

# ***From precision demands to neck and upper extremity pain***

***Maaïke A. Huysmans***

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***From precision demands  
to neck and upper extremity pain***

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promotoren: prof.dr. J.H. van Dieën  
prof.dr. A.J. van der Beek  
prof.dr. M.P. de Looze

copromotor: dr. M.J.M. Hoozemans

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# *Chapter* ***one***

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***General Introduction***

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## General Introduction

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Computer workers frequently report neck and upper extremity pain. In the year 2002, 28% of the general Dutch working population reported to have suffered from pain or stiffness in the neck, shoulder, arms, hands, or wrists in the previous 12 months (Heinrich and Blatter 2005). A survey conducted in 15 European countries showed a prevalence of 25% for work-related neck-shoulder pain and a prevalence of 15% for work-related arm pain (De Kraker and Blatter 2005). The total yearly costs of neck and upper extremity pain in the Netherlands due to decreased productivity, sick leave, chronic disability for work and medical costs were recently estimated at 2.1 billion euros (Blatter et al. 2006).

In the literature, a variety of terms is used to indicate neck and upper extremity pain, such as Repetitive Strain Injuries (RSI), Cumulative Trauma Disorders (CTD), Occupational Overuse Syndrome (OOS), Work-Related Upper Extremity Disorders (WRUEDs) or chronic work-related (trapezius) myalgia. Whereas these terms suggest some sort of mechanism of the development of these symptoms, the aetiology is far from clear. Often no specific, medically, objectifiable disorder is found (“non-specific” pain), and thus the terms “injuries” or “disorders” may be inappropriate. Accordingly, to date more descriptive terms are used to indicate this syndrome, such as “neck and upper limb pain”, “neck and upper extremity symptoms or pain” or more specifically referring to the area that is affected; “neck-shoulder pain” or “arm-hand pain”. The latter terms are also used in the present thesis.

RSI or neck and upper extremity pain has been defined as: *“a multifactorial complaints syndrome affecting the neck, upper back, shoulder, upper and lower arm, elbow, wrist or hand, or a combination of these areas, which leads either to impairment or to participation problems. The syndrome is characterised by a disturbance in the balance between load and physical capacity, preceded by activities that involve repeated movements or prolonged periods spent with one or more of the relevant body parts in a fixed position as one of the presumed aetiological factors”* (Health Council of the Netherlands 2000).

The symptoms in this syndrome are diverse in nature. The following have been reported in literature: pain, stiffness, tingling, clumsiness, loss of coordination, loss of strength, skin discolorations, and skin temperature differences (Yassi 1997; Bongers et al. 1998; Harrington et al. 1998), of which the most prominent one appears to be pain. The variety of symptoms suggests that different anatomical structures are affected, specifically nerves, tendons, muscles and the attachments and connections between different structures.



In the above stated Health Council definition of RSI, repeated movements and static work postures are mentioned as prominent physical risk factors, but in the scientific literature also awkward postures and high forces have been reported to be related to neck and upper extremity pain (Bernard 1997). Furthermore, high precision demands in work tasks have also been suggested to be a risk factor for neck and upper extremity symptoms (Milerad and Ericson 1994; Visser and Van Dieen 2006). However, this has never been thoroughly investigated in high quality epidemiological studies with a longitudinal design. High precision is demanded in very different professions involving fine motor tasks, such as in the work of a dentist, surgeon, crane operator or a watchmaker. But also technical drawing, data entry, and common computer work such as rapidly hitting the correct keys on the keyboard and using a computer mouse, with tasks such as aiming, selecting, and dragging, involve high precision demands.

Beside these physical risk factors psychosocial risk factors, such as stress, high job demands, low job satisfaction and personality traits, such as overcommitment and perfectionist traits have been reported to be associated with neck and upper extremity pain (Bongers et al. 2002; Van Eijsden-Besseling et al. 2004; Van den Heuvel 2006).

Although several factors have been identified to be related to neck and upper extremity pain, the underlying mechanisms are still poorly understood, despite an extensive body of research (Visser and Van Dieen 2006). The large variety in symptoms and risk factors suggests that there is not just one mechanism that explains the development of neck and upper extremity pain, but that several mechanisms may act simultaneously or that different mechanisms act for different risk factors. The presumed role of precision demands in the development of neck and upper extremity pain is plausible on the basis of two different aetiological models. First, the Neuromotor Noise Theory hypothesises that high precision demands in a task could lead to increased muscle activity (Van Galen and De Jong 1995; Van Gemmert and Van Galen 1997; Van Galen and Van Huygevoort 2000) and second, the Johansson Model predicts that muscle activity and pain amplify each other in case precision demands occur (Johansson et al. 2003). In the following paragraphs, the two models will be explained and they will be combined into one model, which outlines how high precision demands in a task might lead to neck and upper extremity pain.

### **Neuromotor Noise Theory**

The generation of movement is an inherently noisy process, rendering motor behaviour variable. The noise is the result of stochastic motor neuron firing processes involved in muscle-force generation, reflex-induced oscillations of force output, feedback and

feedforward servo-mechanisms and mechanical oscillations of muscle tissue, tendons and bones (Van Galen and Van Huygevoort 2000), and leads to force and kinematic variability. This can be illustrated by pointing a laser pointer at a distant target. The laser beam will always display apparently random movements over and around the target area. It appears that the neuromotor noise in the system can be enlarged by the presence of cognitive or emotional stressors (Noteboom et al. 2001; Christou et al. 2004). For example, when giving a presentation in front of a large audience, neuromotor noise may be enhanced and the presenter will have a hard time aiming the laser pointer at specific features on the slides. The precision demanded by the task determines how much kinematic variability can be allowed. This means that either the noise has to be decreased or its effects need to be filtered when high precision is demanded in the task.

Since noise in the neuromotor system is signal-dependent, its effects on kinematics can be decreased by reducing movement speed (Harris and Wolpert 1998). This is reflected in Fitts' law (Fitts 1954), which predicts that in aiming tasks with higher precision demands, movement time is longer, the so-called speed-accuracy trade-off. If reduction of movement time is not an option, the effects of neuromotor noise can be filtered by increasing impedance of the endpoint, which is the resistance against imposed motion (Burdet et al. 2001; Gribble et al. 2003). Impedance can be increased by increasing the level of co-contraction of the agonist and antagonist muscles (Selen et al. 2005) and, in case the end-effector is in contact with the environment, by increasing the friction between the end-effector (e.g. hand, mouse, pen) and the underlying substrate (e.g. table) (Van Galen and Van Huygevoort 2000). In studies in which positional precision of a pen on the surface was demanded, axial pen pressure was used as an indirect measure of endpoint impedance (Van Gemmert and Van Galen 1997; Van den Heuvel and Van Galen 1998; Van Galen and Van Huygevoort 2000).

It must be noted that increasing impedance in response to increased precision demands seems paradoxical, because of the signal-dependency of the noise. However, in a modelling study by Selen et al. (2005) it has been shown that increased co-contraction levels can lead to a decrease of kinematic variability, despite the increase in neuromotor noise (i.e. force variability of the individual muscles). Whether this holds for pen pressure is unknown, but the studies cited above suggest that this may be the case.

Increasing impedance is energetically costly and poses a higher load on muscles (Franklin et al. 2004). The Neuromotor Noise Theory suggests that the higher muscle load, associated with high precision demands may lead to an overload of the muscles.

Especially in tasks with long duration, muscles will not have enough time to recover and fatigue and pain may arise (Van Galen et al. 2002).

### **Johansson Model**

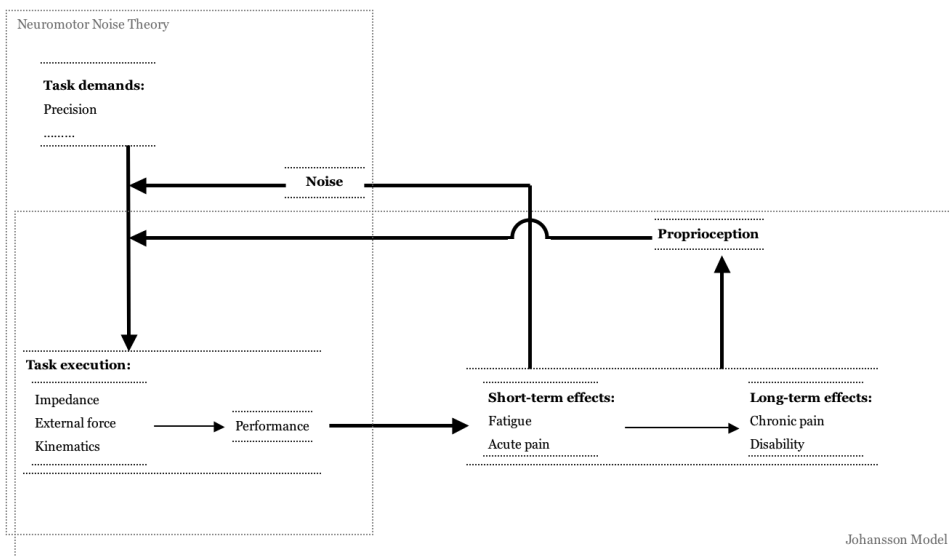
According to the Johansson Model (Johansson et al. 2003), increased concentrations of metabolites in muscles, due to sustained muscle activity, will decrease the accuracy of information transmitted by muscle spindles. When the information of the muscle spindles about muscle length is less accurate, proprioceptive acuity, i.e. the accuracy of perception of movement or position of body parts, will decrease. This reduced proprioceptive acuity is likely to impair the precision of motor control, since motor control is largely dependent on proprioceptive information. Less precise motor control would cause more frequent and/or larger deviations from the required joint positions or trajectories. To prevent such deviations, the muscles around the joints would have to co-contract more strongly. With this solution, performance in a task can be maintained, at the expense of a higher workload for the muscles involved. This solution may initiate a vicious cycle, as a higher muscle activity will accelerate metabolite accumulation. Large concentrations of metabolites will activate nociceptive nerve fibre endings and thus give rise to pain. If this condition is sustained, sensitivity for painful stimuli will increase and chronic pain may develop (Johansson et al. 2003).

### **The Precision-Pain Model**

Although both models described take another point of departure, they largely overlap. Both the Neuromotor Noise Theory and the Johansson Model explain how precision demands can lead to higher muscle activity levels (co-contraction). The Neuromotor Noise Theory does not explicitly mention the negative effects of fatigue on precision of motor control, as the Johansson Model does. However, in terms of the Neuromotor Noise Theory fatigue can be considered as a source of noise, since force variability increases with fatigue (Lorist et al. 2002; Hunter et al. 2004; Huang et al. 2006), eventually affecting the precision of motor control.

Considering the large overlap between both models, it is tenable to combine both into one model, which is illustrated in Figure 1 and will be referred to as the Precision-Pain Model. According to the Precision-Pain Model increased precision demands will affect task execution: endpoint impedance is expected to increase, to achieve the required task performance, especially in tasks in which slowing down is not an option. If such a task is performed for a long duration, the increased muscle activity required to increase endpoint impedance may accelerate fatigue development. Fatigue in turn has

been shown to lead to a diminished proprioception (Pedersen et al. 1999; Bjorklund et al. 2000) and to increased force variability (= noise) (Lorist et al. 2002; Hunter et al. 2004; Huang et al. 2006). Both increased noise and impaired proprioception, will increase the need to compensate for this decreased positional precision to maintain task performance at the required level. Therefore, force and impedance control may be further increased. This will accelerate fatigue development and close the vicious cycle. If this condition is sustained, chronic pain may develop, which may be accompanied by disability. As indicated by the Precision-Pain Model, impedance control may not be the only means to deal with high precision demands. When movement time is restricted, which is assumed by the model, changes in kinematics have been found with precision demands (Mottet and Bootsma 1999; Selen et al. 2006), most likely to minimise the energetically costly impedance control (Franklin et al. 2004). In addition, higher external forces may be applied in case proprioceptive information provides insufficient guidance. For example, in keying excessive keying force may be applied to make sure that a key is activated in spite of uncertainty of vertical fingertip position.



**Figure 1**

*The Precision-Pain Model proposed in this figure is a combination of the Neuromotor Noise Theory (Van Galen and De Jong 1995; Van Gemmert and Van Galen 1997; Van Galen and Van Huygevoort 2000) and the Johansson Model (Johansson et al. 2003) and predicts how high precision demands could lead to chronic neck and upper extremity pain.*

## Aims of this thesis

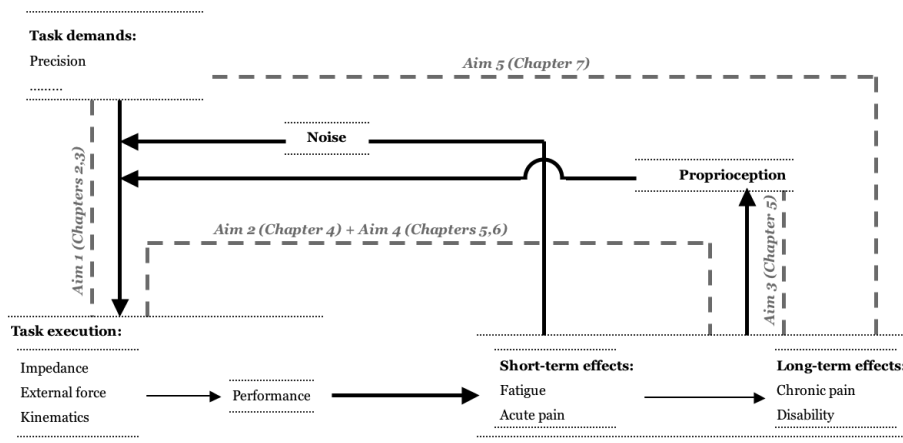
The Precision-Pain Model presented in Figure 1 explains how high precision demands could lead to chronic neck and upper extremity pain and it describes steps in the underlying mechanism. Some of these relations have been investigated previously, but the evidence for most of the relations is limited so far. Therefore, in this thesis it was aimed to investigate the relations implied by the proposed model, mainly in the setting of computer work and task execution with input devices.

The principle aims of this thesis were to investigate:

1. The effects of precision demands on task execution
2. The effects of fatigue on task execution
3. The effects of pain on proprioception
4. The effects of pain on task execution
5. The effects of precision demands on chronic pain

## Outline of this thesis

The principle aims of this thesis will be addressed in different chapters. The place of the aims and the relations tested in the individual chapters are visualised in the Precision-Pain Model in Figure 2.



**Figure 2**

The Precision-Pain Model as proposed in Figure 1 with the dotted lines illustrating the relations investigated in the principle aims and individual chapters of this thesis.

### **Aim 1 *Effects of precision demands on task execution***

The high prevalence of neck and upper extremity pain in crane operators is thought to be in part the result of high precision demands in their work tasks, which is mainly performed with joystick controls (Axelsson and Pontén 1990). The first question concerns the effect of precision demands on task performance and physical load on the operator. Secondly, we wanted to know whether performance in precision tasks can be improved and physical load can be decreased by optimising the size of the joystick control and the display-control gain (output of the machine element (speed) given a certain input (deflection) of the joystick). The optimal gain can be found by balancing the advantages of a relatively high gain (i.e. reduction of the time to reach target) against the advantages of a relatively low gain (i.e. reduction of final corrective movements when close to target) (Buck 1980). In **Chapter 2**, we aimed to investigate the effect of precision demands (2 levels), joystick handle size (short vs. large handle) and display-control gain (3 levels) on task performance, physical load (i.e. wrist and forearm posture and upper extremity muscle activity), perceived exertion, and perceived comfort in operators performing a simulated crane operation task.

In the simulated crane operation task, just like in aiming tasks, precision demands were only varied for the positioning part of the task. In line with Fitts' law (Fitts 1954) it is often observed that with increased precision demands in aiming, movement time increases. This may make it difficult to interpret the effect of the precision demands on muscle activity. On the one hand, muscle activity is expected to decrease as a result of the increased movement time, while on the other hand increased muscle activity is expected because of the increased impedance with increased precision.

Tracking tasks seem to be more suitable than aiming tasks to explore the effects of precision demands on impedance control, because both precision and movement velocity are enforced during the entire task. The relation between precision demands and both direct and indirect measures of impedance has rarely been investigated in tracking. In single-joint tracking an increase of impedance was found with higher precision demands (Selen et al. 2006). However, in addition to impedance control also changes in movement kinematics were reported with smaller targets. The question is whether in more realistic multi-directional tracking, increased impedance is found or that alternative strategies, such as changes in movement kinematics, predominate. Therefore, in **Chapter 3** we investigated how task execution, i.e. task performance, kinematics and impedance, in terms of muscle activity and pen pressure, are affected by precision demands in a 2D tracking task performed with a pen on a digitiser tablet.

### **Aim 2 *Effects of fatigue on task execution***

In the literature, it has been shown that sustained performance of precision tasks (computer work) can lead to fatigue (Jensen et al. 1999; Luttmann et al. 2005). Fatigue has been shown to lead to impaired proprioception (Pedersen et al. 1999; Bjorklund et al. 2000) and to increased force variability, i.e. noise (Lorist et al. 2002; Hunter et al. 2004; Huang et al. 2006). This would imply that precise movements will be more difficult to perform for fatigued subjects. However, whether muscle fatigue indeed leads to impaired task performance or to increased muscle activity, as the Precision-Pain Model predicts, has to our knowledge not been investigated before in computer precision work. In **Chapter 4** it is investigated whether performance in a computer precision task and muscle activity in the forearm are affected by fatigue.

### **Aim 3 *Effects of pain on proprioception***

The Precision-Pain Model predicts that proprioception is impaired in subjects with neck and upper extremity pain. However, it remains to be shown whether proprioception is indeed impaired in subjects with neck and upper extremity pain. This question is addressed in **Chapter 5**.

### **Aim 4 *Effects of pain on task execution***

If subjects with pain show decreased proprioception, how do they cope with the difficulty to perform precise movements? Do they use the same two strategies (impedance control and changes in movement kinematics) as proposed for healthy subjects in response to increased task precision demands? In **Chapter 5**, we investigated in a 2D tracking task for two target sizes whether tracking performance, kinematics, muscle activity, pen pressure and perceived exertion were different between subjects with neck and upper extremity pain and healthy controls. In addition, we investigated whether proprioception and performance in the tracking task were related.

Several studies indicate that in addition to proprioceptive deficits, subjects with neck and upper extremity pain suffer tactile deficits. Since both proprioceptive afference and tactile afference are used as feedback in many motor tasks, tactile deficits may likewise require increased muscle activity. A method that has been shown to provide useful information on tactile afference and motor activity in the upper extremity is to study grip force control in lifting and holding small objects (Johansson 1996; Nowak and Hermsdorfer 2005; 2006). In **Chapter 6**, we aimed to investigate whether grip force is affected in subjects with pain in neck and upper extremity, subjects with a history of pain and subjects without pain in lifting and holding an object. Moreover, it was investigated whether these subjects adapt their grip forces during consecutive lifts after the initial lift of a novel load similarly as healthy controls.

### **Aim 5 *Effects of precision demands on chronic pain***

The Precision-Pain Model proposed in this introduction predicts a causal relationship between precision demands in the task and the development of chronic neck and upper extremity pain. However, it is difficult to assess and quantify exposure to precision in epidemiological studies, using questionnaires or using objective measures. Computer work can be considered as work with high precision demands, with hitting the correct keys on the keyboard and computer mouse use, with tasks such as aiming, selecting, and dragging. Therefore, computer use may be used as a proxy for work with high precision demands. Previous reviews have suggested an association between the duration of computer use and neck and upper extremity pain (Punnett et al. 1997; Tittiranonda et al. 1999; Gerr et al. 2004; Wahlstrom 2005). However, the limitation of these reviews is that they were mainly based on cross-sectional studies. Cross-sectional studies cannot disentangle causes and effects and are, therefore, considered to be inferior to longitudinal studies. To gain more insight in the relationship between the duration of computer use (keyboard and mouse use) and the incidence of hand-arm and neck-shoulder pain, in **Chapter 7** a systematic review of longitudinal studies was performed. Since specific information on potential dose-response relationships is lacking, specific attention was paid to this issue.

### ***General Discussion and Conclusions***

In **Chapter 8**, the findings of this thesis are discussed in the light of the Precision-Pain Model. The combination of the results of the individual chapters, complemented with results in literature, will shed light on the validity of the model in explaining the development of neck and upper extremity pain in tasks with high precision demands. At the end of **Chapter 8**, the final conclusions of this thesis are drawn.

### ***Implications for Practice and Future Research Directions***

In **Chapter 9**, the implications for practice and the recommendations for future research directions are given.







# Chapter *two*

***The effect of joystick handle size  
and gain at two levels of required  
precision on performance and  
physical load on crane operators***

*Maaïke A Huysmans, Michiel P de Looze, Marco JM Hoozemans,  
Allard J van der Beek, Jaap H van Dieën*

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## Abstract

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*The study was designed to determine the effect of joystick handle size and (display-control) gain at two levels of required task precision on performance and physical load on crane operators. Eight experienced crane operators performed a simulated crane operation task on a computer by use of a joystick with either a short or a large handle. The task was performed at three gain levels and at two levels of required precision. Task performance, wrist and forearm postures, upper extremity muscle activity, perceived exertion and perceived comfort were measured. Task performance improved when using the joystick with the short handle and when working at a higher gain, while physical load decreased or remained the same. An increased level of required task precision was associated with a lower performance, but physical load was not affected. External validity of the simulated crane task seemed sufficient enough to extrapolate the results to practice. A joystick with a short handle is recommended, as this leads to an increased performance whilst the operator's physical load decreases or remains the same. Further optimisation of performance and physical load can be achieved by optimising gain settings of the joystick in relation to the task and type of joystick used.*

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## **Introduction**

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Over the last 40 years an extensive mechanisation and rationalisation took place in the forest, mining, and construction industries, which led to a large increase in productivity. Meanwhile, the physical characteristics of the tasks of the workers changed drastically, from physically strenuous work to long periods of low-intensive joystick operation (Attebrant et al. 1997). This joystick operation in machines is characterised by long periods of sitting in fixed, non-neutral body postures, while the hands are moving the controls in repetitive short-cycle movement patterns. In forestry, these activities may take up to 90-95% of the total working time (Hansson 1990), while the number of wrist movements can be even more than 20.000 per shift (Golsse 1989). Moreover, joystick operation often requires a high level of precision with only little room for errors.

The exposure to repetitive upper extremity motion patterns, long work periods, non-neutral body postures and high precision demands are known risk factors for upper extremity complaints (Milerad and Ericson 1994; Punnett and Wegman 2004). Furthermore, the risk of complaints is even more pronounced when a job includes a combination of two or more of these risk factors (Punnett and Wegman 2004). Therefore, it is not surprising that the incidence of complaints of the upper extremity and neck is high among operators. In a cross-sectional study of 1174 forestry machine operators, Axelsson and Pontén (1990) found that 50% of the operators reported an 'overload syndrome', mainly characterised by shoulder and neck complaints. About 90% of the operators associated their complaints with the one-sided static work, the controls and the seat (Axelsson and Pontén 1990).

