulties in performing head movements; a finding that imply a close interaction between neck function and upper limb movement control. Moreover, in people with WAD, a reduced precision of goal-directed arm movements may, in addition, be related to greater pain levels, problems with lifting and carrying and
balance reduction, the latter indirectly indicative of a sensorimotor (proprioceptive) dysfunction of the neck.

This thesis also found that people with chronic neck pain have reduced shoulder repositioning acuity, which may reflect impaired proprioception of the upper limb. This interpretation is corroborated by the result showing that memory function had no effect on the repositioning acuity. This finding partly contradicts the traditional view of memory as an influential component in position-matching tasks, and strengthens the likelihood that the reduced repositioning in neck pain subjects is related to a proprioceptive impairment.

It can also be concluded that reduced shoulder repositioning acuity is related to impaired physical functioning, fear of movement, clumsiness of the hands and impaired neck and arm functioning in people with non-traumatic neck pain. These associations may indicate a relationship between impaired proprioception and ability and/or willingness to engage in physical activities.

Furthermore, acuity of long and short extents of unsighted shoulder repositioning movements constrained to one dimension is concluded to be dependent on different control mechanisms related to position information and movement information respectively.

Finally, this thesis also shows that movement precision in unsighted position-matching and goal-directed pointing to visual targets is in agreement with task specificity principles and may be governed by different control mechanisms. This finding also highlights the complexity of sensorimotor impairments in people with chronic neck pain.

6.9 Future directions

A number of ideas for future research have emerged during the works of this thesis. Naturally, there are questions remaining to be answered in order to be more certain on the implications and conclusions drawn here but also for gaining new insights on the subjects and related subjects presented in the thesis. First of all, further research should address the role of neck function for goal-directed reaching. As indicated in study IV, impaired neck movement function was a major contributing factor for reduced pointing precision. To monitor the movements of the head while performing fast reaching movements could contribute to the understanding of the mechanisms behind impaired reaching precision. Also oculomotor function should be investigated further in relation to goal-directed reaching and neck pain. Along these lines is implementation of some form of manipulation of vision and/or proprioception while performing goal-directed reaching (but also in position-matching) one possible approach. In that respect is also the hypothesis of a direction dependent sensory efficiency (van Beers et al. 2002b), an interesting venue to explore further since experimental manipulation of vision and proprioception, for instance by prisms and vibration, could be needed to disentangle the contribution of these two modalities. It would also be of interest to explore end-point reaching precision in relation to other sensorimotor functions in neck pain, for instance balance function that was indicated to be related to impaired acuity in WAD, but also other kinematic measures like smoothness of movement or movement path alteration. Lastly, to investigate how training of sensorimotor functions like movement control should be performed to be beneficial for, primarily, experienced functioning in tasks and activities but also to other symptoms related to neck pain.
6.10 Clinical implications

Since many every-day tasks depend on good movement precision and timing, impaired precision of goal-directed arm movements can have implications for an individual’s everyday functioning. Even small deficits in precision could compromise the execution of many different tasks. Playing a musical instrument or performing sports activities could obviously be hampered but also many tasks in working life and daily living can be affected. Imagine reaching with your keys to unlock the door to your house or car. Most people have experienced the annoyance of not finding the key hole at the first attempt and can see the small difference of a millimetre that separate success and failure. Even though this example illustrates a trivial problem with no consequences it demonstrates the importance of a fine-tuned sensorimotor control system. In many real life precision tasks a reduced precision can be compensated for by moving slower. In fact, this is something we all do naturally, for instance in new activities, when visual conditions are poor or if the hands get freezing numb. If proprioceptive information from the body is vague, information from other systems, primarily vision, will be up-weighted in the control of movement (Wolpert et al. 1995; van Beers et al. 2002b) and the individual will thus become more dependent on vision for guiding movements. This in turn can put extra strain on the neck, since increased reliance on visual feedback will increase the demands on coordinated eye-head movements. Another strategy used for increasing precision is co-contraction of muscles to “stiffen up” the movement apparatus in order to reduce movement variability (van Galen and van Huygevoort 2000). Co-contraction is a phenomenon that is presumed to underlie the development of many musculoskeletal pain disorders (e.g., Visser et al. 2004), which also has been shown to be more frequent in occupations performing precision tasks under time pressure such as dentists (Akesson et al. 1999) or computer terminal workers (Wahlstrom et al. 2004). Hence, although impaired movement precision can be compensated for, it may nonetheless have harmful consequences due to extra muscle tension and subsequent wearing and tearing of the tissues (Hägg 1991).

The methods used in the present thesis rely on instruments primarily used in research that may in many respects be too elaborate to find a place in medical clinics in the form they are used here. The electromagnetic system used to register kinematics in study IV is however not a complicated system and could be used with ease in for example in rehabilitation clinics. The results of this thesis clearly show that assessment of upper extremity sensorimotor function has potential to be a valuable tool for profiling of patients with chronic neck pain. Movement registration systems, together with validated testing protocols, may provide objective measurement that today is scarce in the clinical care of patients with musculoskeletal pain.

However, when exploring novel fields of clinical assessments there is a balance between being clever enough to find new measures to describe or characterize a disorder and not being too clever so one risks “inventing” new ones. It may be important, therefore, to follow up any such attempt by teasing out the clinical relevance to avoid producing new “knowledge” that is not worth knowing. This is maybe especially important in an era of technological development and creative new equipments that may risk driving the research questions instead of the other way around.
This thesis has not included any interventions of neck pain disorders. Still, the results presented here indirectly support the use of training method aimed at improving movement control and body awareness such as, Body awareness therapy, Feldenkrais therapy or Tai chi quan. These and other methods that put focus on how movements are performed and on the emerging bodily sensations (in sports terms; a form of technique training) may be encouraged on basis of our findings. Training that include a shift of focus from “knowledge of results” to “knowledge of performance” is known to affect movement quality (Schmidt and Lee 1999) and may improve end-point control directly or indirectly, through improved movement coordination, with transfer effects also to everyday functioning. A special focus on movement control of the neck and upper limb may be warranted as well as regimes targeting integration of visual (external) and proprioceptive (internal) frames of reference, since neck function may constitute a key component in such sensory integration.
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