With this high prevalence of musculoskeletal complaints in operators there is a need for ergonomic optimisation of joystick control in terms of reducing workload and maintaining or improving performance. One of the aspects in joystick operation that can be optimised is the joystick handle. The handheld joystick, which has a relatively large handle and is mainly operated with the whole arm and the hand, is most commonly used in heavy machines. Several years ago the mini joystick was introduced in the forest industry, which, as a result of the short handle, is mainly operated by the fingers in the palm of the hand. Results from earlier studies indicated that the use of a mini joystick may be beneficial, from the perspectives of both health and the performance of the operator. Asikainen and Harstela (1993) and Attebrant et al. (1997) found lower muscle activity in the trapezius muscle when the mini joystick was compared with the conventional handheld joystick. The mini joystick also seemed to have a positive effect on performance. Time to complete the task was reduced in the study of

Attebrant et al. (1997) when a mini joystick was used on a forest machine. In the study of Asikainen and Harstela (1993), not the time of task completion but the quality of task performance was improved when the mini joystick was used. This increased performance was explained by saying that ‘the hand and the fingers, with the small muscles of the distal joints, are especially suitable for executing short, fast and precise movements typical of the mini joysticks’. Despite the apparent positive effects of the use of mini joysticks in precision tasks, the application of mini joysticks in industries other than the forest industry, such as the construction industry, is still limited.

Another aspect that can be optimised in joystick operation is display-control gain. In machines operated by joysticks, a change in position of the joystick often results in a change of speed in the element of the machine that is operated. Display-control gain is defined as the output of the machine element (speed) given a certain input of the joystick (position as defined by deflection). With a low gain, a certain deflection of the joystick results in a low speed of the element of the operated machine. With a high gain the same deflection of the joystick will result in a higher speed. The optimal gain can be found by balancing the advantages of a relatively high gain (i.e. reduction of the time to reach target) against the advantages of a relatively low gain (i.e. reduction of final corrective movements when close to target) (Buck 1980). In the literature, little is known about the effect of gain on health-related parameters. The effect of gain on performance has mainly been measured in computer tasks. A U-shaped relationship has been found between gain and movement time, where the minimum movement time represented the optimum gain (Lin et al. 1992).

In the present study the aim was to determine the effect of joystick handle size (short vs. large handle) and (display-control) gain at two levels of required task precision on performance, wrist and forearm posture, upper extremity muscle activity, perceived exertion and perceived comfort in operators performing a simulated crane operation task.

## Methods

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### Subjects

Eight healthy male crane operators participated in the study (mean age 50 (SD 7) years, mean stature 1.85 (SD 0.08) m and mean body weight 98 (SD 17) kg). Prior to the experiment, the subjects completed an informed consent form. All subjects were right-hand dominant and none reported complaints in the back, neck, shoulders or

arms within the previous year. The operators had on average 26 (SD 8) years of experience in working with machines operated by levers or handheld joysticks. None of the operators had experience in working with joysticks with short handles. The study was approved by the Faculty's Ethical Committee.

## General procedure

The subjects were seated in a crane control unit, consisting of a chair with armrests and a joystick on the right-hand side, in front of a computer screen. Seat height, fore-aft position of the chair, height of the armrest, fore-aft position of the armrest and height of the joystick were also adjusted to the anthropometry of each subject, to ensure that subjects sat with knees at  $90^\circ$ , feet flat on the ground, lower arms horizontally on the armrests and upper arms vertical with relaxed shoulders (elbow angle  $90^\circ$ ). The top of the computer screen was placed at eye height in order to keep the neck in a neutral position. Both forearms were neutral with regard to pronation and supination and to ulnar and radial deviation at the wrists. The height of the joystick and fore-aft position of the subject were adjusted in such a way that the subject (in the posture described above) could hold the joystick with the right hand in the middle of the handle (as seen in Figure 1).



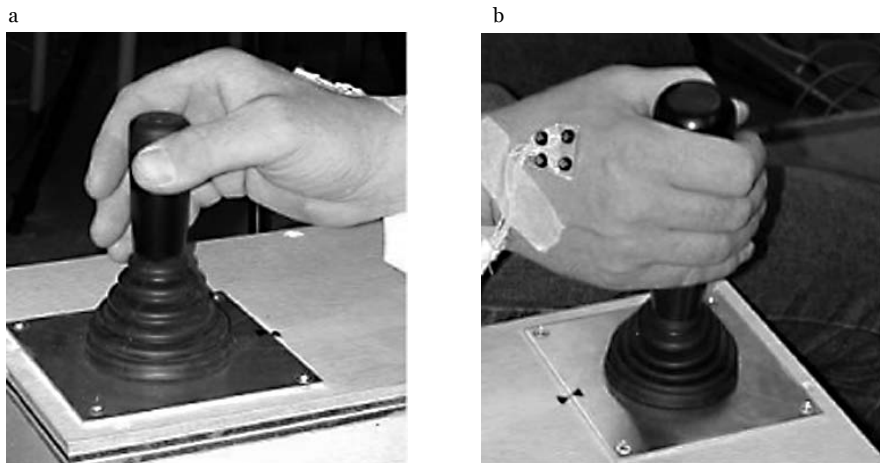
**Figure 1**

*Experimental arrangement; the subject was seated in a crane control unit in front of a computer screen supplied with a joystick on the right hand side.*

First, reference measurements for kinematics were performed. Position of the markers, placed at the hand, forearm and upper arm, were recorded in a standard reference posture, defined as the neutral posture in which the subject was sitting erect, keeping the upper arm vertical, the elbow in  $90^\circ$  flexion and the forearm horizontal, and neutral with regard to pronation and supination (i.e. with thumb pointing upward) and

with regard to ulnar-radial deviation and to palmar-dorsal flexion at the wrist. In the same reference posture, the subject's ranges of motion (ROM) for pronation and supination in the forearm, palmar and dorsal flexion in the wrist and ulnar and radial deviation in the wrist were measured (with movement directions as described in Kee and Karwowski 2001). The subject was asked to move from the reference posture towards the maximum joint angle in the prescribed direction and to maintain this maximum joint angle for 4 s. The ROM for each of the six directions was measured twice.

A joystick control system (Sakae type S50JCK-Yo-25R2G; maximum deflection  $30^\circ$  in each direction, actuating force 7 N; Sakae Tsushin Kogyo Co. Ltd., Kawasaki, Japan) was supplied with a short handle (length 70 mm, diameter 30 mm) and with a large handle (length 140 mm, diameter 40 mm) (Figure 2).



**Figure 2**

*Joystick controls: joystick with the short handle (a) and joystick with the large handle (b).*

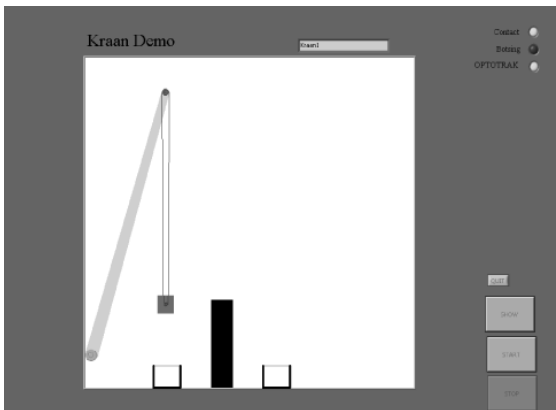
The joystick was used to perform a simulated crane operation task on a computer screen (programmed in LabVIEW; National Instruments Corporation, Austin, TX, USA). A mobile crane was shown in side view with a load attached to the hook of the winch (Figure 3). In front of the crane two containers were shown with an obstacle in between. By moving the joystick, the crane could be operated, which resulted in a movement of the load across the screen. Operation of the simulated crane was in accordance with the basic control arrangement and directions of movement of controls in mobile cranes as given in the ISO 7752 part 2 (ISO 1986). Moving the joystick to the left caused the boom of the crane to move upward and moving the joystick to the right



resulted in moving the boom downward. Moving the joystick forward caused the winch to lower the load, while a backward movement of the joystick resulted in the winch raising the load. Motions in the two axes could be operated simultaneously.

Subjects were instructed to move the load, by operating the boom and the winch of the crane, as often as possible from the left container into the right container and back again within 1 min. The subjects were specifically instructed to avoid errors, such as bumping the load into the side or the bottom of the container or bumping into the obstacle. When an error was made, the subject was notified by a beep. No further feedback on performance (i.e. number of times the load was put into a container or the number of errors) was given.

To become acquainted with the task, the subjects performed ten 1-min practice trials. A pilot study showed that these ten practice trials were required to obtain a stable performance at the task.



**Figure 3**

*Computer simulation of the crane task. In a side-view a mobile crane was shown with a load attached to the hook of the winch. In front of the crane two containers were shown with an obstacle in between.*

All subjects performed the task using both the joystick with the short handle and the one with the large handle. In addition, three (linear) display-control gains were tested: a low, middle and high gain. Each of the tested gains consisted of a combination of a gain for the boom and a gain for the winch. From a pilot study three gain combinations were selected that operators felt were realistic. Finally, subjects performed the task with two levels of required task precision determined by the size of the container; in the high precision condition the size of the container was  $\frac{4}{3}$  (12 mm x 12 mm) the size of the load, while in the low precision condition the container was  $\frac{5}{3}$  (15 mm x 15 mm) the size of the load. Four operators started with the joystick with the short handle,

while the other four started with the large handle. With each joystick the six experimental conditions (a combination of three levels of gain and two levels of required precision) were assigned in a randomised order. Each condition was performed twice.

## **Measurement and data analysis**

### ***Performance measures***

Displacement of the joystick resulted in a change of voltage in the built-in potentiometers. The output voltage was registered by the computer and resulted in a corresponding angular velocity of the boom or the velocity of the winch cable on the screen. The angle of the boom and the length of the winch cable determined the position of the load on the screen. The x- and y-coordinates of the centre of the load were recorded by the computer with a sampling frequency of 50 Hz. Two performance measures were calculated for each experimental trial of 1 min: 1) number of repetitions; 2) number of errors. The number of repetitions was expressed as the number of times that the load was moved from one container to the other, plus the fraction of the final trajectory that was covered before the end of the trial. The numbers of errors were recorded.

### ***Physical measures***

**Kinematics.** Small plastic plates, each with four LED markers, were attached to the following body segments at the subject's right hand side: upper arm (on the lateral side, just proximal of the lateral epicondyle); forearm (on the dorsal side, just proximal of the styloid processes); and hand (on the dorsal side, just proximal of the second and third head of the metacarpal bone) (as shown in Figure 1). These specific locations were selected to ensure that the movement between each plate and the segment during movement of the upper extremity would be minimal. The 3D marker positions were recorded using an opto-electronic system (Optotrak; Northern Digital Inc., Waterloo, Ontario, Canada) with one camera unit (containing three cameras) sampling at 50 Hz. For each segment three visible markers were used to calculate the joint angles.

3D kinematics were measured to calculate the angle of the hand with regard to the forearm and the angle of the forearm with regard to the upper arm during the experimental trials and during the ROM measurements, all expressed relative to the angles in the neutral standardised reference posture, aligned with the global axes system. To calculate the angles, a local coordinate system was determined for each segment (upper arm, forearm and hand) in the standardised reference posture, using the surface drawn through the three markers for each segment (hand, forearm and upper arm). Then, for all experimental trials and ROM measurements, the same local coordinate system was determined at each moment in time. Subsequently, the coordinate system in the

reference posture was used to calculate the orientation of the anatomical axes of each segment at each instant of time. Next, both elbow and wrist angles were determined by calculating the orientation of the coordinate system of the distal segment (i.e. forearm for elbow angles and hand for wrist angles), in the coordinate system of the proximal segment (i.e. upper arm for elbow angles and forearm for wrist angles). Finally, Euler angles were calculated for both the elbow joint and the wrist joint by decomposing the rotation in the following order:

- elbow joint: flexion and extension, pronation and supination and abduction and adduction (the pronation and supination angles were used in the analysis);
- wrist joint: palmar and dorsal flexion, ulnar and radial deviation and rotation (the former two rotations were used in the analysis).

The ROM for each joint angle (forearm pronation and supination, wrist palmar and dorsal flexion and wrist ulnar and radial deviation) was determined by finding the maximum value for a running average window of 1 s of the two attempts in each extreme joint position. The time series recorded for angles at wrist and elbow during the experimental trials were normalised to the individual ROM in the corresponding movement direction. Median joint angles were determined for each condition. Furthermore, normalised time series were divided into the percentage of time spent in joint angles of 50-100 % ROM and the percentage of time spent in joint angles of 75-100% of ROM during the task. Wrist and forearm angles of 0-50% ROM are considered to be acceptable joint postures; joint postures larger than 50% ROM are considered to be undesirable and if these postures have to be adopted for a long period of time, ergonomic interventions are recommended. Moreover, joint postures between 75-100% ROM are considered to be extreme joint postures, which should be avoided at all times.

**Muscle activity.** The electromyographic (EMG) signals of six muscles at the subject's right side were recorded:

- in the neck-shoulder: M. (Musculus) trapezius pars descendens (TRR);
- in the upper arm: M. biceps brachii (BB) and M. triceps brachii lateral caput (TBL);
- in the forearm: M. extensor carpi radialis (ECR), M. extensor carpi ulnaris (ECU) and M. flexor carpi radialis (FCR).

Bipolar Ag/AgCl (Blue Sensor) surface electrodes, with a gel-skin contact area of 1 cm<sup>2</sup>, were positioned according to Basmajian (1989) with an inter-electrode distance of 25 mm. A reference electrode was placed on the seventh spinous process. EMG signals were amplified 20 times (Porti-17<sup>TM</sup>, TMS, Enschede, The Netherlands; input impedance >10<sup>12</sup> Ω, Common Mode Rejection Ratio (CMRR) > 90 dB), band-pass

filtered (10-400 Hz) and A-D converted (22-bits) at a sample frequency of 1000 Hz. EMG signals were full-wave rectified and low-pass filtered at 10 Hz (fourth order Butterworth filter) using MATLAB (The MathWorks, Inc., Natick, MA, USA) (Clancy et al. 2002). The mean activity level was calculated.

### ***Subjective measures***

**Perceived exertion.** After the second attempt of each experimental condition, the rating of perceived exertion in the upper body (neck, shoulders, elbows, hands) was measured using a 10-point Borg scale (Borg 1982).

**Perceived comfort.** After finishing all experimental trials with one joystick, the crane operators were asked to rate their perceived comfort of that particular joystick on a 7-point scale with '1' indicating that the joystick was 'very uncomfortable' and '7' that the joystick was 'very comfortable' (Kuijt-Evers et al. 2005).

### ***Statistical analysis***

Repeated-measures ANOVA were used to determine the main effects of joystick (two levels), gain (three levels), precision (two levels) and attempt (two levels) on number of repetitions, number of errors, normalised pronation and supination, normalised ulnar and radial deviation, normalised palmar and dorsal flexion and muscle activity. The effects of joystick handle (two levels), gain (three levels) and precision (two levels) on perceived exertion were also evaluated using an ANOVA for repeated measures. One-way ANOVA and paired t-tests with Bonferroni corrections were used for post-hoc testing. The effect of joystick handle on perceived comfort was tested by a paired t-test. A *p*-value less than 0.05 was considered to be statistically significant.

## **Results**

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A main effect of attempt (first vs. second attempt) was not found. This indicates that the performance on the task was consistent and that a learning effect was not present. Therefore, the independent variable 'attempt' is not reported in the results below.

### **Performance measures**

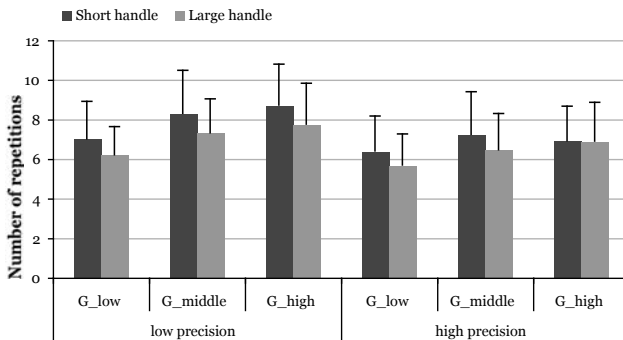
#### ***Number of repetitions***

Main effects were found for joystick handle size ( $p = 0.017$ ), (display-control) gain ( $p = 0.000$ ), and precision ( $p = 0.001$ ) on the number of repetitions. The use of the

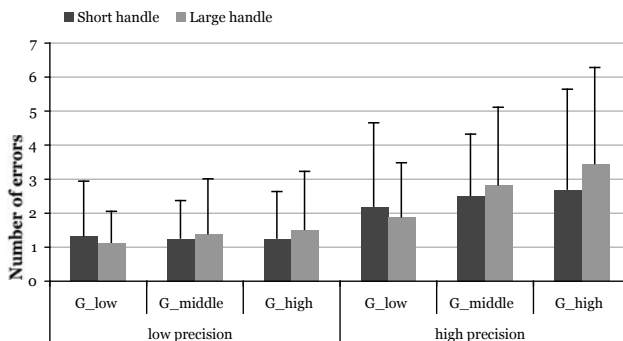
short handle led to significantly more repetitions compared with the large handle. At the lowest gain, significantly fewer repetitions were established compared with the higher gains (middle gain and high gain). Finally, in the high precision condition, the number of repetitions was significantly lower compared with the low precision condition (Figure 4). In addition, two significant interaction effects on number of repetitions were found, namely, joystick handle size \* precision ( $p = 0.027$ ) and gain \* precision ( $p = 0.017$ ), which indicated that at higher precision demands the differences between handles and gains became smaller.

**Number of errors**

The number of errors was only affected by the precision demands of the task ( $p = 0.009$ ). In the high precision condition, significantly more errors were made compared with the low precision condition (Figure 5). No other main or interaction effect on the number of errors was found.



**Figure 4**  
Mean and standard deviation (error bars) of the number of repetitions for the joystick with the short handle and the large handle at the three gain levels (G\_low, G\_middle, G\_high) and at low and high precision.



**Figure 5**  
Mean and standard deviation (error bars) of the number of errors for the joystick with the short handle and the large handle at the three gain levels (G\_low, G\_middle, G\_high) and at low and high precision.

## Physical measures

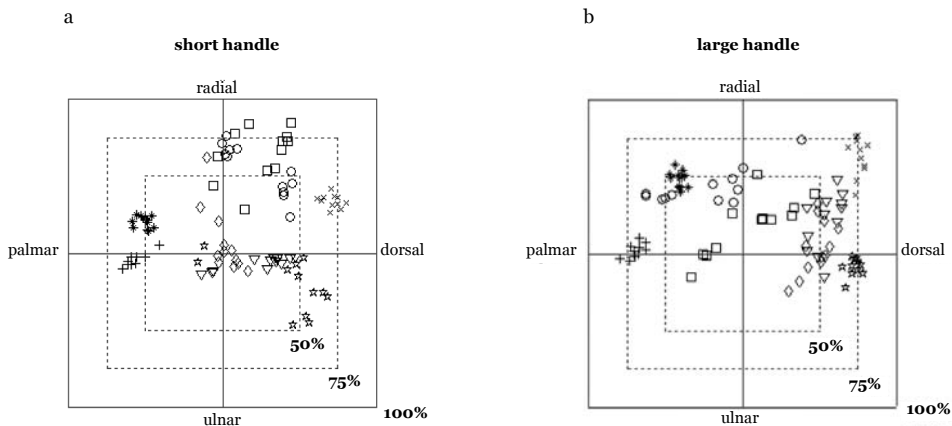
### Joint kinematics

Large inter-individual differences were found for the median posture in which the joystick was operated. Figure 6 shows the median posture in palmar and dorsal flexion and in ulnar and radial deviation for all subjects in all conditions for the joystick with the short handle and for the one with the large handle. Table 1 shows the mean and standard deviation of the absolute ROM in each movement direction.

**Table 1**

*The mean and standard deviation of the absolute range of motion values as measured in the standardised reference posture.*

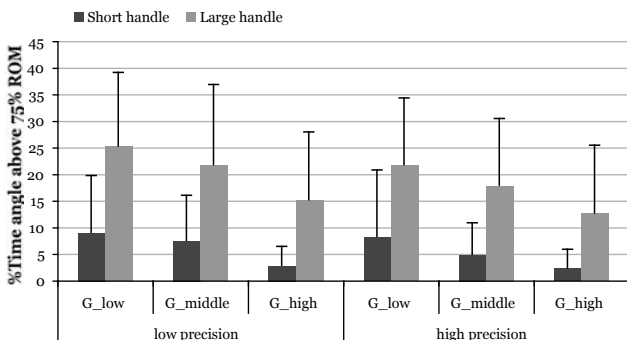
	Wrist joint angles [°]				Elbow joint angles [°]	
	Palmar flexion	Dorsal flexion	Ulnar deviation	Radial deviation	Pronation	Supination
Mean	63.86	38.23	22.27	14.78	57.51	67.59
SD	7.47	8.73	3.49	2.24	8.58	9.45



**Figure 6**

*Median wrist posture in which the joystick was operated. (a), values for the joystick with the short handle. (b), values for the joystick with the large handle. Each symbol represents a subject, for whom all conditions are presented.*

The percentage of time above 50% ROM in pronation and supination, ulnar-radial deviation and palmar-dorsal flexion was not significantly affected by joystick handle size, gain or precision. However, the percentage of time in palmar and dorsal flexion above 75% ROM was significantly affected by handle size ( $p = 0.029$ ) and gain ( $p = 0.013$ ). With the joystick with the large handle, a significantly higher percentage of time was spent in extreme palmar and dorsal flexion (Figure 7). A Bonferroni post-hoc test revealed that at the lowest gain more time was spent in extreme palmar and dorsal flexion compared with the highest gain. No effect of joystick handle size, gain or precision was found on percentage of time in extreme (>75% ROM) ulnar-radial deviation or pronation and supination. In fact, no time at all was spent in extreme (>75% ROM) pronation and supination. Interaction effects were not observed for extreme forearm or wrist postures.



**Figure 7**

Mean and standard deviation (error bars) of the percentage of time spent in palmar and dorsal flexion above 75% range of motion (ROM) for the joystick with the short handle and the large handle at the three gain levels ( $G_{low}$ ,  $G_{middle}$ ,  $G_{high}$ ) and at low and high precision.

### Upper extremity muscle activity

The mean muscle activity of the TRR, BB, TBL, ECR, ECU and FCR were not significantly affected by joystick handle size, gain or precision. Only for the ECU muscle a significant interaction was found for joystick and precision ( $p = 0.028$ ). The difference in ECU activity between the short and the large handle was larger at lower precision demands, with the joystick with the large handle demanding a higher ECU activity.

### Subjective measures

#### Perceived exertion on task

Joystick handle size and gain did not effect perceived exertion. Perceived exertion was significantly affected by precision ( $p = 0.008$ ) (low precision: mean exertion 2.6 (SD 0.2); high precision: mean exertion 3.6 (SD 0.4)). With high precision demands, the task was considered to be more demanding as compared with low precision demands.

### ***Perceived comfort of joysticks***

There was no significant effect of joystick handle size on perceived comfort (short handle: mean comfort 5.1 (SD 1.2); large handle: mean comfort 4.9 (SD 1.1)). Four participants gave higher comfort ratings to the short handle, two participants rated comfort of the large handle higher and two participants gave similar ratings to both joystick handles.

## **Discussion**

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The present study was designed to compare the use of joysticks with a large and a short handle at three levels of display-control gain and at two levels of required task precision with regard to performance, wrist and forearm posture, muscle activity, perceived exertion and perceived comfort. The results showed that performance improved when using the short handle and when working at a higher gain, while physical load decreased or remained the same. An increased level of task precision was associated with lower performance, but physical load was not affected.

All crane operators showed a higher productivity when using the joystick with the short handle. This is likely a result of the smaller ROM associated with moving the short handle, thus making the overall time to cover the movement span shorter and, therefore, increasing productivity (number of repetitions). It is remarkable that, even though none of the operators had ever worked with joysticks with short handles, they were immediately more productive when using this handle. A higher productivity with a short handle was also found in a field study by Attebrant et al. (1997). In one of three tasks tested, task duration was reduced when working with a short handle. For the other two tasks they found no effect of type of handle on performance. This result may be explained by the shorter task duration of these two tasks, which may have been too short to find an effect, or by the fact that quality of task performance may have been different for the two different handles. The latter was observed in a study by Asikainen and Harstela (1993), who found that with a short handle task duration remained the same but the accuracy of task performance increased. However, quality of task performance was not reported by Attebrant et al. (1997). In the present study the accuracy was kept at a relatively constant level by instructing the participants to avoid errors, such as bumping the load into the side or the bottom of the container or bumping into the obstacle, while at the same time striving for as many repetitions as possible. Effects of handle size and gain did not lead to differences in the number of errors and, therefore, the main productivity measure was reflected in the number of repetitions.

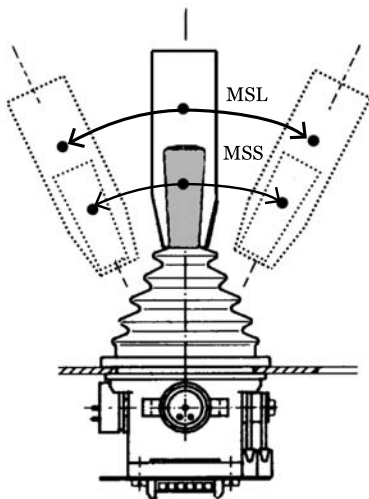


The differences in the ways the two joystick handles are operated can explain why a significantly longer time was spent in extreme wrist postures when the large handle was used. Because of the larger movement span, relatively large movements of the arm are required to control the large handle. In addition, because the joystick is held with the whole hand, the hand has to follow the required deflection of the joystick, for which relatively large wrist angles are needed. The joystick with the short handle requires less arm and wrist movements because of the shorter movement span and because the joystick is not continuously held with the whole hand, but mainly manipulated with the fingers. However, during joystick operation with the short handle, wrist postures were not neutral continuously. When the joystick was moved near the margins of its movement span, larger wrist angles and movement of the arm were observed, probably caused by the combination of the deflection angle and the length of the handle. Further optimisation of both joystick handle length and maximum deflection angle is recommended to achieve joystick operation with relatively neutral wrist positions and minimal arm movements. This would make it possible to use the armrests effectively and to unload the neck-shoulder muscles.

No effect of joystick handle size on muscle activity was found, and since the data showed no systematic trend, it is expected that differences would remain absent when a larger population would have been tested. This is in disagreement with the findings of Attebrant et al. (1997), who found that muscle activity increased when a conventional, large handle was used, as compared with a short handle. One of the reasons that no effect was found may be that the stiffness of the joysticks was kept constant in the present study. In the study of Attebrant et al. (1997), the stiffness of the conventional joystick was higher than the stiffness of the joystick with the small handle, resulting in a decrease in muscle activity when operating the joystick with the small handle. Also Lindbeck (1985; see Hansson 1990) reported higher muscle load associated with higher lever resistance. Another reason for finding no effect of joystick handle on muscle activity may be that there was not enough contrast in the ways that the short and the large handle were operated. The differences between the two joysticks tested in the study of Attebrant et al. (1997) seemed to be greater. Operation of their mini joystick did not necessitate movement of the arm (since their handle was shorter), whereas their conventional joystick required movement of the entire arm. Moreover, their conventional joystick was operated with the hand on top of the joystick and with the forearm pronated, whereas their mini joystick was operated with the forearm in a neutral position with regard to pronation and supination. It may also be that the expected effect of handle size on muscle activity was undone by the higher working speed observed when handling the short handle, which resulted in an increased productivity.

In the present study, muscle activity was also not affected by precision demands in the task, whereas some studies have shown that, as a result of higher precision demands, muscle activity increased (Milerad and Ericson 1994; Laursen et al. 1998; Visser et al. 2004). However, it has also been reported that, with higher precision demands, muscle activity can remain unchanged or even decrease, if the higher precision is compensated with a lower working speed (Birch et al. 2000a; 200b; Visser et al. 2004), as was the case in the present study.

For the joystick with the large handle in the simulated crane operation task in this study, the optimal gain was probably not reached, as performance still improved at the highest gain. Although not statistically significant, for the joystick with the short handle the middle gain in the high precision condition tended to be the optimal gain (Figure 4). Different optimal gains for the joysticks with the short and large handle are to be expected because, for the same deflection angle of both handles, the movement span in which precision needs to be regulated is smaller for the short handle (Figure 8). When the same movement span is covered by both handles, the deflection angle of the short handle is larger and thus a higher speed is generated (as is a higher gain). This would imply that the optimal gain to work precisely is lower for the short handle.



**Figure 8**  
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*Movement span of the large handle (MSL) is larger than the movement span of the short handle (MSS) while the maximum deflection angle of the joystick is the same.*

Optimal gain may not only be affected by joystick characteristics, such as handle size, but also by task characteristics. In the present study the simulated crane operation task consisted of two phases: 1) a movement phase with low precision demands; 2) a positioning phase in which precision was varied (high and low). Although it is expected that including the two phases in the simulated crane operation task increases generalisation, in practice the ratio between the two phases will not be equal to the ratio in the simulation and the ratio will vary considerably across tasks. A relatively high gain (small joystick movement, high speed) will be favourable for tasks with a relatively large movement phase, and a relatively low gain (large joystick movement, slow speed) will be favourable for tasks with a relatively large positioning phase. Therefore, determining the optimal gain for machine operations involving joystick control may be difficult and task specific. It may be advisable to design joystick control such that gain settings of the machine can be changed depending on the type of task that is performed.

Experienced crane operators had to perform a crane operation task simulated on a computer screen. It may be questionable whether the simulation was representative for real-life crane tasks. First, the sling of the winch was not programmed in the task, which excluded the effect of inertia of the load and external influences on the load, such as wind. Second, visual feedback of the task was given from a side view, whereas normally the task is viewed from behind (from the cabin). Finally, no whole body vibrations were present during performance of the simulated crane operation task, as opposed to the shocks and vibrations normally present in the crane cabin due to, for example, vibrations of the motor system, driving or working on uneven ground or to movements of the load. However, simulating the crane operation task allowed for a high level of standardisation and, thus, results are minimally biased by external influences. Moreover, experienced crane operators participated in the study. They were accustomed to the task they performed, to the way the joystick had to be controlled and to operating the joystick with the large handle. Because they were not used to working with a short handle, the task was practiced with this handle until a stable performance was reached. The crane operators emphasised that, in spite of the simplifications in the task, the crane task and crane control unit felt realistic. It may, therefore, be concluded that the results of the present study may be applicable to machines that are used for tasks similar to those tested in this study, i.e. mobile cranes, tower cranes and harbour cranes.

The results of the present study indicate that the joystick with the short handle is advisable for application in practice. The short handle may contribute to an increase in productivity and a more desirable physical load for the operator. Also, the potential for increased productivity may increase the opportunity to take micro breaks, which

have been shown to have a positive effect in reducing discomfort (McLean et al. 2001). Further optimisation of the joystick with the short handle is advisable because, in some cases, maximum deflection of the joystick was still associated with extreme wrist postures. By further shortening of handle length and/or limiting the angular deflection, joysticks can be designed that can be operated without extreme wrist postures, while the forearm is resting on an armrest. In this process, movement span of the joystick should be kept as large as possible and the optimal machine gain should be adjusted to this movement span. Even though the crane operators who took part in this study confirmed that task and crane unit felt very realistic, it seems advisable to test the joystick with the short handle in a field study on the specific machine in which it will be introduced. Besides joystick design, it can also be concluded from the present study that performance and physical load on the operator could be further optimised by adjusting gain settings to the task. It is recommended to optimise gain settings and joystick design simultaneously in relation to the task constraints observed in practice.

## **Acknowledgements**

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We would like to acknowledge the contributions of Het Zwarte Corps, Suraj Bachoe and Dennis Lindeboom, the advisory board of TNO Work and Employment and the technical support of Leon Schutte and Bert Coolen.





# Chapter *three*

.....  
***Sub-movement organisation  
and impedance are modulated  
in response to precision  
demands in 2D tracking***  
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*Maaïke A Huysmans, Marco JM Hoozemans, Allard J van der Beek,  
Michiel P de Looze, Jaap H van Dieën*  
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submitted

## Abstract

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*In the present study, we investigated how tracking performance, sub-movement organisation and endpoint impedance were affected by target size in a 2D tracking task performed with a pen on a digitiser tablet. 26 subjects took part in an experiment, in which either a small dot or a large dot was tracked, while it moved quasi-randomly across a computer screen, at a constant velocity of 2 cm/s. Subjects were instructed to keep the cursor as well as possible positioned within target by moving the pen across the digitiser tablet. Sub-movements were quantified according to the fluctuations in the speed profile, with the slope between the amplitude of the speed pulses and their duration defined as the speed pulse gain. Impedance was assessed by measuring pen pressure and muscle activity. The manipulation of precision level was successful, since mean distance to target and the standard deviation of this distance were significantly smaller with the small target than with the large target. With a small target, subjects trailed more behind the centre of target and used sub-movements with larger amplitudes and of shorter duration, resulting in higher tracking accuracy. This change in sub-movement organisation was accompanied by higher pen pressure, while at the same time co-contraction in the forearm was increased, which both indicate higher endpoint impedance. In conclusion, increased precision demands were accommodated by both a different organisation of sub-movements and higher endpoint impedance in a 2D tracking task performed with a pen on a digitiser tablet.*

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## Introduction

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Every day tasks such as threading a needle, buttoning up your shirt, writing, or working with a computer keyboard or mouse, require positional precision of the end-effectors, i.e. hands or input device. The positional precision of the end-effector is limited, because motor control is a noisy process in which force variability causes kinematic variability (Harris and Wolpert 1998). In order to meet precision requirements in the task, this kinematic variability of the system needs to be decreased or filtered. Since neuromotor noise is signal-dependent, i.e. it increases with the magnitude of the motor command, the noise can be decreased by reducing movement speed, thus allowing higher positional precision (Harris and Wolpert 1998). This is reflected in Fitts' law, which predicts longer movement times with increased task difficulty (Fitts 1954). However, reduction of movement velocity is not a feasible option in all motor tasks. In case high precision is required in a task with fixed movement times, kinematic variability can be filtered or suppressed by increasing (mechanical) impedance, which is the resistance to imposed motion (Burdet et al. 2001; Gribble et al. 2003). Limb impedance can be increased by increasing the level of co-contraction of the agonist and antagonist muscles (Selen et al. 2005). In addition, Van Galen and De Jong (1995) suggested that in case the end-effector is in contact with the environment, endpoint impedance can also be increased by increasing the friction between the end-effector and the substrate. In their studies, in which positional precision of a pen on the surface was required, axial pen pressure was shown to increase with increasing task complexity (Van den Heuvel et al. 1998). Both muscle activity levels and pen pressure can be considered as indirect measures of endpoint impedance. Direct measures of limb impedance are often obtained by perturbation experiments, in which damping and stiffness are estimated from the restoring force and amplitude of the displacement of the limb (Burdet et al. 2001; Selen et al. 2006a,b), but in these studies the end-effector is not in contact with the environment.

Increased impedance in response to increased precision demands seems paradoxical because of the signal-dependency of the neuromotor noise. Increased muscle activity would imply increased force variability, and thus kinematic variability. However, in a modeling study by Selen et al. (2005) it has been shown that increased co-contraction levels can lead to a decrease of movement variability, despite the increase in neuromotor noise. Moreover, experimental evidence for increased co-contraction levels with smaller targets has been found in time constrained aiming tasks (Laursen et al. 1998; Gribble et al. 2003; Osu et al. 2004; Visser et al. 2004; Sandfeld and Jensen 2005). Direct estimates of elbow impedance, as obtained by applying torque perturbations to the arm during aiming movements, further supported the idea that impedance in-

creased with smaller targets (Selen et al. 2006a). However, no effect was found of precision demands on pen pressure in graphical aiming (Van Galen and Van Huygevoort 2000). It may be that in aiming tasks, in which precision is only required in a small part of the task, friction with the environmental substrate is not used to increase impedance.

Tracking tasks may be more suitable than aiming tasks to explore impedance control with precision demands. In tracking, the degrees of freedom are more limited, since instantaneous movement velocity of the end-effector is constrained and positional accuracy is required continuously. The evidence for increased co-contraction with precision demands in tracking tasks is, however, scarce. Joint impedance during single joint elbow tracking, was found to be higher with higher precision demands (Selen et al. 2006b). However, in addition to higher impedance subjects changed the organisation of their sub-movements while tracking. Oscillations in the velocity profile are seen as numerous sub-movements of tracking. Sub-movements were quantified according to the fluctuations in the speed profile, with the slope between the amplitude of the speed pulses and their duration defined as the speed pulse gain. With smaller targets, sub-movement gain was found to be higher, as a result of larger sub-movement amplitudes with invariant duration, leading to a smaller kinematic variability. This most likely reflects faster error-corrections enabling the subject to stay closer to the centre of target. However, another movement strategy was found in a study by Selen et al. (2007a), when neuromotor noise was increased by inducing fatigue. With fatigue, subjects maintained their percentage time on target, despite the larger kinematic variability, by reducing the percentage of time that was spent behind the centre of target. This suggests use of a feed-forward strategy. Moving closer to the centre of target was most likely possible because the target trajectory was predictable. It was striking that during recovery, subjects stuck to this strategy. Since single-joint tracking tasks are strongly constrained it can be questioned whether the findings of these studies (Selen et al. 2006b, 2007a) can be generalised to less artificial tracking tasks, in which multiple degrees of freedom are available. In multi-directional tracking with a computer mouse, no effects of precision demands on muscle activity levels were found (Visser et al. 2004). However, it could be that kinematic variability was higher with changes in sub-movement organisation or that a more feed-forward strategy was applied with a smaller target, but these measures were not collected in that particular study. It is likely that alternative means, like changes in sub-movement organisation, are favoured since impedance control is likely to be energetically inefficient (Selen et al. 2007a). It is possible that in tracking tasks with more degrees of freedom, alternative strategies predominate and impedance control is not used.

Therefore, in the present study, we aimed to investigate how tracking performance, sub-movement organisation, impedance, as indicated by muscle activity levels and pen pressure, and perceived exertion were affected by target size in a 2D tracking task performed with a pen on a digitiser tablet. To prevent feed-forward strategies, in the present study an unpredictable target trajectory was used. We hypothesised that in this multi-directional tracking task impedance control was not used in response to increased precision demands and that changes in sub-movement organisation would predominate. More specifically, in line with Selen et al. (2006b), an increase of sub-movement gain was expected with increased precision demands.

## **Methods**

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### **Subjects**

26 subjects participated in the study, 4 males and 22 females (mean and standard deviation (SD) of age = 42.4 (SD = 10.7) years, body height = 173.1 (SD = 8.7) cm and body weight = 65.7 (SD = 7.5) kg). All subjects were right hand dominant and had normal or corrected to normal vision. None of the subjects reported symptoms in the neck, shoulders or arms in the previous year, or had a history of musculoskeletal disorders in the neck or upper extremities. Prior to participation, subjects signed an informed consent. The study was approved by the Medical Ethics Committee of the VU University Medical Centre.

### **Procedure**

Subjects performed a tracking task with a pen on a digitiser tablet while looking at a computer screen. Seat height and screen height were adjusted to the anthropometrics of the subject, to ensure that subjects sat with a knee angle of 90°, feet flat on the ground, upper arms vertical with relaxed shoulders and elbows flexed 90°. The forearm was supported by the arm rests of the chair. The tablet was placed in front of the subject, with the lower side at the edge of the table and the midline of the tablet corresponding to the midline of the subject. The top of the computer screen was placed at eye height (Figure 1).



**Figure 1**

*Picture of a subject in the experimental set-up.*

The task consisted of tracking a target dot, which moved quasi-randomly across part of the computer screen with a constant velocity of 20 mm/s. Subjects were instructed to keep the cursor (dot with a diameter 1.9 mm) positioned as well as possible within the target dot by moving the pen on the tablet. The pen movement corresponded one to one with the cursor movement on the screen. Subjects started with performing four practice trials of 1 min each with a target dot of 12.8 mm in diameter. Between the practice trials subjects rested for at least 3 min to prevent fatigue. Then subjects performed four tracking trials with a duration of 2 min, two trials with a small target dot (ST, diameter 6.4 mm), the high precision condition, and two trials with a large target (LT, diameter 19.2 mm), the low precision condition. A different target trajectory was used for the experimental trials and the practice trials, to prevent subjects from recognising the trajectory after several trials. For the experimental trials, the same trajectory was used, because the level of precision that can be achieved seems to be dependent on factors such as location and movement direction (Brouwer et al. 2001; Fernandez et al. 2004; Brouwer and Faris, 2007). Therefore, it appears that the level of difficulty cannot be fully standardised in random trajectories. Subjects were encouraged to explore different working techniques during the practice trials, for instance keeping their writing hand on the tablet or not, but were instructed to apply only their preferred technique during the experimental trials.

The order of the tracking trials was balanced across subjects, choosing one of the following orders: ST LT ST LT; ST LT LT ST; LT ST LT ST or LT ST ST LT. In between the trials at least 5 min of rest were taken to prevent fatigue.

## Data acquisition and analysis

### ***Tracking performance***

The tracking task was programmed in LabVIEW (National Instruments Corporation). The trajectory is presented in Figure 2. The target moved within a window of 0.16 m high and 0.22 m wide on the computer screen. Horizontal and vertical position of the pen on the tablet (WACOM Europe, Intuos A4, Model: GD-0912-R) were measured with a spatial accuracy of 0.25 mm, at a sample frequency of 100 Hz. After low-pass filtering the horizontal and vertical position of the pen (4<sup>th</sup> order Butterworth filter with a cut-off frequency of 12 Hz), the following measures were calculated using MATLAB (The MathWorks, Inc.):

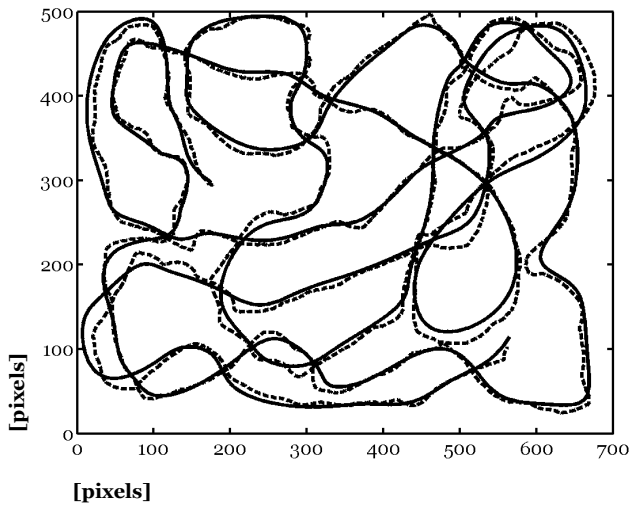
1. Percentage time on target (%TT), the percentage of the total number of samples for which the cursor was completely within the target.
2. Mean distance to target (MDT), mean distance between the centre of the target and the centre of the cursor.
3. Standard deviation of distance to target (SDDT), the standard deviation of the distance between the centre of the target and the centre of the cursor.
4. Percentage lag (%lag), the percentage of the total number of samples for which the centre of the cursor was behind the midline of target (the line through the centre of target perpendicular to the target movement direction).

### ***Sub-movement organisation***

The oscillations in the velocity profile are seen as numerous sub-movements of tracking. These sub-movements were analysed similarly to Roitman et al. (2004), Passalar et al. (2005) and Selen et al. (2006b). Before differentiating the position signals, these were low-pass filtered using a 5<sup>th</sup> order Butterworth filter with a cut-off frequency of 5 Hz. Then the following measures were calculated:

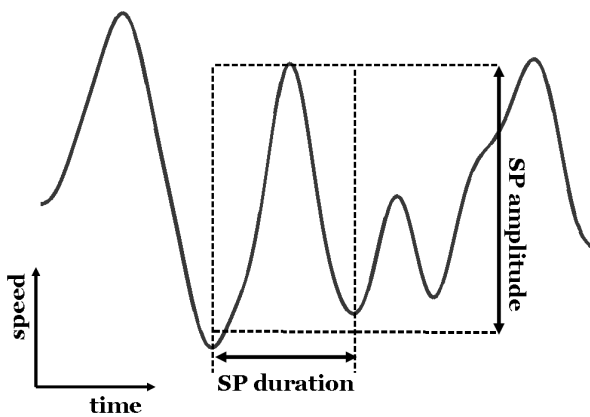
1. Mean duration of a speed pulse (SP duration), duration of a single speed pulse is the time between two successive local minima in the velocity profile (Figure 3).
2. Mean amplitude of a speed pulse (SP amplitude), the amplitude of a single speed pulse is the difference between a local maximum in the velocity profile and the average value of the two nearest minima (Figure 3).
3. Speed pulse gain (SP gain), the slope of the linear regression between SP durations and SP amplitudes.

The cut-off frequency of 5 Hz was chosen because at this frequency the median frequency of the velocity signal corresponded best with the calculated median SP duration. Speed pulses that were too short to be actual speed pulses were in this way excluded from the analysis.



**Figure 2**

Tracking trajectory of the experimental trials is shown with the solid line. An example of the position of the cursor is presented by the dashed line.



**Figure 3**

Section of the velocity profile, showing the speed pulses. The amplitude (SP amplitude) and duration (SP duration) of a single speed pulse are indicated.

### **Impedance**

As indicators of endpoint impedance we studied the level of pen pressure and upper extremity muscle activity.

Axial pressure of the pen on the tablet was measured at a tip activation pressure of 0.3 to 4 N, with a sensitivity of 0.0036 N, at a sample frequency of 100 Hz and the result was averaged over the 2-min trial.

Muscle activity was assessed of eight muscles in the neck and upper extremities, i.e.:

- M. extensor carpi radialis right (ECRr) and left side (ECrL);
- M. flexor carpi radialis right (FCRr) and left side (FCrL);
- M. deltoideus pars clavicularis right side (DCr);
- M. deltoideus pars acromialis right side (DAr);
- M. trapezius pars descendens right (TDr) and left side (TDl).

To measure muscle activity, bipolar Ag/AgCl surface electrodes (Blue Sensor, gel-skin contact area of 1 cm<sup>2</sup>), were positioned on the muscle bellies, according to the locations described by Basmajian (1989) with an inter-electrode distance of 25 mm, after shaving of hair, skin abrasion and cleaning the skin with alcohol. Location of the electrodes was confirmed by palpation of the muscle, while the subject performed a contraction against manual resistance, i.e. dorsal flexion and radial abduction of the wrist (ECRr and ECrL), palmar flexion and radial abduction of the wrist (FCRr and FCrL), anteflexion of the arm (DCr), abduction of the arm (DAr) and lifting the shoulders (TDr and TDl). A reference electrode was placed on the C7 spinous process. EMG signals were amplified 20 times (Porti-17™, TMS, Enschede, The Netherlands, input impedance > 10<sup>12</sup> Ω, CMRR > 90 dB), band-pass filtered (10-400Hz) and A-D converted (22-bits) at a sample rate of 1000 samples/s. EMG signals were full-wave rectified and low-pass filtered at 5 Hz (4<sup>th</sup> order Butterworth) using MATLAB (The MathWorks, Inc.). For the EMG signals the Amplitude Probability Distribution Function (APDF) was calculated. Subsequently, three percentiles were used to express the static level (P10), the median level (P50), and the peak level (P90) (Jonsson 1988).

### ***Perceived exertion***

After each tracking task, subjects were asked to rate their perceived mental exertion and their physical exertion in the upper body, using a 10-point Borg-scale (Borg 1982).

### ***Statistical analysis***

Two-way MANOVAs (target size (2) \* trial (2)) for repeated measures were used to test the effect of target size and trial on tracking performance (i.e. %TT, MDT, SDDT and %lag), sub-movement organisation (i.e. SP gain, SP amplitude and SP duration), impedance (pen pressure and muscle activity of the eight muscles), and on perceived exertion (i.e. perceived mental and physical exertion). Furthermore, the effects of target size (2) and time (2) on tracking performance, sub-movement organisation, impedance and perceived exertion variables separately were tested using univariate ANOVAs. *p*-values smaller than 0.05 were considered statistically significant.

## Results

### Tracking performance

MANOVA for repeated measures showed significant overall effects of target size and trial on tracking performance (Table 2). Also, the interaction effect of target size and trial on tracking performance was significant. Univariate ANOVA revealed that when tracking the smaller target, subjects spent a significantly less time with the cursor within target (i.e. %TT) than when tracking the larger target (Tables 1 and 2). Mean distance to the centre of target (MDT) and the standard deviation of this distance (SDDT) were both significantly smaller with the smaller target. The time that subjects spent behind the midline of the target (%lag) was significantly larger with the smaller target, 83 (SD = 6) % of the time, as opposed to 75 (SD = 10) % of the time with the larger target.

The univariate ANOVAs also showed that all tracking performance measures were significantly affected by trial. In the first trial %TT was significantly smaller and MDT, SDDT and %lag were significantly larger than in the second trial. Only for %TT a significant interaction effect of target size and trial was found. This interaction effect seemed to be caused by a ceiling effect. With the smaller target, %TT increased in the second trial, while with the larger target in the first trial the maximum score of 100% was already approached, leaving little room for improvement in the second trial.

**Table 1**

*Mean and standard deviations (SD) (N = 26) of tracking performance measures of tracking the small and the large target, the first and the second trial.*

Variable	Small target Mean (SD)		Large target Mean (SD)	
	Trial 1	Trial 2	Trial 1	Trial 2
%TT [%]	45.49 (9.30)	49.95 (9.36)	99.24 (1.14)	99.55 (0.54)
MDT [cm]	0.26 (0.03)	0.24 (0.03)	0.31 (0.05)	0.29 (0.04)
SDDT [cm]	0.13 (0.01)	0.12 (0.01)	0.16 (0.03)	0.16 (0.02)
%lag [%]	83.39 (5.11)	82.31 (7.79)	76.62 (9.90)	73.25 (10.42)



**Table 2**

Statistical results of the effects of target size and trial on tracking performance. Asterisk (\*) indicates statistically significant difference, i.e. the *p*-value is smaller than 0.05. Partial Eta Squared ( $\eta_p^2$ ) is given as a measure of effect size.

Target size			Trial			Target size x Trial			
MANOVA	$F_{(4,21)}$	<i>p</i> -value		$F_{(4,21)}$	<i>p</i> -value		$F_{(4,21)}$	<i>p</i> -value	
%TT, MDT, SDDT, %lag	238.298	0.000*		8.609	0.000*		6.756	0.001*	
Univariate ANOVAs	$F_{(1,24)}$	<i>p</i> -value	$\eta_p^2$	$F_{(1,24)}$	<i>p</i> -value	$\eta_p^2$	$F_{(1,24)}$	<i>p</i> -value	$\eta_p^2$
%TT	882.072	0.000*	0.974	26.421	0.000*	0.524	15.713	0.001*	0.396
MDT	66.402	0.000*	0.735	15.464	0.001*	0.392	0.071	0.792	0.003
SDDT	91.849	0.000*	0.793	7.233	0.013*	0.232	1.004	0.326	0.040
%lag	18.974	0.000*	0.431	7.037	0.014*	0.220	1.649	0.211	0.062

### Sub-movement organisation

Organisation of the sub-movements was significantly affected by target size and trial as shown with MANOVA for repeated measures (Table 4). The interaction effect of target size and trial was also found to be significant for sub-movement organisation.

Follow-up analyses with univariate ANOVAs showed that the SP gain was significantly larger with a smaller target, due to a significantly larger SP amplitude and a significantly shorter SP duration (Tables 3 and 4). This means that subjects made sub-movements with larger and faster speedpulses when tracking a smaller target. It was found that the SP gain was significantly lower in the second trial than in the first trial, due to a significantly smaller SP amplitude and a significantly longer SP duration. The interaction effect for target size and trial only reached significance for SP gain. With the small target, the SP gain decrease in the second trial was larger than with the large target. This seems to be in line with the interaction effect on %TT and is most likely also caused by a ceiling effect with more room for improvement with the small target in the second trial. In the sub-movement analysis, a 5<sup>th</sup> order Butterworth filter with a cut-off frequency of 5 Hz was chosen to avoid spurious speed pulse detection. However, for cut-off frequencies of 4 or 6 Hz similar statistical effects were found.

**Table 3**

Mean and standard deviations (SD) ( $N = 26$ ) of sub-movement organisation measures of tracking the small and the large target, the first and the second trial.

Variable	Small target Mean (SD)		Large target Mean (SD)	
	Trial 1	Trial 2	Trial 1	Trial 2
SP gain [cm/s <sup>2</sup> ]	5.215 (1.169)	4.666 (1.138)	3.906 (0.923)	3.811 (0.729)
SP amplitude [cm/s]	1.609 (0.282)	1.496 (0.274)	1.291 (0.285)	1.223 (0.258)
SP duration [s]	0.350 (0.032)	0.358 (0.029)	0.368 (0.025)	0.376 (0.029)

**Table 4**

Statistical results of the effects of target size and trial on sub-movement organisation.

Asterisk (\*) indicates statistically significant difference, i.e. the  $p$ -value is smaller than 0.05.

Partial Eta Squared ( $\eta_p^2$ ) is given as a measure of effect size.

MANOVA	Target size			Trial			Target size x Trial		
	$F_{(3,23)}$	$p$ -value		$F_{(3,23)}$	$p$ -value		$F_{(3,23)}$	$p$ -value	
SP gain, SP amplitude, SP duration	42.039	0.000*		20.740	0.000*		3.116	0.046*	
Univariate ANOVAs	$F_{(1,24)}$	$p$ -value	$\eta_p^2$	$F_{(1,24)}$	$p$ -value	$\eta_p^2$	$F_{(1,24)}$	$p$ -value	$\eta_p^2$
SP gain	61.972	0.000*	0.713	17.086	0.000*	0.406	7.593	0.011*	0.233
SP amplitude	125.155	0.000*	0.834	45.604	0.000*	0.646	2.061	0.163	0.076
SP duration	23.235	0.000*	0.482	14.360	0.001*	0.365	0.002	0.969	0.000

## Impedance

MANOVA for repeated measures showed a significant main effect of target size on impedance and the effect of trial was nearly significant ( $p = 0.052$ ) (Table 5). The interaction effect of target size and trial was not significant for impedance ( $p = 0.311$ ).

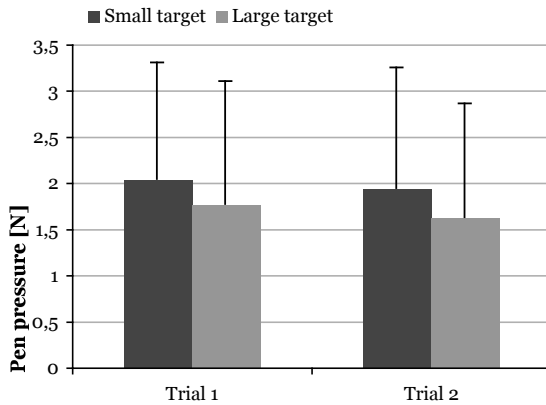
Univariate ANOVA showed that when tracking a small target, subjects produced significantly higher pen pressures than when tracking a large target (Table 5 and Figure 4). Pen pressure was also significantly affected by trial, in the second trial pen pressure was significantly lower than in the first trial. No interaction effect of target size and trial was found for pen pressure.

Muscle activity levels P10, P50 and P90 showed similar results. Therefore only the P50 results are reported. For a small target, muscle activity in the ECRr, ECRL, FCRr, FCRL, and DAr was significantly higher than for the large target. For the DCr, TDr and TDI no significant effects of target size were found (Table 5 and Figure 5). Only for the ECRL and FCRr a significant effect of trial was found, indicating that the muscle activity in the second trial was significantly lower than in the first trial. A significant interaction effect of target size and trial was found for ECRL, indicating that subjects lowered their muscle activity in the ECRL in the second trial as compared to the first trial for the small target, whereas the muscle activity in the second trial for the large target remained more or less the same as in the first trial.

**Table 5**

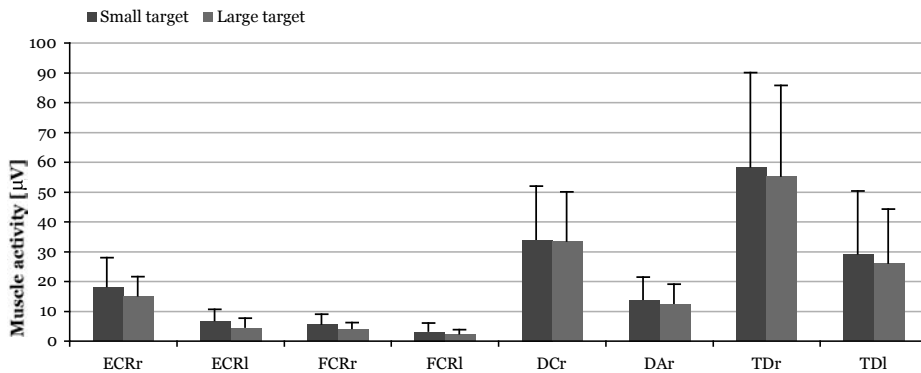
Statistical results of the effects of target size and trial on pen pressure and muscle activity. Asterisk (\*) indicates statistically significant difference, i.e. the p-value is smaller than 0.05. Partial Eta Squared ( $\eta_p^2$ ) is given as a measure of effect size.

MANOVA	Target size			Trial			Target size x Trial		
	F <sub>(9,16)</sub>	p-value		F <sub>(9,16)</sub>	p-value		F <sub>(9,16)</sub>	p-value	
Pen pressure and 8 muscles measured	4.732	0.003*		2.507	0.052		1.298	0.311	
Univariate ANOVAs	F <sub>(1,24)</sub>	p-value	$\eta_p^2$	F <sub>(1,24)</sub>	p-value	$\eta_p^2$	F <sub>(1,24)</sub>	p-value	$\eta_p^2$
Pen pressure	14.054	0.001*	0.360	6.055	0.021*	0.195	0.080	0.799	0.003
ECRr	21.943	0.000*	0.467	3.609	0.069	0.126	0.021	0.887	0.001
ECRL	17.461	0.000*	0.411	6.193	0.020*	0.199	8.350	0.008*	0.250
FCRr	14.795	0.001*	0.372	6.727	0.016*	0.212	0.300	0.589	0.012
FCRL	6.044	0.021*	0.195	3.359	0.079	0.118	0.343	0.563	0.014
DCr	0.189	0.668	0.007	3.839	0.061	0.133	0.153	0.699	0.006
DAr	4.276	0.049*	0.146	2.792	0.107	0.100	0.691	0.414	0.027
TDr	1.545	0.255	0.058	0.822	0.373	0.032	2.333	0.139	0.085
TDI	2.856	0.103	0.103	0.003	0.960	0.000	1.867	0.184	0.070



**Figure 4**

Mean and standard deviation (error bars) of the pen pressure is shown for both trials for the small and for the large target.

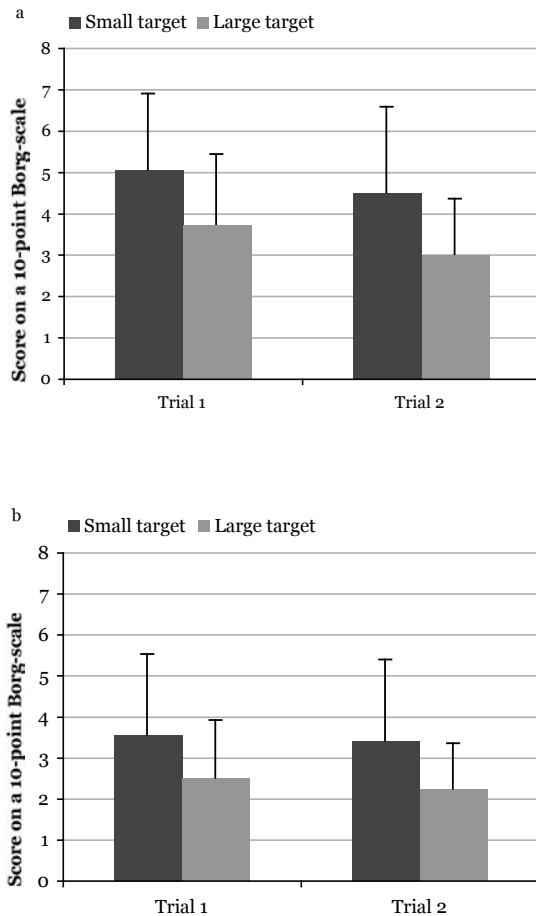


**Figure 5**

Muscle activity in the eight muscles; *M. extensor carpi radialis right (ECRr)* and left side (*ECRI*), *M. flexor carpi radialis right (FCRr)* and left side (*FCRI*), *M. deltoideus pars clavicularis right side (DCr)*, *M. deltoideus pars acromialis right side (DAr)*, *M. trapezius pars descendens right (TDr)* and left side (*TDI*). For the small and for the large target the mean and standard deviation (error bars) of both trials is given.

### Perceived exertion

MANOVA for repeated measures showed significant main effects of target size and trial on perceived exertion (Table 6). The interaction effect of target size and trial was not significant for perceived exertion. Follow-up analyses with univariate ANOVAs revealed that both perceived mental exertion and perceived physical exertion were rated significantly higher when tracking the smaller target (see Table 6 and Figure 6b) and in the first trial as compared to the second trial.



**Figure 6**  
*Mean and standard deviation (error bars) of a) perceived mental exertion and b) perceived physical exertion rated on a 10-point Borg-scale in the two trials for the small and for the large target.*

**Table 6**

Statistical results of the effects of target size and trial on perceived mental and physical exertion. Asterisk (\*) indicates statistically significant difference, i.e. the  $p$ -value is smaller than 0.05. Partial Eta Squared ( $\eta_p^2$ ) is given as a measure of effect size

	Target size			Trial			Target size x Trial		
MANOVA	F <sub>(2,21)</sub>	p-value		F <sub>(2,21)</sub>	p-value		F <sub>(2,21)</sub>	p-value	
Perceived mental and physical exertion	19.391	0.000*		4.557	0.023*		0.233	0.794	
Univariate ANOVAs	F <sub>(1,24)</sub>	p-value	$\eta_p^2$	F <sub>(1,24)</sub>	p-value	$\eta_p^2$	F <sub>(1,24)</sub>	p-value	$\eta_p^2$
Perceived mental exertion	28.369	0.000*	0.532	7.828	0.010*	0.238	0.138	0.713	0.005
Perceived physical exertion	17.892	0.000*	0.417	6.633	0.016*	0.210	0.381	0.542	0.015

## Discussion

In the present study, we aimed to investigate how tracking performance, sub-movement organisation and endpoint impedance were affected by target size when subjects performed a 2D tracking task with a pen on a digitiser tablet. In line with the hypothesis we found that with smaller targets subjects changed their sub-movement organisation towards larger sub-movements with shorter duration. In contrast with the hypothesis, we found that subjects also increased their pen pressure and muscle co-contraction, indicative of a higher impedance, when tracking a smaller target.

With the larger target, MDT was significantly larger than with the smaller target. This indicates that subjects used the space provided by the larger target effectively, and accepted a larger distance from the centre of target. This is in line with several earlier studies (Osu et al. 2004; Visser et al. 2004; Selen et al. 2006b) that all found a smaller distance to the middle of target when tracking smaller targets. However, the task appeared also to be performed in a different way. With a smaller target, subjects showed a smaller variation of MDT (SDDT), and spent more time behind the middle half of target (%lag).

In line with our hypothesis, SP gain was significantly larger with the small target as compared to the large target caused by larger SP amplitudes and shorter SP durations. Selen et al. (2006b) also found higher SP gain and SP amplitudes with smaller targets. However, they did not find changes in SP duration. Similarly, in the studies by Pasalar et al. (2005) and Roitman et al. (2004), different tracking velocities led to changes in SP gain and SP amplitude, but not to changes in SP duration. Hence, a constant SP duration was found in these previous studies, in contrast to the present study, which may have been due to the fact that these previous studies all used cyclic and thus predictable target trajectories. Another reason may be that in the study of Selen et al. (2006b), the difference in target sizes was not as large as in the present study. Finally, previous studies may have lacked statistical power, since small numbers of subjects were tested and the effects of precision demands on SP duration found in the present study were small. Intermittency of tracking, as evident with the detection of sub-movements, seems to be highly dependent on visual feedback allowing comparison of the target and cursor position. For example, depriving the subject of visual feedback (Miall et al. 1993) or increasing distance between visual feedback of the target and the cursor, i.e. separation of cues (Reed et al. 2003) led to smoother tracking. Our data thus underscore the importance of feedback modulation in response to changes in precision demands.

The question remains, whether subjects not only changed their movement kinematics, but also simultaneously increased endpoint impedance. In contrast to our hypothesis, we found higher pen pressure with higher precision demands, which implies higher endpoint impedance. Visser et al. (2004) did not find an effect of precision demands on grip forces on the computer mouse during tracking. However, grip forces on the mouse are not necessarily related to pressure of the mouse on the environmental substrate. In aiming tasks, pen pressure has been shown to be affected by time pressure and mental load, but not by precision demands (Van Galen and Van Huygevoort 2000). However, in graphical aiming, precision is only required at the endpoint. Consequently, impedance may be increased only in the last phase of the movement (Osu et al. 2004) and pen pressure averaged over the whole movement would not necessarily reveal such an effect.

Indications for higher impedance were also found in the fact that muscle activity in the antagonistic pair, ECR and FCR, in the dominant arm was increased with precision demands. This is in line with the higher impedance found with higher precision demands in single joint tracking (Selen et al. 2006b). Visser et al. (2004) found no indications for increased antagonistic co-contraction with high precision tracking. Only a tendency towards increased forearm flexor activity was found with high

precision, while forearm extensor activity was unaffected. While higher co-contraction will generally increase impedance, this may not necessarily be its primary aim. In the present study, the higher muscle activity could be related to the higher pen pressure, as in handwriting grip force in the pen and normal force to the surface appear to be correlated (Chau et al. 2006), and higher grip forces imply higher forearm muscle activity. Alternatively, the higher muscle activity could be related to the changes in the velocity profile with precision. The magnitude of the increase in muscle activity was modest, suggesting that energetic costs will be limited. Nevertheless, physical exertion was perceived significantly higher when tracking a smaller target. Although the relation between muscle activity and impedance is monotonous (Selen et al. 2006b), the effect of the small increase in muscle activity on impedance is unknown.

We found that muscle activity in the ECR and FCR in the non-dominant and non-active side of the body was also significantly increased with higher precision demands. The simultaneous activation of muscles on the contralateral side, which has no functional reason, may be the result of contralateral motor irradiation (Ridderikhoff et al. 2005). Contralateral irradiation of activation appears to be a graded phenomenon, related to the degree of target muscle activation (Zijdwind and Kernell 2001). This finding may suggest that motor unit excitation increases with higher precision demands in a rather unspecific way and implies that some caution is merited in interpreting the increase in muscle activity from a functional perspective. A general increased motor excitability with increased precision demands seems not likely, since muscle activity in the left and right trapezius muscle was not affected by precision demands. We could have expected trapezius muscle activity in this study to be significantly increased with precision demands. Since, trapezius muscle activity was found highly responsive to increases in mental demands (Waersted et al. 1996; Westgaard et al. 2006) and subjects perceived tracking a small target as significantly more mentally demanding than tracking a large target in the present study.

In the present study, subjects performed four practice trials, because this had been found to be enough to eliminate learning effects, and to get highly reliable performance outcomes, i.e. %TT, MDT and SDDT (Huysmans et al. 2008). Nevertheless, the fact that tracking performance and kinematics were affected by trial, indicates that learning continued during the experimental trials. The changes in performance with multiple trials pointed at a relative lowering of the demands with practice. Most of the effects found in the kinematics as well as in perceived exertion were in line with this, i.e. changes were opposite to those found with a smaller target size, which thus provides additional evidence of the adaptation of tracking kinematics to changes in (relative) precision demands. In contrast to previous studies (Thoroughman and Shadmehr



1999; Osu et al. 2002), muscle activity did not decrease over trials. Interestingly, most subjects had not recognised that they had tracked the same target trajectory for four times. This was most likely due to the fact that the target trajectory was rather long and complex and thus unpredictable for the subject and to the fact that only the instantaneous target position was visible on the screen. Even though it seems unlikely that the improvement in tracking performance in the second trial could be completely explained by target memorisation, it cannot be excluded that the improvement in performance was partly due to target memorisation.

The effects of precision demands on sub-movement organisation found in the present study with a 2D multi-joint tracking task are largely in line with the outcomes of the single joint tracking task by Selen et al. (2006b). In response to higher precision demands, subjects made sub-movements with higher SP gain, resulting in higher movement accuracy. At the same time they trailed more behind the centre of target. This seems to reflect a feedback mechanism for error correction. At the same time, the data supported the use of increased endpoint impedance. Tracking a smaller target resulted in significantly higher pen pressure, while at the same time co-contraction in the forearm was slightly but significantly larger. In the study of Selen et al. (2006b), the higher impedance with a smaller target was most likely due to an increase of co-contraction and possibly to some extent due to increased reflex gains, while the strategy of increasing impedance by friction with the substrate was not available.

In conclusion, higher precision demands led to a different organisation of sub-movements and to increased impedance in a 2D tracking task performed with a pen on a digitiser tablet, as was hypothesised. With a smaller target, subjects trailed more behind the centre of target and used corrective movements with larger speed pulses of shorter duration, resulting in higher tracking accuracy, i.e. a smaller distance between cursor and the centre of the target. This strategy was accompanied by higher pen pressure and increased co-contraction in the forearm, presumably to increase endpoint impedance.

## **Acknowledgements**

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We would like to thank Bert Coolen for the technical assistance and programming the tracking task.



# Chapter *four*

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## ***Fatigue effects on tracking performance and muscle activity***

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*Maaïke A Huysmans, Marco JM Hoozemans, Allard J van der Beek,  
Michiel P de Looze, Jaap H van Dieën*

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## Abstract

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*It has been suggested that fatigue affects proprioception and consequently movement accuracy, the effects of which may be counteracted by increased muscle activity. To determine the effects of fatigue on tracking performance and muscle activity in the M. extensor carpi radialis (ECR), 11 female participants performed a 2-min tracking task with a computer mouse, before and immediately after a fatiguing wrist extension protocol. Tracking performance was significantly affected by fatigue. Percentage time on target was significantly lower in the first half of the task after the fatigue protocol, but was unaffected in the latter half of the task. Mean distance to target and the standard deviation of the distance to target were both increased after the fatigue protocol. The changed performance was accompanied by higher peak EMG amplitudes in the ECR, whereas the static and the median EMG levels were not affected. The results of this study showed that subjects changed tracking performance when fatigued in order to meet the task instruction to stay on target. Contrary to our expectations, this did not lead to an overall higher muscle activity, but to a selective increase in peak muscle activity levels of the ECR.*

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## **Introduction**

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Long duration of computer work, and especially mouse use, is an important risk factor for hand-arm symptoms (Punnett et al. 1997; Tittiranonda et al. 1999; Gerr et al. 2004; Wahlstrom 2005; IJmker et al. 2007). In a recent review, indications were found for a dose-response relationship between hours of computer use and hand-arm symptoms (IJmker et al. 2007). Even though low forces are involved in mouse use, muscle fatigue building up through the workday is seen as a precursor (Sjogaard and Sogaard 1998) or even as a direct cause of hand-arm symptoms (Armstrong et al. 1993; Jensen et al. 1999; Westerblad et al. 2000). Indications of fatigue have indeed been found in forearm muscles after a few hours of computer work (Jensen et al. 1999; Luttmann et al. 2005).

The role of fatigue in the development of hand-arm symptoms was elaborated in a model formulated by Johansson et al. (2003). According to this model, metabolites released in the muscle as a result of fatigue and/or muscle pain may lead to a decrease in the proprioceptive acuity, i.e. the accuracy of perception of movement or position of body parts. This reduced proprioceptive acuity is likely to lead to reduced accuracy in performance. When high precision is required in a task, the increased noise in the system needs to be compensated. This can be done by increasing limb stiffness through a higher level of muscle activity (Van Galen and De Jong 1995; Gribble et al. 2003; Selen et al. 2005). With this solution, performance in a precision task can be maintained, at the expense of a higher workload of the muscles involved. This solution may, however, initiate a vicious cycle, as a higher muscle activity will accelerate fatigue development. Continuous duration of this vicious cycle may increase the risk of chronic hand-arm symptoms.

In several studies it has already been shown that proprioceptive acuity is indeed diminished as a result of muscle fatigue (Pedersen et al. 1999; Bjorklund et al. 2000). Whether muscle fatigue also leads to a decreased task performance in computer precision tasks, has to our knowledge not been investigated so far. The effect of fatigue on task performance has been investigated in precision tasks, other than computer tasks. Some studies have reported a significant decrease in shooting performance (Hoffman et al. 1992; Evans et al. 2003), hammering performance (Hammarskjold and Harms-Ringdahl 1992) and throwing performance (Forestier and Nougier 1998) due to fatigue, whereas others found no significant effect of fatigue in similar tasks (Cote et al. 2005; Huffenus et al. 2005). Cote et al. (2005) and Huffenus et al. (2005) showed that even though performance, in terms of trajectory of the hand during hammering and

throwing, was unchanged after the fatigue protocol, the underlying kinematics of the arm were affected.

Computer mouse use, such as aiming, selecting and dragging, often requires high precision. However, the effects of fatigue on performance in precision tasks such as throwing, shooting and hammering, cannot readily be generalised to mouse use. Most of these tasks are highly dynamic and require large movements of the entire arm, in contrast with the fine manipulative actions during mouse use. In addition, postures and support of the body and arm in these tasks are quite different from mouse use. In the present study, we aimed to investigate whether performance in a computer task and muscle activity in the *M. extensor carpi radialis* on the side operating a computer mouse, are affected by fatigue. We chose to use a tracking task, since it allows a continuous quantification of the accuracy achieved. Moreover, movement velocity is enforced in tracking and therefore can be considered to be more or less constant. This excludes reduction of movement velocity as a compensatory strategy to maintain accuracy, and facilitates interpretation of EMG data.

We hypothesised that subjects would either show decreased accuracy at the same or a higher muscular activity, or would maintain accuracy at the expense of higher muscle activity.

## Methods

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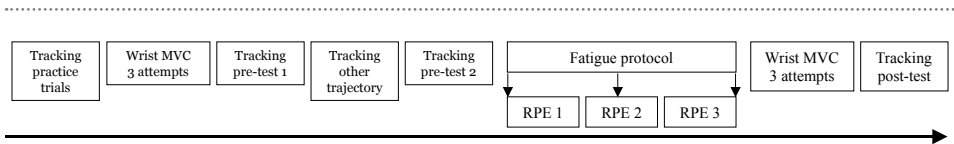
### Subjects

Eleven healthy females participated in the study (mean and standard deviation (SD) of age 24.3 (SD 2.7) years, body height 171.7 (SD 4.9) cm and body weight 65.7 (SD 7.5) kg). Subjects were recruited among university students. Prior to the experiment, the subjects filled out an informed consent. Subjects were included in the study if they reported an extensive experience in working with the computer mouse and if they were right hand dominant for mouse use (one subject was left-handed in writing and other tasks). Subjects were excluded from the study if they reported symptoms in the neck, shoulders or arms within the previous year or had a history of musculoskeletal disorders in the upper limb. The study was approved by the local Ethical Committee.

### General Procedure

Subjects were seated at a computer. Seat height and screen height were adjusted to the anthropometrics of the subject, to ensure that subjects sat with a knee angle of 90°, feet flat on the ground, vertical upper arms with relaxed shoulders and elbows flexed 90°, while two-thirds of the forearms rested horizontally on the working surface and the right hand rested on a computer mouse. The top of the computer screen was placed at eye height.

First, subjects practiced the tracking task, by performing four practice trials of 1 min each (Figure 1). The subjects were instructed to keep the cursor as much as possible within target by moving the computer mouse. Between the practice trials subjects rested for at least 3 min to prevent fatigue.

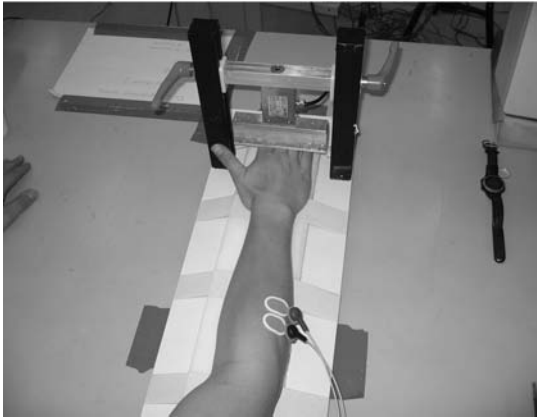


**Figure 1**

*Time course of the experimental protocol. Subjects started with the tracking practice trials, as shown on the left, and ended with the tracking post-test, as shown on the right.*

Subjects then sat at the wrist extension device (Figure 2), which was located next to the computer. Subjects rested their forearm on the board, in a pronated position, with their hand underneath a force transducer. The transducer was placed perpendicular to the hand 1 cm distal of the basis of the proximal phalanx of the index finger (Figure 2). The subjects conducted three maximal wrist extensions against the force transducer, with at least 1 min in between the attempts. The maximum force over the three attempts was defined as the maximum voluntary contraction (MVC), and was used to set a target force of 15% MVC for the fatigue task.

Subjects moved back to the computer, where they performed three tracking tasks of 2 min each, the first (pre-test 1) and last (pre-test 2) were used to determine the reliability of the performance measures. In between these two pre-tests, in which subjects followed the exact same tracking trajectory, another tracking trajectory was offered to prevent subjects from memorising the test trajectory. To prevent fatigue, at least 3 min of rest were taken between the three tasks.



**Figure 2**

*Wrist extension device in which the MVC of the wrist extension was measured and the fatigue protocol was conducted.*

After pre-test 2, the fatigue task was performed, consisting of an isometric wrist extension at 15% MVC for 10 min. Subjects were asked to assume the same position at the wrist extension device as during the maximum wrist extensions. The required force was shown with a line on a computer screen. Feedback of the actual force applied on the force transducer was also shown on the computer screen. The subjects were instructed to keep the plotted actual wrist extension force as well as possible positioned over the line of the required force. At the beginning of the fatigue protocol, after 5 min, and at the end of the fatigue protocol subjects were asked to rate their perceived exertion (RPE) (Figure 1). After the protocol was finished, subjects were asked again to perform three maximum wrist extensions, with a rest of a few seconds only between the attempts, to prevent recovery from the fatigue protocol.

After the maximum wrist extensions, subjects were asked to take place behind the computer as quickly as possible. As soon as they sat in the right position, with the hand situated on the computer mouse, the post-test of the tracking task was started (Figure 1), the trajectory of which was exactly the same as of pre-test1 and pre-test 2.

## **Measurements and data analysis**

### ***Tracking task***

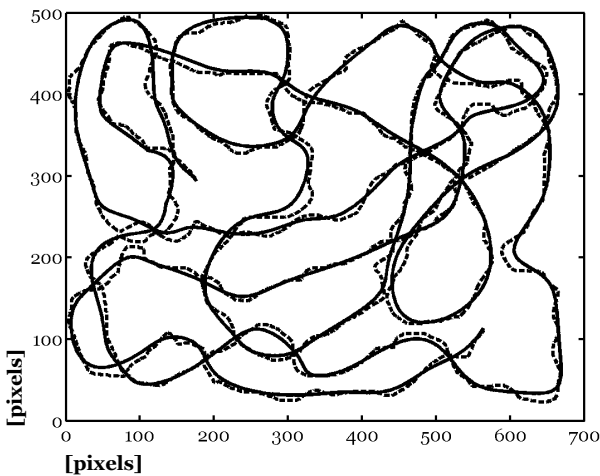
In the 2-min tracking tasks, subjects had to keep the cursor (a dot with a diameter of 6 pixels, 1.9 mm) positioned within a target dot (diameter 16 pixels, 5.1 mm), which moved quasi-randomly across part of the computer screen (window height = 500 pixels; window width = 700 pixels), at a constant velocity (20 mm/s). The screen resolution was 3.133 pixels per 1 mm. The cursor was controlled by a computer mouse, with an intermediate gain setting, i.e. 1:4 (mouse movement relative to cursor



movement). The tracking task was programmed in LabVIEW (National Instruments Corporation). The trajectory is presented in Figure 3. The horizontal and vertical position of both cursor and target were collected at 100 Hz.

The following performance measures were calculated using MATLAB (The MathWorks, Inc.), after calculating for each sample the distance between the centre of the target and the centre of the cursor:

1. %Time on target (%TT), the percentage of the total number of samples for which the cursor was completely within the target, i.e. the distance between target centre and cursor centre was equal to or smaller than 5 pixels.
2. Mean distance to target (MDT), mean distance between the centre of the target and the centre of the cursor (pixels).
3. Standard deviation of distance to target (SDDT), i.e. the standard deviation of the distance between the centre of the target and the centre of the cursor (pixels).



**Figure 3**

*Target path of the tracking task that subjects had to follow during pre-test 1 and 2 and the post-test is shown by the solid line. An example of the position of the cursor is presented by the dotted line.*

These three performance measures were calculated for both pre-tests and the post-test. To determine whether fatigue effects would diminish during the 2-min tracking task, performance measures for the first and second half of the tracking task were calculated separately.

### **Fatigue protocol**

Wrist extension force was obtained from the force transducer (AST-E, bandwidth = 200, DC = 19-28 V, 2 kN, +/- 5V) with a sample rate of 1000 Hz. The signal was low-pass filtered (4th order Butterworth filter) with a cut-off frequency of 5 Hz using MATLAB (The MathWorks, Inc.). For each second of the fatigue protocol the mean and standard deviation (as a measure of force variability) of the force were calculated.

### ***Perceived Exertion***

Subjects were asked to rate their perceived exertion in the upper body before, half way (at 5 min) and after the fatigue protocol, using a 10-point Borg-scale (Borg 1982).

### ***EMG***

Electromyographic signals of the M. extensor carpi radialis (ECR) were measured at the side operating the computer mouse in 8 of the 11 subjects. Bipolar Ag/AgCl (Blue Sensor) surface electrodes, with a gel-skin contact area of 1 cm<sup>2</sup>, were positioned on the muscle belly at one third of the line between the lateral elbow skin fold to mid wrist with the arm in pronated position (Basmajian 1989) with an inter-electrode distance of 25 mm, after standard skin preparation. The location of the electrodes was confirmed by palpation of the muscle during extension and radial abduction of the wrist against resistance. A reference electrode was placed on the C7 spinous process. EMG signals were amplified 20 times (Porti-17™, TMS, Enschede, The Netherlands, input impedance > 10<sup>12</sup> Ω, CMRR >90 dB), band-pass filtered (10-400Hz) and A-D converted (22-bits) at a sample rate of 1000 Hz. EMG signals were full-wave rectified and low-pass filtered at 5 Hz (4<sup>th</sup> order Butterworth) using MATLAB (The MathWorks, Inc.). For the EMG signals the Amplitude Probability Distribution Function (APDF) was calculated for the first and second minute of the task separately. The APDF analysis quantifies EMG activity levels by calculating the static level (P10), the median level (P50), and the peak level (P90), which indicate activity levels above which the muscle activity is found for 10%, 50% and 90% of the recording time, respectively (Jonsson 1988). In addition, the mean EMG amplitude and the mean power frequency (MPF) of the EMG signals of the ECR were calculated for each second of the fatigue protocol. MPF was derived from the raw EMG using a Fast Fourier Transformation (FFT). The data were separated in 1-s intervals, which were entered into the algorithm in order to establish a power density spectrum (using a Hanning window of 1000 samples with no overlap). The power density spectrum was used to determine the MPF for each 1-s interval. The MPF of the ECR was also calculated for each second of pre-test 2 and the post-test of the tracking task. Moreover, for the tracking tasks, also the overall mean value of the MPF was calculated.

### ***Statistical analysis***

Dependent variables were all normally distributed as tested with Kolmogorov-Smirnov tests. Therefore, only parametric statistics were used to test for significant differences. First, it was tested whether the fatigue protocol was effective. The effect of fatigue on the maximum voluntary wrist extension force was tested using a paired t-test. Differences between the three ratings of perceived exertion during the fatigue protocol were tested using an ANOVA for repeated measures. Bonferroni correction was used for post-hoc

testing. For each individual subject, the time courses of the mean extension force, standard deviation of the extension force, the MPF values of the ECR and the mean EMG amplitude of the ECR during the fatigue protocol were analysed, by fitting a regression line through the values spaced at 1-s intervals. For each regression line it was tested whether the slope deviated significantly from zero and a paired t-test was used, to test for differences between the mean value at the start of the fatigue protocol and at the end of the fatigue protocol as estimated from the regression line. The same analysis was performed on the MPF, to test whether fatigue developed during tracking. Again, a paired t-test was used, to test whether the overall mean MPF of the ECR of each subject during the pre-test and the post-test differed significantly from each other, as a result of fatigue.

The reliability of tracking performance measures was tested by calculating the intra class correlation (ICC) (Bland 1990) between the two pre-tests, and by MANOVA for repeated measures it was tested whether differences in tracking performance (%TT, MDT and SDDT) were present between pre-test 1 and pre-test 2. To test for the effect of the fatigue protocol on performance and muscle activity measures, differences between pre-test 2 and the post-test were calculated. A two-way MANOVA (fatigue (2) \* time (2)) for repeated measures was used to test the effect of fatigue and time in the tracking task on tracking performance measures: %TT, MDT and SDDT. Another two-way MANOVA (fatigue (2) \* time (2)) for repeated measures was used to test for the effect of fatigue and time on dependent measures P10, P50 and P90 of the ECR. Furthermore, the effects of fatigue (2) and time (2) on performance and muscle activity variables separately were tested using univariate ANOVAs. For all statistical tests, a significance level of 0.05 was used.

## **Results**

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### **Effectiveness of fatigue protocol**

We can conclude that the fatigue protocol was effective, as the MPF of the ECR dropped significantly during the fatigue protocol for each subject and the variability of the force as well as the perceived exertion increased significantly during the fatigue protocol. Moreover, the maximum wrist extension force of subjects was significantly lower after the fatigue protocol (Table 1).

**Table 1**

Mean and standard deviation (SD) of the MPF of the *M. extensor carpi radialis* (ECR), mean EMG-amplitude of the ECR, mean force, and standard deviation of the force at the start and the end of the fatigue protocol are given, as estimated from the regression line through the 1-s values.

Measure	Moment in fatigue protocol			Statistical test	
	Start	Middle	End	p - value	Individual regression lines
MPF of ECR [Hz]	85.90 (SD = 12.43)		77.43 (SD = 9.66)	$p = 0.004^*$	8 - (N = 8)
Mean EMG- amplitude of ECR [ $\mu$ V]	49.98 (SD = 12.01)		57.92 (SD = 10.31)	$p = 0.129$	5 -, 3 + (N = 8)
Mean Force [%MVC]	14.7 (SD = 0.28)		14.4 (SD = 0.44)	$p = 0.018^*$	8 -, 2=, 1 + (N = 11)
SD of force [%MVC]	0.19%MVC (SD = 0.10)		0.48 (SD = 0.23)	$p = 0.000^*$	10 +, 1 = (N = 11)
Wrist extension MVC [%MVC]	100 (SD = 0.0)		93.3 (SD = 8.1)	$p = 0.015^*$	
Perceived Exertion	3.4 (SD = 1.3)	5.8 (SD = 1.2)	7.1 (SD = 1.1)	<b>ANOVA and all post-hoc tests:</b> $p \leq 0.002^*$	

In addition, the number of subjects is given for whom the slope of the regression line was significantly positive (+), not significant (=) or significantly negative (-). Also, wrist extension MVC at the start and the end of the fatigue protocol is given. Significant effects are indicated with an asterisk \*.

## Reliability of the tracking task

The performance measures, %TT, MDT and SDDT had very good reliability with ICC values of 0.98, 0.99 and 0.92, respectively (Bland and Altman 1990). Moreover, no significant differences were found between pre-test 1 and pre-test 2 on performance measures %TT, MDT, SDDT as tested with MANOVA for repeated measures, and univariate ANOVAs.

## Effects of fatigue on tracking performance

MANOVA for repeated measures showed a significant effect of fatigue on performance measures when pre-test 2 was compared with the post-test. Post-hoc analysis using univariate ANOVA revealed that a significant interaction was present between fatigue and time for %TT (Table 2). In the first half of the tracking task after the fatigue protocol, %TT was lower, while in the second half of the task this difference disappeared

(Figure 4a). There was no main effect of fatigue on %TT, but %TT was significantly affected by time.

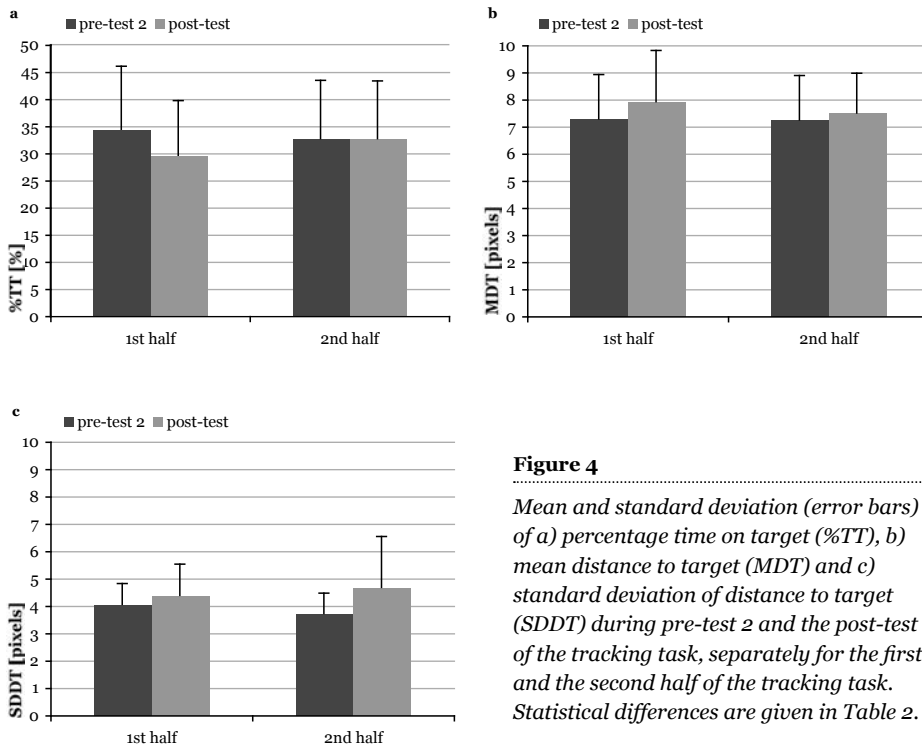
**Table 2**

*P-values of the multivariate analysis and univariate analyses of the effects of fatigue and time on the performance measures: percentage time on target (%TT), mean distance to target (MDT) and standard deviation of distance to target (SDDT) during tracking.*

	MANOVA	ANOVAs		
	%TT, MDT, SDDT	%TT	MDT	SDDT
<b>Fatigue</b>	$p = 0.032^*$	$p = 0.107$	$p = 0.011^*$	$p = 0.025^*$
<b>Time</b>	$p = 0.053$	$p = 0.008^*$	$p = 0.033^*$	$p = 0.945$
<b>Interaction</b>	$p = 0.155$	$p = 0.034^*$	$p = 0.187$	$p = 0.294$

Significant effects are indicated with an asterisk \*.

Univariate ANOVAs showed that MDT and SDDT were both significantly affected by fatigue, and higher after the fatigue protocol (Table 2). MDT was also significantly affected by time, with MDT somewhat lower in the second half of the task (Figure 4b). However, the interaction between fatigue and time was not significant. For SDDT there was no effect of time, and there was no significant interaction effect of fatigue and time. However, whereas MDT appeared to be lower in the second half of the task, there was a tendency for the SDDT to be higher in the latter half of the post-test (Figure 4c).



**Figure 4**  
 Mean and standard deviation (error bars) of a) percentage time on target (%TT), b) mean distance to target (MDT) and c) standard deviation of distance to target (SDDT) during pre-test 2 and the post-test of the tracking task, separately for the first and the second half of the tracking task. Statistical differences are given in Table 2.

### Effects of fatigue on EMG amplitude and MPF during tracking

MANOVA showed no significant overall effects of fatigue and time for P10, P50 and P90 of the EMG signals of the ECR. Moreover, there was no significant interaction effect for fatigue and time (Table 3). Univariate analyses revealed that only the P90 in the ECR was significantly higher after the fatigue protocol (Table 4 and Figure 5).

**Table 3**

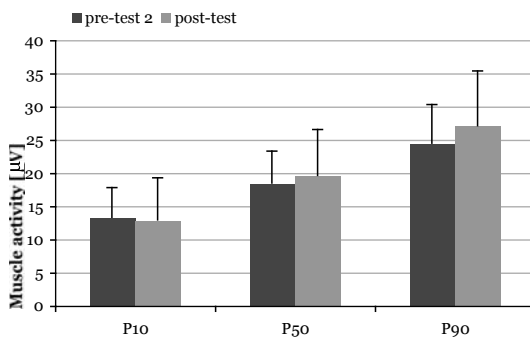
*P-values of the multivariate analysis and univariate analyses of the effects of fatigue and time on the P10, P50 and P90 of the APDF of the M. extensor carpi radialis (ECR) during tracking. Significant effects are indicated with an asterisk \*.*

	MANOVA	ANOVAs		
	P10, P50, P90	P10	P50	P90
<b>Fatigue</b>	<i>p</i> = 0.098	<i>p</i> = 0.902	<i>p</i> = 0.313	<i>p</i> = 0.046*
<b>Time</b>	<i>p</i> = 0.620	<i>p</i> = 0.162	<i>p</i> = 0.188	<i>p</i> = 0.234
<b>Interaction</b>	<i>p</i> = 0.728	<i>p</i> = 0.331	<i>p</i> = 0.220	<i>p</i> = 0.325

**Table 4**

Mean absolute difference and standard deviation (SD) between the two pre-tests and pre-test 2 and post-test on performance measures: percentage time on target (%TT), mean distance to target (MDT) and standard deviation of the distance to target (SDDT).

	%TT	MDT	SDDT
<b>Pre-test 1 – Pre-test 2</b>	1.94 (SD = 1.99)	0.20 (SD = 0.17)	0.22 (SD = 0.22)
<b>Pre-test 2 – Post-test</b>	4.33 (SD = 3.43)	0.49 (SD = 0.42)	0.73 (SD = 0.96)



**Figure 5**

Mean and standard deviation (error bars) of the P10, P50 and P90 of the APDF of the M. extensor carpi radialis (ECR) for pre-test 2 and the post-test. Statistical differences are given in Table 3.

There was no effect of fatigue on the frequency content of the EMG of the ECR during the tracking tasks. A paired t-test showed that the overall mean MPF during pre-test 2 of the tracking task was not significantly different from the overall mean MPF during the post-test. Moreover, for none of the subjects the regression line through the 1-s MPF values of the ECR, during either pre-test 2 or post-test, significantly deviated from zero.

## Discussion

### Summary of results

The purpose of this study was to investigate the effect of fatigue on tracking performance and on muscle activity levels of the ECR. The fatigue protocol was effective and tracking performance was significantly affected by the fatigue protocol. First, %TT was significantly lower in the first half of the post-test, but was unaffected in the latter half. Second, MDT and SDDT both increased due to fatigue. A tendency was found for MDT

to be increased mainly in the first half of the post-test, whereas SDDT appeared to be increased mainly in the second half. The changed performance on the tracking task after the fatigue protocol was accompanied by a higher peak EMG amplitude (P90) in the ECR, whereas the static level (P10) and median level (P50) of the ECR were not affected.

### **Fatigue protocol**

Since the fatigue protocol appeared to be effective, it is likely that proprioception was diminished. Bjorklund et al. (2000) and Pedersen et al. (1999) reported a reduced position and movement sense in the shoulder after a fatigue protocol of comparable or even lower intensity and duration. In addition, we found that variability of the force increased during the fatigue protocol, which has also been reported by other authors (Hunter and Enoka 2003; Nielsen 2004), probably due to recruitment of larger motor units (Jensen et al. 2000; Holtermann and Roeleveld 2006). Though reduced steadiness of force is not explicitly mentioned in the Johansson Model (Johansson et al. 2003), it adds to the difficulty of achieving high accuracy when fatigued.

### **Effect on performance measures**

In accordance with the Johansson Model (Johansson et al. 2003), we hypothesised that due to fatigue, task performance would either decrease or be unchanged at the expense of a higher muscular load. We found that performance was affected by fatigue. In the first half of the post-test, tracking accuracy (%TT) was decreased, but %TT was unaffected in the second half of the post-test. Moreover, MDT and SDDT were significantly higher after the fatigue protocol, illustrating the increased difficulty to achieve the required accuracy. In the literature, both a decreased and an unchanged performance have been reported due to fatigue in precision tasks, other than computer tasks. This apparent contradiction may be explained by differences in sensitivity of the outcome measures used in these studies. Hoffman et al. (1992) reported that, if they had only used the number of hits (a discrete performance measure which was in line with their task instructions), no effect would have been found, whereas other, continuous, measures of accuracy in shooting were affected by fatigue. In the present study, MDT and SDDT also appear more sensitive to fatigue than %TT.

The interaction effect between fatigue and time found for %TT, appears to imply that recovery took place during the task, since %TT was lower in the first half of the post-test, but not in the second half. Evans et al. (2003) also reported decreased shooting performance immediately after a fatiguing protocol, while most of the performance



measures were back to baseline values within 5 min. However, in the present study a main effect of fatigue was found for MDT and SDDT. This suggests that subjects did not recover from fatigue, but changed the way they performed the task in order to meet the task requirement to stay on target. In former studies it has also been shown that the decline in accuracy of movement control as a result of fatigue or diminished proprioception could be compensated to a large extent under the guidance of visual feedback (Sainburg et al. 1993; Vuillerme et al. 2001; Romero et al. 2003).

A higher variability of the distance to target indicates that larger corrective movements may have been made. Larger corrective movements would involve higher accelerations of the hand in the fatigued state, which suggests that task requirements were met at the expense of a higher muscular effort.

### **Effect on ECR EMG**

The Johansson Model (Johansson et al. 2003) predicts that a decline in the ability to work accurately, due to fatigue, may call for an increased stability, which can be achieved through increased co-contraction (Van Galen and De Jong 1995; Gribble et al. 2003; Selen et al. 2005). Increased co-contraction would imply a higher overall muscle activity in the forearm muscles and therefore also in the ECR. However, in the present study, only the P90 of the ECR was significantly increased after the fatigue protocol, whereas the P10 and P50 were unaffected. A higher muscular effort in order to increase limb stability does not appear a plausible explanation for the increased P90 level, since this would likely have affected the P10 and P50 also.

An increase in EMG amplitude could also be caused by a decrease in frequency content of the EMG signals, which is often found with fatigue (Hägg 1992). However, since the MPF of the EMG signals during tracking was the same before as after the fatigue protocol this explanation seems not likely. Moreover, Iridiastadi (2006) reported that fatigue-related decreases in MPF not only resulted in an increase of the P90, but also of the P10 and P50 values, with the strongest effect on the P50 value. For these reasons, it is not likely that the sole increase in the P90 level could be ascribed to a decrease in MPF.

The increased P90 is most likely a selective adaptation, related to the higher variability of the distance to target (SDDT). As stated above, the higher SDDT implies higher accelerations of the hand, possibly related to an increase in scaling of corrective movements. Feedback correction may offer a more efficient strategy to compensate for fatigue effects than co-contraction, which is more energy consuming (Selen et al. 2006b).

## Limitations

Unfortunately, the actual corrective movements could not be quantified with our data, due to the insufficient spatial resolution of the measurements. In future studies the use of a higher resolution is recommended in order to be able to analyse the kinematics in greater detail, such as to study the fluency of movement, defined as the number of zero-crossings of the acceleration curve (Smeulders et al. 2001; 2002), and the amplitude and duration scaling of sub-movements, as reported for instance by Roitman et al. (2004) and Selen et al. (2006b).

Scaling the size of corrective movements may be the dominant mechanism in a tracking task such as the present one, in which performance is highly dependent upon visual feedback, because of the unpredictable nature of the target movement. It remains to be tested whether in other precision tasks, especially tasks that are more under feedforward control, co-contraction becomes a more prominent mechanism to compensate for fatigue effects on precision.

Although the fatigue protocol in general was effective, the level of fatigue may have varied between subjects. The time to exhaustion at the contraction level used varies considerably between subjects (Nielsen 2004). This means that the level of fatigue may have been substantially different between subjects. On the one hand, this may have affected the statistical power of this study negatively. On the other hand, consistent effects on performance were found, suggesting that such effects can be expected to occur at different fatigue levels.

The fatigue protocol was relatively demanding, when compared to, for example, computer tasks, to limit the duration of the test protocol. It remains to be tested whether fatigue as a result of long duration of computer use also leads to a changed performance, and as a result of this, to higher peak EMG-amplitudes, as has been found in the present study.

In order to be able to address differences in tracking performance to the intervention, i.e. the fatigue protocol, it is important that tracking performance is a reliable measure. The intra class correlation (ICC) (Bland 1990) of the performance measures showed a high reliability of the task. However, ICC is highly driven by *between*-subject variability and it is possible that a high ICC is found with substantial *within*-subject variability. Table 4 shows that the effect of fatigue is about twice as large as the between-trial variability, as calculated by the absolute difference in performance measures between the two pre-tests. Even though effect sizes are rather small, tracking performance thus appears sensitive to fatigue.

The present results cannot readily be generalised to normal computer work, since the computer task used in the present study is rather artificial in comparison to normal computer work, i.e. both the level of precision demands and working speed were standardised. During normal computer work it is likely that subjects compensate for fatigue by reducing their work speed, as has been found in response to higher precision demands when performing aiming tasks (Laursen et al. 1998; Birch et al. 2000b; Fernandez and Bootsma 2004). However, stressful conditions, like time pressure, may force employees into larger or more corrective movements to maintain productivity. In future studies, it would be interesting to investigate whether subjects with hand-arm symptoms show similar changes in tracking performance as shown in the present study.

## **Conclusions**

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In support of the Johansson Model (Johansson et al. 2003), we found that task performance was affected by fatigue. Subjects were able to maintain performance according to task instructions in the second minute of the post-test, but they were further from the target and the variability of distance to target was higher. This indicates that subjects adopted a strategy with larger corrective movements. This did not coincide with a higher overall muscle activity of the ECR as expected. However, peak activity of the ECR was increased, probably related to higher accelerations of the hand due to larger corrective movements. This increased peak activity may accelerate fatigue development and may still close the vicious cycle as proposed in the Johansson Model (Johansson et al. 2003).

## **Acknowledgements**

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We thank Merle Blok and Mariëlle Eversdijk for their contribution to the measurements and Bert Coolen for his technical support.



# Chapter *five*

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***Position sense acuity and tracking performance in subjects with non-specific neck and upper extremity pain and healthy controls***

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*Maike A Huysmans, Marco JM Hoozemans, Allard J van der Beek, Michiel P de Looze, Jaap H van Dieën*

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Clinical Neurophysiology, conditionally accepted

## Abstract

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*In the present study we aimed to investigate whether neck and upper extremity pain affects position sense acuity and performance, organisation of sub-movements, pen pressure and muscle activity in a tracking task. 23 subjects with neck and upper extremity pain and 26 healthy controls participated in the study. Position sense acuity was measured while subjects pointed at targets, without vision of their arm and hand. In the tracking task, subjects were instructed to keep a cursor as well as possible positioned within a target dot, by moving a pen on a tablet while the target moved with a constant velocity across the computer screen. Position sense acuity and tracking precision were significantly impaired in subjects with neck and upper extremity pain as compared to healthy controls. No differences between groups were found in sub-movement organisation, pen pressure and muscle activity during tracking. The results suggest that subjects with neck and upper extremity pain are limited in performing precision tasks, but do not support the notion that this problem is compensated by increased effort which might contribute to perpetuation of pain. Knowledge on position sense acuity and performance in precision tasks in subjects with neck and upper extremity pain as compared to controls is needed to get more insight in onset mechanisms of the pain.*

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## **Introduction**

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Despite an extensive body of literature, the pathophysiology of non-specific neck and upper extremity pain, also referred to as repetitive strain injury (RSI), is poorly understood (Visser and Van Dieen 2006). It has been suggested that impaired proprioception plays an important role in the onset and perpetuation of RSI (Johansson et al. 2003). Proprioception is the perception of movement or position of body parts in relation to each other. Its quality is mostly assessed by measuring the positioning accuracy of the limb, while vision of the limb is blocked. In subjects with similar symptoms, such as whiplash associated disorders, subjects with chronic neck pain or subjects with epicondylitis, diminished position sense acuity in neck, shoulder or elbow was found (Revel et al. 1991; Feipel et al. 2006; Sandlund et al. 2006).

Proprioceptive information is important for motor control (Sainburg et al. 1995). If the quality of this information is diminished, precise movements will be more difficult to perform. When precision demands in a task increase, healthy subjects increase the positional accuracy of the end-effector, i.e. their hand or handheld tool, by applying two different strategies. First, they increase endpoint impedance, which is the resistance of the endpoint against imposed motion (Burdet et al. 2001; Gribble et al. 2003), through increasing muscular co-activation and increasing friction between end-effector and the substrate, e.g. increasing pen pressure (Selen et al. 2006b; Huysmans et al. submitted). Second, subjects change performance and movement kinematics. When tracking a small target for example, they trail more behind the centre of target and make larger corrective movements (sub-movements) of shorter duration than when tracking a large target (Selen et al. 2006b; Huysmans et al. submitted). If proprioception would indeed be impaired in subjects with neck and upper extremity pain and, as a result of this, these subjects would have more difficulty to perform precise movements, the question arises whether they compensate similarly for their impaired precision as healthy subjects do in response to increased task precision demands.

In the present study, we aimed to investigate if proprioception is impaired in subjects with neck and upper extremity pain, by testing position sense acuity in a 2D pointing task without visual information of the position of the arm and hand. Moreover, we investigated in a 2D tracking task for two target sizes whether tracking performance, organisation of sub-movements, endpoint impedance, as assessed by pen pressure and muscle activity, and perceived exertion were different for subjects with neck and upper extremity pain and healthy controls. Finally, we investigated whether performance in the position sense acuity task and performance in the tracking task were related.

## Methods

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### Subjects

23 Subjects with pain in neck and upper extremity and 26 healthy controls participated in the study. Subjects were recruited with advertisements in a local newspaper and among employees of the university. All subjects were right hand dominant, and had normal or corrected to normal vision. Subjects were excluded from the study, if they had experienced neurological problems.

Subjects with pain all had pain in the neck or right shoulder. Twelve of them also experienced pain in the right arm, wrist and/or hand, and 13 of them also had pain in the left shoulder, arm, wrist and/or hand. They reported to have experienced this pain for an average of 3.7 years (SD = 2.8, range = 0.5 to 10), and for at least four weeks in the last three months, four days in the last week and at the day of measurement. On a 11-point numerical scale ranging from 0 “no pain” to 10 “worst pain ever” (Von Korff et al. 1992) subjects scored their worst pain in the last three months with a mean of 6.4 (SD = 1.9, range = 3 to 10), their average pain in the last three months with 5.0 (SD = 1.9, range = 2 to 9), and their pain at the day of measurement with 3.7 (SD = 2.0, range = 1 to 10). Disability of the subjects was measured with the Dutch version of the 30-item Disabilities of the Arm, Shoulder and Hand (DASH, <http://www.dash.iwh.on.ca>) questionnaire, resulting in a score between 0 “no disability” and 100 “extreme disability”. Subjects with neck and upper extremity pain scored on average 23.7 (SD = 8.7). Subjects were all working in spite of their pain when participating in the experiment.

The healthy controls had no history of pain in the neck and upper extremities and no other musculoskeletal problems in the month prior to the day of measurement. They experienced no disabilities due to musculoskeletal problems.

For demographic subject characteristics see Table 1. Prior to participation subjects signed an informed consent. The study was approved by the Medical Ethical Committee of the VU University Medical Centre.



**Table 1**

General subject information for the subjects with pain and the healthy controls is given. *T*-test and Chi-square results of the statistical differences between both subject groups.

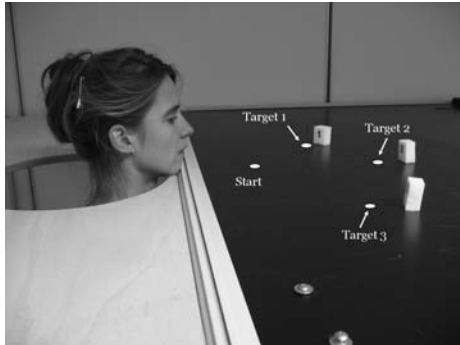
Number of subjects	Age [year]	Gender	Body Height [cm]	Body Weight [kg]	BMI [kg/m <sup>2</sup> ]	
Subjects with pain	23	43.0 (SD = 10.7) range = 24 to 61	4 male 19 female	173.0 (SD = 9.7) range = 150 to 198	68.9 (SD = 14.9) range = 48 to 110	22.9 (SD = 4.1) range = 16.6 to 36.8
Healthy controls	26	42.4 (SD = 11.1) range = 24 to 62	4 male 22 female	173.1 (SD=8.7) range = 157 to 191	70.6 (SD = 12.1) range = 51 to 95	23.6 (SD = 4.2) range = 17.9 to 36.2
<b>Statistical test results</b>		$F_{(1,48)} = 0.780$ , $p = 0.781$	$\chi^2_{(1)} = 0.036$ , $p = 0.850$	$F_{(1,48)} = 0.016$ , $p = 0.899$	$F_{(1,48)} = 0.410$ , $p = 0.525$	$F_{(1,48)} = 0.519$ , $p = 0.475$

## Position sense acuity task

### Procedure

For testing position sense acuity, subjects were standing, with their chin resting in a standardised position on a large tablet, which was placed upside down (Calcomp Digitizer Products, Drawingboard III, Model no. 34480, size: 0.92 x 1.22 m). On top of the tablet, a starting point and 3 target dots were visible (Figure 1a). For exact location of targets with respect to starting point see Figure 4. Subjects were instructed to point to the targets, under the tablet, with a pen held in their dominant hand, with the pen tip pointing upwards. The pen was held right below the pen tip with fingers folded around it (Figure 1b), such that there was no tactile contact between fingers and tablet while pointing. Subjects could not see the pen or their arm and hand during the task. Each pointing movement was started in the starting point, located right in front of the subject. In order to guarantee that subjects started each pointing movement from the exact same position, a small piece of foam was attached underneath the tablet to guide the subjects to the correct position. From the starting point subjects had to point to one of the three targets, as verbally indicated by the experimenter. Subjects were instructed to make a pointing movement at a comfortable speed (not too fast), without touching the tablet. When they felt they had reached the position of the target, they touched the tablet with the pen tip. Contact between pen and tablet was signalled by a beep. After that they had to return to the starting point, to start a new pointing movement. Subjects practiced the task by making 10 pointing movements. When the procedure and pointing movements were clear to the subject and the movements were correctly performed, the actual measurement protocol was started. Each target was pointed at 20 times and the order of the targets was randomised. After each block of 10 pointed targets, subjects took a rest break for 2 min to prevent fatigue.

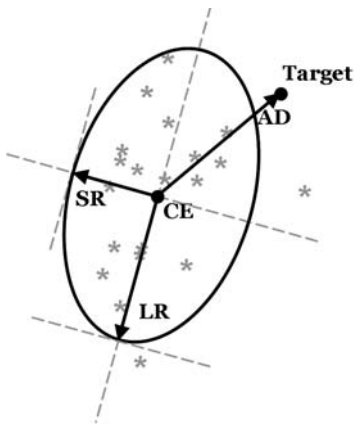
a



b



c



**Figure 1**

*Measurement set up for the position sense acuity task. Subjects rest their chin in the standardised position and see the starting point and the three targets on top of the tablet (a). Subjects point at the targets under the tablet with a pen in their hand (b). In (c) a typical example is given of the ellipse, fitted to the 95% confidence interval of 20 pointed targets (\*) at the actual target. The absolute error is defined as the absolute distance (AD) between the centre of the ellipse (CE) and the actual target. The variable error is defined as the area of the ellipse, calculated as  $\pi$  \* longest radius (LR) of ellipse \* shortest radius of ellipse (SR).*

### **Data acquisition and analysis**

Horizontal and vertical coordinates of the pointed positions were collected with a spatial accuracy of 0.025 cm. Data points per target were fitted with an ellipse corresponding to the 95% confidence interval, with the centre of the ellipse corresponding to the mean coordinates of the positions pointed at for each target. The following dependent variables were calculated (Figure 1c):

1. Absolute error, defined as the distance between the centre of the ellipse and the actual target position.
2. Variable error, defined as the area of ellipse (i.e.  $\pi$  \* longest radius of ellipse \* shortest radius of ellipse).

## **Tracking task**

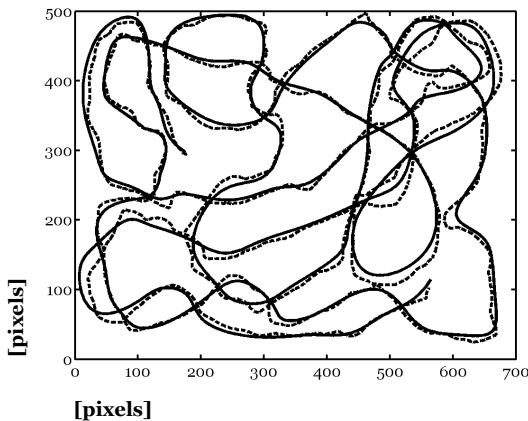
### ***Procedure***

For the tracking task, subjects were seated behind a desk. They had to use a pen on a small digitiser tablet (WACOM Europe, Intuos A4, Model: GD-0912-R) placed on the desk, while looking at a computer screen. Seat height and screen height were adjusted to the anthropometrics of the subject, to ensure that subjects sat with a knee angle of 90°, feet flat on the ground, upper arms vertical with relaxed shoulders and elbows flexed 90°. The forearm was supported by the arm rests of the chair. The tablet was centred in front of the subject, with the lower side at the edge of the table. The top of the computer screen was placed at eye height.

The task consisted of tracking a target dot, which moved quasi-randomly across part of the computer screen with a constant velocity of 20 mm/s. Subjects were instructed to keep the cursor (dot with a diameter of 1.9 mm) positioned as well as possible within the target dot by moving the pen on the tablet. The pen movement corresponded one to one with the cursor movement. Subjects started with performing four practice trials of 1 min each with a target dot of 12.8 mm in diameter. Between the practice trials subjects rested for at least 3 min to prevent fatigue. Then, subjects performed four tracking trials with a duration of 2 min, two trials with a small target dot (ST, diameter 6.4 mm), and two trials with a large target dot (LT, diameter 19.2 mm). A different target trajectory was used for the experimental trials and the practice trials, to prevent subjects from recognising the trajectory after several trials.

Subjects were encouraged to explore different working techniques during the practice trials, but were instructed to choose a certain technique prior to the experimental trials and keep it constant during the experimental trials.

The order of the tracking trials was balanced across subjects, either ST-LT-ST-LT; ST-LT-LT-ST; LT-ST-LT-ST or LT-ST-ST-LT. In between the trials at least 5 min of rest was taken to prevent fatigue.



**Figure 2**

*Tracking trajectory of the experimental trials is shown with the solid line. An example of the position of the cursor is presented by the dashed line.*

### **Data acquisition and analysis**

**Tracking performance.** The tracking task was programmed in LabVIEW (National Instruments Corporation). The trajectory is illustrated in Figure 2. The target moved within a window of 0.16 m high and 0.22 m wide on the computer screen. Horizontal and vertical position of the pen on the tablet was measured in tablet pixels with a spatial accuracy of 0.25 mm, at a sample frequency of 100 Hz. After low-pass filtering the horizontal and vertical position of the pen with a 4<sup>th</sup> order Butterworth filter with a cut-off frequency of 12 Hz, the following measures were calculated using MATLAB (The MathWorks, Inc.):

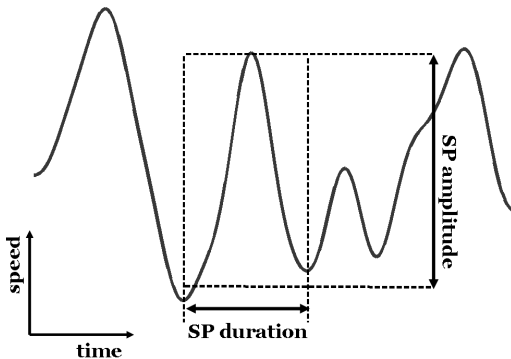
1. Percentage time on target (%TT), the percentage of the total number of samples for which the cursor was completely within the target.
2. Mean distance to target (MDT), mean distance between the centre of the target and the centre of the cursor.
3. Standard deviation of distance to target (SDDT), the standard deviation of the distance between the centre of the target and the centre of the cursor.
4. Percentage lag (%lag), the percentage of the total number of samples for which the centre of the cursor was behind the midline of target (the line through the centre of target perpendicular to the target movement direction).

**Sub-movement organisation.** After differentiating the filtered position signals, the velocity signal was obtained. Oscillations in the velocity profile were seen as numerous sub-movements of tracking. These sub-movements were analysed similarly to previous studies (Roitman et al. 2004; Pasalar et al. 2005; Selen et al. 2006b). Before differentiating the position signals, these were low-pass filtered using a 5<sup>th</sup> order Butterworth filter with a cut-off frequency of 5 Hz. The cut-off frequency of 5 Hz was chosen because at this frequency the median frequency of the velocity signal corresponded

best with the calculated median SP duration. Speed pulses that were too short to be actual speed pulses were in this way excluded from the analysis.

Then, the following measures of were calculated:

1. Mean duration of speed pulses (SP duration), the mean time between two successive local minima in the velocity profile (Figure 3).
2. Mean amplitude of speed pulses (SP amplitude), the mean difference between a local maximum in the velocity profile and the average value of the two nearest minima (Figure 3).
3. Speed pulse gain (SP gain), the slope of the linear regression between SP durations and SP amplitudes.



**Figure 3**

*Section of the velocity profile, showing the speed pulses. The amplitude (SP amplitude) and duration (SP duration) of a single speed pulse are indicated.*

**Impedance.** As indicators of endpoint impedance we studied the level of pen pressure and upper extremity muscle activity.

Axial pressure of the pen on the tablet was measured with a sensitivity of 0.0036 N at a rate of 100 s<sup>-1</sup> and averaged over the 2-min tracking trial.

Muscle activity was assessed of eight muscles in the neck and upper extremities, i.e.:

- M. extensor carpi radialis right (ECRr) and left side (ECrL);
- M. flexor carpi radialis right (FCRr) and left side (FCrL);
- M. deltoideus pars clavicularis right side (DCr);
- M. deltoideus pars acromialis right side (DAr);
- M. trapezius pars descendens right (TDr) and left side (TDl).

To measure muscle activity, bipolar Ag/AgCl surface electrodes (Blue Sensor, gel-skin contact area of 1 cm<sup>2</sup>), were positioned on the muscle bellies, according to the locations described by Basmajian (1989) with an inter-electrode distance of 25 mm, after standard skin preparation. Location of the electrodes was confirmed by palpation of the muscle, while the subject performed a contraction against manual resistance, i.e. dorsal flexion and radial abduction of the wrist (ECRr and ECRL), palmar flexion and radial abduction of the wrist (FCRr and FCRL), anteflexion of the arm (DCr), abduction of the arm (DAr) and lifting the shoulders (TDr and TDL). A reference electrode was placed on the C7 spinous process. EMG signals were amplified 20 times (Porti-17™, TMS, Enschede, The Netherlands, input impedance > 10<sup>12</sup> Ω, CMRR > 90 dB), band-pass filtered (10-400Hz) and A-D converted (22-bits) at a sample rate of 1000 s<sup>-1</sup>. EMG signals were full-wave rectified and low-pass filtered at 5 Hz (4<sup>th</sup> order Butterworth) using MATLAB (The MathWorks, Inc.). From these resulting signals, the Amplitude Probability Distribution Function (APDF) was calculated. Subsequently, three percentiles were used to express the static level (P10), the median level (P50), and the peak level (P90) (Jonsson 1988).

**Perceived exertion.** Immediately after tracking, subjects were asked to rate their perceived *mental* exertion and their perceived *physical* exertion during tracking, using 10-point Borg-scales (Borg 1982).

### Statistical analysis

Differences between subjects with neck and upper extremity pain and healthy controls in age, gender, body height, and body weight were tested with t-tests and with a Chi-square test. ANOVAs for repeated measures with subject group as a between-subject factor and target as a within-subject factor were used to test for the effect of neck and upper extremity pain on the absolute and variable error in the position sense acuity test. The effects of neck and upper extremity pain and of precision demands on tracking performance, sub-movement organisation, impedance (pen pressure and muscle activity), and perceived exertion were tested with MANOVAs for repeated measures with group as a between-subject factor and target size and trial as within-subject factors. Follow-up tests were performed with univariate ANOVAs for repeated measures. *P*-values smaller than 0.05 were considered statistically significant.

A 2-tailed Pearson's correlation was used to determine the relation between position sense acuity measures (mean for the three targets) and tracking performance and kinematics measures for the small and the large target (mean for the two trials). Only

the measures that were significantly different between subject groups were used in this analysis.

## Results

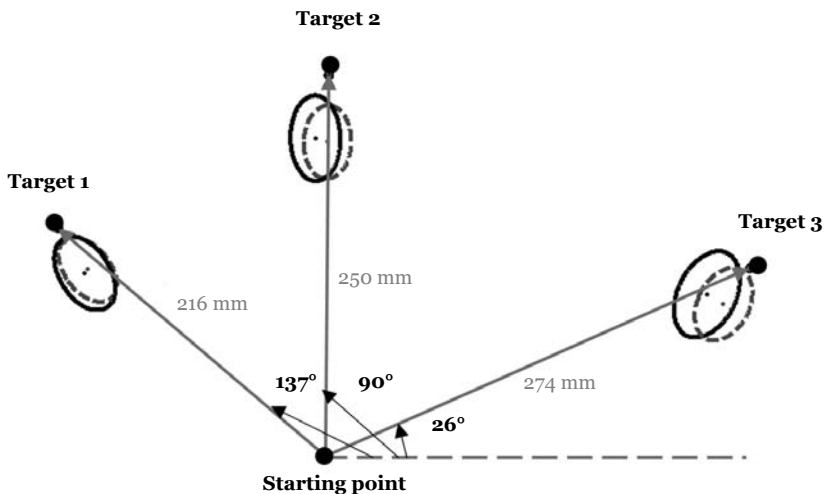
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T-tests and a Chi-square test showed that subject groups were not different in terms of age, gender, body height, body weight, and BMI (Table 1).

### Position sense acuity task

#### *Performance*

ANOVAs for repeated measures revealed that the absolute error was not significantly different between groups. Whereas the variable error, expressed as the area of the ellipses describing the 95% confidence interval of the pointed targets, was significantly larger for cases as compared to controls (Tables 2 and 3 and Figure 4). No interaction effects for subject group and target were found, neither for the absolute nor for the variable error.



**Figure 4**

Mean ellipses of all subjects for the three targets. Ellipses with the solid line represent the data of the subjects with neck and upper extremity pain. Ellipses with the dashed line represent the data of the healthy control subjects. Also given are the distances between the starting point and the three targets and the angles between the line from starting point to target with the right horizontal.

**Table 2**

Mean and standard deviations (SD) of position sense task performance measures.

Variable	Subjects with neck and upper extremity pain Mean (SD)			Healthy controls Mean (SD)		
	Target 1	Target 2	Target 3	Target 1	Target 2	Target 3
Absolute error [mm]	38.52 (20.63)	48.01 (22.76)	38.28 (20.55)	35.74 (17.93)	45.67 (23.09)	34.73 (19.55)
Variable error [mm <sup>2</sup> ]	62.17 (28.70)	64.34 (28.75)	81.14 (35.43)	50.81 (19.19)	51.92 (17.38)	61.26 (30.95)

**Table 3**

Statistical results of the ANOVAs for repeated measures to test the effects of target and subject group on position sense performance measures. Asterisk (\*) indicates statistically significant difference, i.e. the *p*-value is smaller than 0.05.

	Subject group		Target		Subject group x Target	
	F <sub>(2,94)</sub>	<i>p</i> -value	F <sub>(1,47)</sub>	<i>p</i> -value	F <sub>(1,94)</sub>	<i>p</i> -value
Absolute error	0.269	0.607	21.690	0.000*	0.061	0.941
Variable error	5.091	0.029*	9.023	0.000*	0.748	0.476

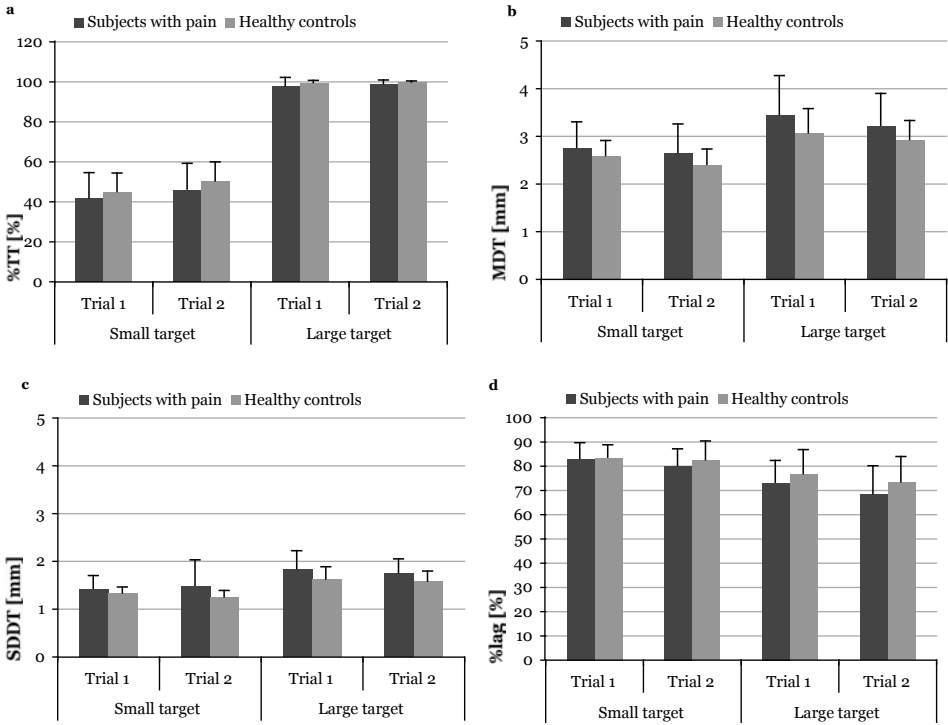
## Tracking task

Our main interest in this study was the difference between subject groups. Therefore, we will first address group differences. Next, effects of target size and trial on the dependent measures will be described.

### Tracking performance

MANOVA for repeated measures showed a *p*-value of 0.056 for the effect of subject group on tracking performance (Table 4). Follow-up analyses with univariate ANOVAs for repeated measures showed that MDT and SDDT were both significantly larger in cases than in controls, but that %TT and %lag were not different between subject groups (Table 5 and Figure 5). There were no interaction effects of group and target size and of group and trial in either the MANOVA for tracking performance or the separate univariate ANOVAs.





**Figure 5**

Tracking performance for the subjects with neck and upper extremity pain and healthy controls, Figure 5a showing the percentage time on target (%TT), 5b mean distance between cursor and centre of target (MDT), 5c the standard deviation of the distance to target (SDDT) and 5d percentage lag (%lag).

**Table 4**

Statistical results of MANOVAs for repeated measures to test for the effects of subject group, target size and trial on tracking performance, sub-movement organisation, impedance, perceived exertion. Asterisk (\*) indicates statistically significant difference, i.e. the p-value is smaller than 0.05.

MANOVAs	Main effects						Interaction effects					
	Subject group		Target size		Trial		Group x target size		Group x trial		Target size x trial	
	F <sub>(4,42)</sub>	p-value	F <sub>(4,42)</sub>	p-value	F <sub>(4,42)</sub>	p-value	F <sub>(4,42)</sub>	p-value	F <sub>(4,42)</sub>	p-value	F <sub>(4,42)</sub>	p-value
Tracking performance	2.510	0.056	358.335	0.000*	14.082	0.000*	0.960	0.440	1.252	0.340	13.901	0.000*
	F <sub>(3,46)</sub>	p-value	F <sub>(3,46)</sub>	p-value	F <sub>(3,46)</sub>	p-value	F <sub>(3,46)</sub>	p-value	F <sub>(3,46)</sub>	p-value	F <sub>(3,46)</sub>	p-value
Sub-movement organisation	0.312	0.816	59.058	0.000*	6.228	0.001*	0.299	0.826	2.196	0.101	1.647	0.192
	F <sub>(6,37)</sub>	p-value	F <sub>(6,37)</sub>	p-value	F <sub>(6,37)</sub>	p-value	F <sub>(6,37)</sub>	p-value	F <sub>(6,37)</sub>	p-value	F <sub>(6,37)</sub>	p-value
Impedance	0.360	0.947	7.021	0.000*	3.951	0.001*	0.991	0.465	1.184	0.334	2.201	0.045*
	F <sub>(2,50)</sub>	p-value	F <sub>(2,50)</sub>	p-value	F <sub>(2,50)</sub>	p-value	F <sub>(2,50)</sub>	p-value	F <sub>(2,50)</sub>	p-value	F <sub>(2,50)</sub>	p-value
Perceived exertion	18.283	0.000*	38.407	0.000*	3.697	0.031*	0.722	0.491	3.444	0.041*	0.506	0.606

**Table 5**  
 Statistical results of univariate ANOVAs for repeated measures to test for the effects of subject group, target size and trial on tracking performance and sub-movement organisation. Asterisk (\*) indicates statistically significant difference, i.e. the p-value is smaller than 0.05.

	Univariate ANOVAs						Interaction effects											
	Subject group			Target size			Trial			Group x target size			Group x trial			Target size x trial		
	F <sub>(1,47)</sub>	p-value		F <sub>(1,47)</sub>	p-value		F <sub>(1,47)</sub>	p-value		F <sub>(1,47)</sub>	p-value		F <sub>(1,47)</sub>	p-value		F <sub>(1,47)</sub>	p-value	
<b>Tracking performance</b>																		
%TT	2.489	0.122	1370.791	0.000*	25.038	0.000*	1.100	0.300	0.018	0.895	0.000*	1.100	0.300	0.018	0.895	20.566	0.000*	
MDT	4.573	0.038*	107.759	0.000*	11.008	0.002*	1.281	0.264	0.000	0.985	0.435	1.281	0.264	0.000	0.985	0.622	0.435	
SDDT	7.767	0.008*	64.560	0.000*	1.013	0.320	0.082	0.776	0.678	0.415	0.209	0.082	0.776	0.678	0.415	1.627	0.209	
%lag	1.770	0.109	59.274	0.000*	20.178	0.000*	1.318	0.257	1.647	0.206	0.028*	1.318	0.257	1.647	0.206	5.155	0.028*	
<b>Sub-movement organisation</b>																		
SP gain	0.464	0.499	97.749	0.000*	2.394	0.128	0.044	0.835	5.249	0.026*	0.056	0.044	0.835	5.249	0.026*	3.848	0.056	
SP amplitude	0.597	0.443	163.254	0.000*	16.301	0.000*	0.004	0.949	2.662	0.109	0.186	0.004	0.949	2.662	0.109	1.802	0.186	
SP duration	0.092	0.763	33.264	0.000*	0.735	0.395	0.696	0.408	5.861	0.019*	0.656	0.696	0.408	5.861	0.019*	0.201	0.656	

### ***Sub-movement organisation***

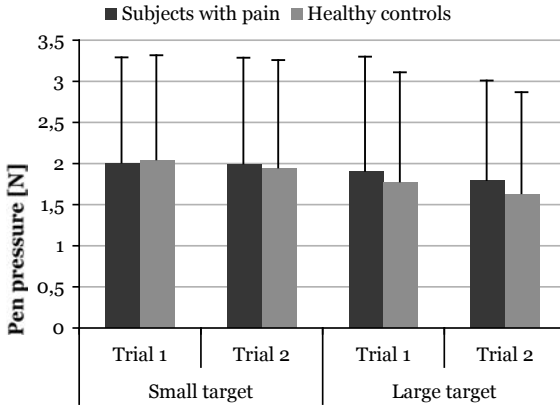
In the multivariate analysis of the measures concerning the organisation of sub-movements there was no significant effect of subject group ( $p = 0.816$ ) (Table 4). Also the interaction effects of group and target size and group and trial did not reach significance with  $p$ -values of respectively  $p = 0.440$  and  $p = 0.340$ . Univariate ANOVAs showed neither an effect of group, nor interaction effects of group and target size and group and trial on SP gain, SP amplitude and SP duration (Tables 5 and 6).

**Table 6**  
*Mean and standard deviations (SD) of sub-movement organisation for subjects with neck and upper extremity pain and healthy controls for the small and the large target in the first and second trial.*

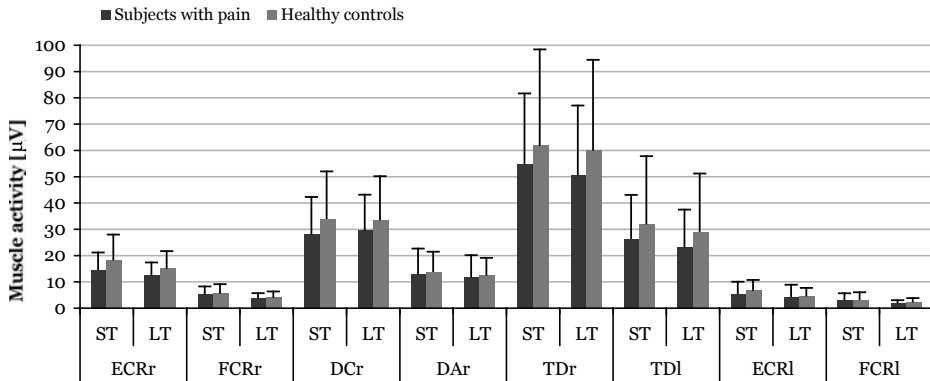
Variable	Subjects with neck and upper extremity pain Mean (SD)				Healthy controls Mean (SD)			
	Small target		Large target		Small target		Large target	
	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2
<b>sub-movement organisation</b>								
SP gain [cm/s <sup>2</sup> ]	5.09 (1.44)	5.12 (1.28)	4.02 (0.99)	4.11 (1.08)	5.22 (1.17)	4.67 (1.14)	3.91 (0.92)	3.81 (0.73)
SP amplitude [cm/s]	1.64 (0.38)	1.59 (0.31)	1.34 (0.38)	1.31 (0.34)	1.61 (0.28)	1.50 (0.27)	1.29 (0.29)	1.22 (0.26)
SP duration [s]	0.36 (0.03)	0.36 (0.03)	0.37 (0.03)	0.37 (0.03)	0.35 (0.03)	0.36 (0.03)	0.37 (0.02)	0.38 (0.03)

### ***Impedance***

Muscle activity levels P10, P50 and P90 showed similar results. Therefore only the analyses for the P50 values in the MANOVA for repeated measures will be reported. MANOVA for repeated measures showed that indicators of impedance were not significantly affected by group (Table 4). The interaction effects of group and target size and group and trial were also not significant for indicators of impedance. With univariate ANOVAs no significant main effect of subject group for pen pressure or muscle activity were found (Table 7 and Figures 6 and 7). A significant interaction effect of group and trial was shown for muscle activity in the TDI and the ECRI. Both in the TDI and ECRI subjects with neck and upper extremity pain showed higher muscle activity in the second trial as compared to the first trial, whereas the controls lowered their muscle activity in the second trial.



**Figure 6**  
 Pen pressure during tracking for subjects with neck and upper extremity pain and healthy controls.



**Figure 7**  
 Muscle activity in the *M. extensor carpi radialis right (ECRr)* and left side (*ECRI*), *M. flexor carpi radialis right (FCRr)* and left side (*FCRI*), *M. deltoideus pars clavicularis right side (DCr)*, *M. deltoideus pars acromialis right side (DAr)*, *M. trapezius pars descendens right (TDr)* and left side (*TDI*) during tracking, for subjects with neck and upper extremity pain and healthy controls, the average value of the two trials is given for tracking the small target (ST) and for the large target (LT).

**Table 7**  
 Statistical results of univariate ANOVAs for repeated measures to test for the effects of subject group, target size and trial on impedance (pen pressure and muscle activity). Asterisk (\*) indicates statistically significant difference, i.e. the p-value is smaller than 0.05.

	Univariate ANOVAs						Main effects						Interaction effects					
	Subject group		Target size		Trial		Group x target size		Group x trial		Target size x trial		Group x target size		Group x trial		Target size x trial	
	F <sub>(1,47)</sub>	p-value	F <sub>(1,47)</sub>	p-value	F <sub>(1,47)</sub>	p-value	F <sub>(1,47)</sub>	p-value	F <sub>(1,47)</sub>	p-value	F <sub>(1,47)</sub>	p-value	F <sub>(1,47)</sub>	p-value	F <sub>(1,47)</sub>	p-value	F <sub>(1,47)</sub>	p-value
Pen pressure	0.306	0.552	15.599	0.000*	5.705	0.021*	1.127	0.294	0.473	0.495	0.366	0.548	0.882	0.352	0.147	0.703	2.231	0.142
ECRr	2.786	0.102	27.856	0.000*	11.903	0.001*	0.055	0.816	0.191	0.664	2.991	0.090	1.4444	0.235	0.306	0.583	0.005	0.944
FCRr	0.237	0.629	39.181	0.000*	23.170	0.000*	0.054	0.817	0.058	0.810	0.026	0.872	0.885	0.352	2.728	0.105	1.004	0.321
DCr	1.310	0.258	0.248	0.621	3.120	0.084	0.047	0.830	4.768	0.034*	2.224	0.142	1.839	0.181	5.458	0.024*	4.702	0.035*
DAr	0.131	0.719	10.681	0.002*	3.775	0.058	0.268	0.607	0.013	0.908	1.159	0.287	0.909	0.304	1.082	0.304	2.586	0.114
TDr	0.909	0.345	5.356	0.025*	0.001	0.979	0.001	0.009*	2.079	0.156	1.082	0.304	0.001	0.025*	0.001	0.979	0.001	0.979
TDl	1.138	0.291	7.366	0.009*	2.079	0.156	0.047	0.830	4.768	0.034*	2.224	0.142	1.839	0.181	5.458	0.024*	4.702	0.035*
ECRl	0.723	0.399	17.872	0.000*	1.082	0.304	0.001	0.025*	0.001	0.979	0.001	0.979	0.001	0.025*	0.001	0.979	0.001	0.979
FCRl	0.388	0.536	19.341	0.000*	2.586	0.114	0.001	0.025*	0.001	0.979	0.001	0.979	0.001	0.025*	0.001	0.979	0.001	0.979



### ***Perceived exertion***

MANOVA for repeated measures showed a significant effect of subject group on perceived exertion ( $p < 0.001$ ) (Table 4). A significant interaction effect was observed for subject group and trial ( $p = 0.041$ ). Univariate ANOVAs showed that perceived physical exertion was rated significantly higher by the subjects with pain, namely 5.03 (SD = 1.88) as compared to 2.90 (SD = 1.63) for healthy controls (Tables 8 and 9). The significant interaction effect of subject group and trial for perceived exertion showed that subjects with pain perceived the second trial as physically more demanding, whereas the healthy controls scored this trial the same as the first trial. No interaction effect was present of subject group and target size.

### **Relation between position sense acuity and tracking performance**

The variable error in the position sense acuity task was significantly different between subject groups. In the tracking task, differences between subject groups were found for MDT and SDDT. Therefore the 2-tailed Pearson's correlation was used to determine the relation between the variable error of position sense acuity task (mean for the three targets) and tracking performance measures; MDT and SDDT (mean value of the two trials for the small target and for the large target were tested separately). Significant correlations of 0.418 and 0.566 were found between the variable error and tracking performance measures MDT and SDDT respectively, but only in the small target condition (Table 10). In the large target condition no significant correlation between variable error and tracking performance was found.

**Table 8**  
 Mean and standard deviations (SD) of perceived mental and physical exertion for subjects with neck and upper extremity pain and healthy controls for the small and the large target in the first and second trial.

	Subjects with neck and upper extremity pain Mean (SD)				Healthy controls Mean (SD)			
	Small target		Large target		Small target		Large target	
	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2
Perceived mental exertion	5.4 (2.1)	5.0 (2.2)	3.3 (1.5)	3.3 (1.7)	5.0 (1.8)	4.5 (2.1)	3.7 (1.7)	3.0 (1.3)
Perceived physical exertion	5.6 (1.8)	5.9 (1.9)	4.1 (1.8)	4.5 (2.0)	3.5 (2.0)	3.4 (2.0)	2.5 (1.4)	2.2 (1.1)

**Table 9**

Statistical results of univariate ANOVAs for repeated measures to test for the effects of subject group, target size and trial on perceived mental and physical exertion. Asterisk (\*) indicates statistically significant difference, i.e. the p-value is smaller than 0.05.

	Main effects						Interaction effects					
	Subject group		Target size		Trial		Group x target size		Group x trial		Target size x trial	
	F <sub>(1,47)</sub>	p-value	F <sub>(1,47)</sub>	p-value	F <sub>(1,47)</sub>	p-value	F <sub>(1,47)</sub>	p-value	F <sub>(1,47)</sub>	p-value	F <sub>(1,47)</sub>	p-value
Perceived mental exertion	1.390	0.244	71.578	0.000*	5.261	0.026*	1.242	0.270	1.750	0.192	0.365	0.549
Perceived physical exertion	30.392	0.000*	73.365	0.000*	0.291	0.592	0.936	0.338	6.835	0.012*	0.205	0.653

**Table 10**

*Pearson's correlation coefficient (r) and p-values of the correlations between the variable error in the position sense acuity task and tracking task performance measures, mean distance to the centre of the target (MDT) and standard deviation of the distance to target (SDDT) for the small and the large target, respectively abbreviated as ST and LT.*

Pearson's Correlation 2-tailed N=48	Tracking task measures					
	MDT ST		MDT LT		SDDT LT	
	r	p-value	r	p-value	r	p-value
Position sense acuity	0.418	0.003*	0.237	0.105	0.566	0.000*
Variable error					0.280	0.054

## Effects of target size and trial

In the present article, we focused on differences between subjects with neck and upper extremity pain and healthy control subjects and on interaction effects for subject group and target size and for subject group and trial. However, several interesting main effects of both target size and trial on the dependent variables were found. In a previous article we reported extensively on the effects of target size and trial on tracking performance, sub-movement organisation, pen pressure, muscle activity and perceived exertion in the healthy controls tested in the present study (Huysmans et al. submitted). These overall results remained similar when we added the subjects with neck and upper extremity pain in the analysis. In summary, MANOVAs for repeated measures showed that tracking performance, sub-movement organisation, impedance and perceived exertion were all significantly affected by target size and trial (Table 4). The interaction effect of target size and trial was only significant for tracking performance and impedance.

Univariate analyses showed that when tracking a small target subjects spent significantly less time on target, whereas MDT and SDDT were significantly smaller than with a large target (Table 5 and Figure 5). Moreover, with a small target, subjects trailed more behind the centre of target (i.e. larger %lag). SP duration was significantly shorter with a small target and the SP amplitude significantly larger, which resulted in a significantly larger SP gain when tracking a small target (Tables 5 and 6). Pen pressure and muscle activity were also significantly affected by target size. Tracking a small target resulted in significantly higher pen pressure and a significantly higher muscle activity, in all muscles measured, than tracking a large target (Table 7 and Figures 6 and 7). In the previous study (Huysmans et al. submitted) in which only the data of the healthy controls were analysed, we found no significant effect of target size on trapezius muscle activity (TDr:  $p = 0.255$ , TDI:  $p = 0.103$ ). Since in the present study no interaction effect of subject group and target size was found, the significant effect of target size on trapezius muscle activity in the present study can most likely be explained by the higher power ( $N=49$ , instead of  $N=26$  in the previous study). Univariate ANOVA showed that tracking the small target was perceived mentally and physically significantly more demanding than tracking a large target (Tables 8 and 9).

%TT, MDT, %lag, and SP amplitude were significantly affected by trial. In the first trial, %TT, %lag, and SP amplitude were significantly smaller and MDT was significantly larger than in the second trial (Tables 5 and 6 and Figure 5). A main effect of trial was also found for pen pressure and muscle activity in the right ECR and FCR (Table 7). In the second trial, pen pressure and muscle activity in the ECRr and FCRr were significantly smaller than in the first trial. Perceived mental exertion was also significantly

affected by trial (Table 9). Mental exertion was perceived as less demanding in the second trial as compared to the first trial (Table 8). These effects can most probably be attributed to learning, even though memorisation of (parts of) the tracking trajectory can not be excluded.

## **Discussion**

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The present study aimed to investigate whether neck and upper extremity pain affects position sense acuity and performance, organisation of sub-movements, pen pressure, muscle activity and perceived exertion in a tracking task. We found that position sense acuity was impaired in subjects with neck and upper extremity pain and that these subjects show lower tracking performance. There were no signs of differences in sub-movement organisation or endpoint impedance between subject groups. Subjects with and without neck and upper extremity pain showed similar pen pressure and muscle activity during tracking. Nevertheless, subjects with neck and upper extremity pain perceived the tracking task as physically more demanding, whereas mental exertion was rated similarly. A significant correlation between position sense acuity and performance in the tracking task was observed.

In the position sense acuity task, the absolute error, i.e. the distance between the centre of the ellipse and the actual target was not different between subject groups, while the variable error, i.e. the area of ellipse, was significantly larger in the subjects with neck and upper extremity pain. Where absolute errors give information about the current status of the calibration of position sense acuity, variability is a more suitable measure of the degree of noise within the information processing system and thus of the acuity of proprioceptive localisation (Clark et al. 1995). Thus, the significantly larger area of the ellipse in subjects with neck and upper extremity pain implies that position sense acuity was impaired in these subjects. This result is in line with the reduced repositioning accuracy reported for similar subject populations, such as subjects with chronic neck pain (Revel et al. 1991), whiplash disorders (Feipel et al. 2006; Sandlund et al. 2006) and lateral epicondylitis (Juul-Kristensen et al. 2006). For the head and neck in whiplash patients Armstrong et al. (2005) found no position sense impairment, but this may have been due to the fact that the whiplash patients in this study were less severely affected than those in the studies of Feipel et al. (2006) and Sandlund et al. (2006). The choice for testing position sense acuity in a multi-joint functional pointing task instead of testing it in a single joint repositioning task, was based on the fact that in everyday life information on hand position is more meaningful than joint angle

information (Van Beers et al. 1998). It is likely that in the subjects with neck and upper extremity pain the affected proprioception is not limited to a single joint, similar to the fact that the pain is mostly not limited to a single joint in these subjects. In subjects with whiplash disorders, not only neck (Revel et al. 1991; Feipel et al. 2006), but also shoulder position sense (Sandlund et al. 2006) and elbow position sense (Knox et al. 2006) were affected.

Subjects with neck and upper extremity pain showed higher MDT and SDDT during tracking than healthy controls. This is in line with the larger distance to target as reported for subjects with pain in the arm, wrist and/or hand during tracking (Brouwer et al. 2001; Brouwer and Faris 2007). In a tracing task, Jensen et al. (2002) found no accuracy differences between subjects with upper extremity pain and controls, but it was not clear if the time to complete the task was standardised in this study. When movement time is not restricted, subjects with upper extremity pain have been reported to perform tasks slower (Madeleine et al. 1999; Smeulders et al. 2001; Madeleine et al. 2003; Harman and Ruyak 2005). Tracking performance measures MDT and SDDT were significantly correlated with position sense acuity while tracking the small target. The impaired precision in tracking thus may be due to the impaired proprioception. An alternative explanation may be that the pain may have competed with task demands for attention (Roe et al. 2001). Reduced attention in subjects with pain could explain the higher variability in the position sense task and the larger errors in the tracking task. The larger errors in tracking were most likely not the result of a lack of motivation or a lack of effort, because subjects with and without neck and upper extremity pain showed similar muscle activity and pen pressure levels.

Subjects with pain did not compensate their lack of positional precision by changing tracking kinematics. This is in line with results found for a deafferented subject (Miall et al. 1996). RMS tracking error was about 50% larger in the deafferented subject than in controls, but the frequency content of the tracking kinematics was identical to that of the control subjects (Miall et al. 1996). This indicates that the organisation of sub-movements is not dominated by proprioceptive control loops, but by the visual feedback loop. Subjects with pain did also not compensate for their reduced tracking precision by increasing endpoint impedance. Pen pressure and muscle activity levels were similar for subjects with pain and healthy controls. A study on aiming did reveal a more abrupt increase in pen pressure in subjects with neck and upper extremity pain as compared to controls, but average pen pressure was not different (Bloemsaat et al. 2004). The effect of pain on muscle activity levels in literature is not conclusive. Lower (Sjogaard et al. 2006), similar (Roe et al. 2001; Holte and Westgaard 2002; Goudy and McLean 2006) and higher trapezius muscle activity levels (Szeto et al. 2005) have

been reported for office workers with pain as compared to those without pain. In the forearm extensors, similar muscle activity levels (Roe et al. 2001) and in the neck extensors, lower muscle activity levels (Szeto et al. 2005) have been reported for symptomatic office workers. However, in most of these studies, performance or movement velocity was not measured or standardised, and different normalisation procedures were applied, which complicates the interpretation and comparison of the muscle activity results. In the present study, muscle activity values were not normalised. This may have resulted in a loss of power, but avoids bias of the results when normalisation values are not similar between groups. For example, lower muscle activity and forces have been reported for subjects with pain when performing a maximum voluntary contraction (Schulte et al. 2006; Sjogaard et al. 2006). Since no tendencies were found for an effect, and the number of subjects in the present study should provide sufficient statistical power (Mathiassen et al. 2002), we do not expect different outcomes if more subjects were to be tested.

Increased muscle activity is thought to play an important role in the onset and perpetuation of neck and upper extremity pain (Johansson et al. 2003). It has been suggested that, as a result of fatigue and/or cell damage, metabolites are released in the muscle, which leads to a decrease in proprioceptive acuity as well as pain. The negative effects of impaired proprioception on motor control can be counteracted by an increase in muscle activity. This is thought to initiate a vicious cycle, as a higher muscle activity will accelerate metabolite accumulation. However, contrary to what is expected in this model (Johansson et al. 2003), we did not find a higher muscle activity in subjects with neck and upper extremity pain. This implies that the vicious cycle is not closed, possibly because reduced performance on the task had no consequences for the subject, and therefore, this pathophysiological model was not supported. Because of the cross-sectional nature of the study we can only speculate whether the impaired position sense is the cause or the effect of the pain. It is recommended to investigate position sense acuity in a longitudinal study in order to get more insight in its role in the development of neck and upper extremity pain.

Even though the task in the present study is highly standardised, the results could be generalised to practice. Subjects with neck and upper extremity pain will have more difficulty with tasks demanding a high level of precision. If allowed, they are likely to reduce their movement speed. And if movement velocity is imposed and there are no direct consequences of working less accurate, like in the present study, their level of precision will likely be reduced. Furthermore, if both movement velocity and precision are imposed in the task, subjects with pain are possibly forced to increase impedance or fail to perform the task. In this way impaired position sense acuity could increase

disability levels in subjects with pain in neck and upper extremity. Brouwer et al. (2001; 2007) have indeed shown that impaired precision in tracking was positively related to disability score and impairment level.

We can conclude that position sense acuity was impaired in subjects with neck and upper extremity pain and that this could contribute to their reduced precision observed in a computer tracking task. Subjects with neck and upper extremity pain did not compensate for their reduced tracking performance by changing tracking kinematics or increasing endpoint impedance. Despite their similar muscle activity and pen pressure as healthy controls, subjects with neck and upper extremity pain perceived the tracking task as physically more demanding. Subjects with neck and upper extremity pain did not show higher muscle activity levels as compared to healthy controls, hence it is not likely that the onset or perpetuation of pain is the result of a vicious cycle in which pain and muscle activity amplify each other.







# Chapter **six**

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## ***Grip force control in patients with neck and upper extremity pain and healthy controls***

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*Maaïke A Huysmans, Marco JM Hoozemans, Bart Visser,  
Jaap H van Dieën*

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## Abstract

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*In the present study, we investigated whether sensory and motor problems in patients with non-specific neck and upper extremity pain could be ascribed to a deficit of sensory-motor integration. Therefore, grip force control and adaptation of grip force, were measured in 81 subjects with pain in neck and upper extremity, 32 subjects with a history of pain and 39 subjects without pain, during repetitively lifting and holding of an object. The object (300 g) was lifted vertically over 20 cm and held for 5 s, using the dominant arm (the affected arm in all cases). The object was novel to the subjects when lifted for the first time, and was lifted five times consecutively. Grip forces orthogonal to the object's surface and its vertical acceleration were measured. Subjects with pain used significantly higher grip forces than both other groups, while the vertical acceleration was not different. After the initial lift, all groups significantly reduced the maximum grip force. Subjects with neck and upper extremity pain consistently use higher grip forces than controls, but adjust grip forces by a similar amount after the first lift. Compensation of impaired sensory information rather than a general deficit in sensory-motor integration seems to account for these findings.*

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## Introduction

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Despite an extensive body of literature, the pathophysiology of work-related, non-specific neck and upper extremity pain, also referred to as repetitive strain injury (RSI), is still poorly understood (Visser and Van Dieen 2006). Besides pain, sensory dysfunction (Byl et al. 1996a; Greening and Lynn 1998; Jensen et al. 2002; Greening et al. 2003) and lack of accuracy in fine-motor tasks (Brouwer et al. 2001) have been reported in these patients. In addition, some studies have provided evidence for excessive motor output, apparent in high forces applied during typing and graphical aiming (Feuerstein et al. 1997; Bloemsaat et al. 2004) and increased muscle activity levels (Veiersted 1994; Holte and Westgaard 2002; Madeleine et al. 2003). Combining these sensory and motor symptoms may suggest a deficit in sensory-motor integration in patients with neck and upper extremity pain.

Studying grip force control in lifting and holding small objects with the hand has been shown to provide useful information on the interaction of sensory function and motor activity in the upper extremity (Johansson 1996; Nowak and Hermsdorfer 2005, 2006). When an object is lifted for the first time, healthy subjects usually apply a higher than required grip force, but then rapidly adjust it within a few lifts, to be only slightly higher than the minimum necessary to prevent the object from slipping (Johansson and Westling 1984; Westling and Johansson 1984; Johansson 1996).

Patients with disorders, such as Parkinson's disease, focal hand dystonia and carpal tunnel syndrome (Odergren et al. 1996; Thonnard et al. 1997; Lowe and Freivalds 1999; Nowak and Hermsdorfer 2006), but also healthy subjects after anaesthetising the fingers (Johansson and Westling 1984; Johansson 1996; Nowak et al. 2001) use significantly higher grip forces than healthy controls during repetitive object lifting. This has been interpreted mainly as a result of impaired sensory-motor processing (Johansson 1996; Odergren et al. 1996). However, patients with focal dystonia have been shown to adapt their grip forces after lifting a novel object, like healthy controls do, despite the fact that their grip forces remained significantly elevated (Nowak et al. 2005; Nowak and Hermsdorfer 2006). This adaptation was indicative of adequate integration of sensory information in the control of later lifts, and the authors hypothesised, in accordance with Schenk and Mai (2001), that the excessive grip forces may be learned behavior (Nowak et al. 2005; Nowak and Hermsdorfer 2006).

Because of the sensory dysfunction, lack of accuracy in fine-motor tasks, and indications of increased motor output in subjects with neck and upper extremity pain, we aimed to investigate whether grip force is affected in subjects with pain in the neck

and upper extremity, subjects with a history of such pain and subjects without pain in lifting and holding an object. Moreover, it was investigated whether these subjects adapt their grip forces during consecutive lifts after the initial lift of a novel load. Finally, we investigated whether grip force levels and adaptation of grip force were related to pain level.

## Methods

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### Participants

Subjects were recruited among attendants of a conference of a national association for patients with neck, shoulder, arm and/or hand pain and among visitors of a health fair. Potential participants were asked to participate in a short experiment in which they would be asked to lift five times a cylindrical object in size and mass similar to a coffee mug. No further information on the aims or intended dependent variables of the study was given. In case subjects agreed to participate, they first signed an informed consent and completed a questionnaire covering general subject characteristics and specific information about the presence of neck, shoulder, arm and/or hand pain. In total 152 subjects took part in the experiment, of which 91 were female and 61 male. The protocol had been approved by the ethical committee of the VU University Medical Centre.

### Procedure

Subjects had to lift a cylindrical object that was constructed from two halves of a PVC cylinder (diameter is 74 mm). Inside a copper weight was suspended to obtain a total weight of 300 g. Within the two shells of the object a force transducer (Futek, LSB200) was placed, which measured forces orthogonal to the shell of the object. On top of the object, an accelerometer (Brüel and Kjaer 4507, 2693 Nexus conditioning amplifier) was placed, measuring the acceleration of the object in the vertical direction.

The object was placed in front of the subject such that a yellow dot (diameter = 5 mm) in the middle of the object, corresponding to the position of the force transducer within, was placed 20 cm below elbow height, by adjusting the height of the support on which the object was placed (Figure 1). Elbow height was defined as the distance between the floor and the lowest point on the olecranon, while the subject was standing upright with the forearm flexed in 90°. Subjects stood in front of the object, in such a way that they could pick it up from the support with their upper arm hanging

vertically beside their body. They were not allowed to touch the object before the first command to lift the object was given.

During lifting, subjects wore a tight-fitting, elastic knitted glove (85% acrylic, 13% polyester, 2% elastane) to ensure that friction between fingers and object would be similar for all subjects. Two sizes of otherwise identical gloves were available to ensure a proper fit.

Subjects were instructed to lift the object, with their dominant hand, gently from the support to elbow height, by putting their thumb on the dot (to ensure that grip force was applied in the direction of the force transducer) and their fingers on the opposite side of the object. Specific attention was paid that no fingers were put underneath the object. Subjects were asked to hold the object steady at elbow height for 5 s, as the experimenter counted out loud. After these 5 s, subjects put the object gently back on the support. Between lifts, a minimum rest of 5 s was given. In total, five consecutive lifts were performed, during which grip forces on the object and vertical accelerations of the object were measured continuously.



**Figure 1**

*This picture illustrates the measurement set-up, with the subject wearing a glove and holding the object at elbow height, after lifting it over a distance of 20 cm from the support.*

### **Data analysis subject information**

According to the answers on the questionnaire, 152 subjects were divided into different groups for the data analysis.

First of all, subjects were assigned to one of three groups according to the presence of pain in neck, shoulder, arm and/or hand:

- 1) Subjects with pain: subjects with pain in neck, shoulder, arm and/or hand on the dominant side (including bilateral) for at least a month at the moment of measurement.
- 2) Subjects with a history of pain: subjects free of pain in neck, shoulder, arm and/or hand for at least a month at the moment of measurement, but who had experienced pain during one or more periods of at least 1 month in the previous 5 years.
- 3) Subjects without pain: subjects free of pain in neck, shoulder arm and/or hand at the moment of measurement and without a history of pain in neck, shoulder, arm and/or hand in the previous 5 years.

All subjects had normal or corrected to normal vision.

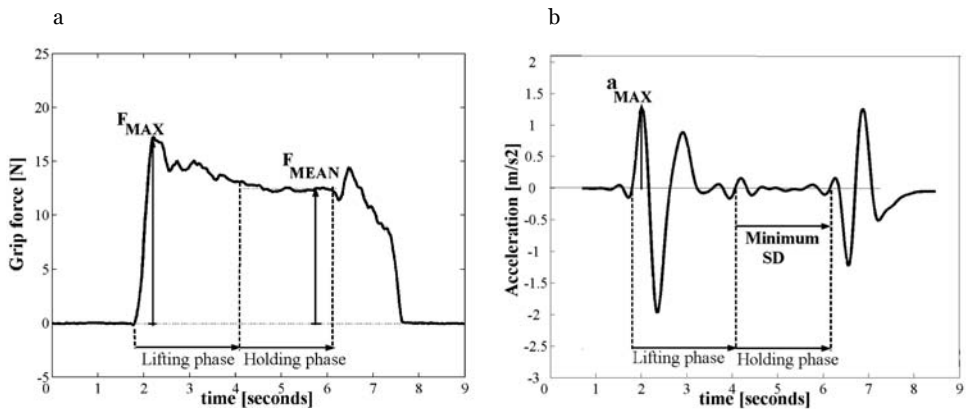
Then, the subjects with pain were divided into a low pain and a high pain subgroup according to the rating of their pain level on a 11-point numerical rating scale, in which 0 was labelled with “no pain at all” and 10 with “highest pain imaginable”. The median pain score was used as a cut-off point for low and high pain.

### **Data analysis force and acceleration data**

Data of the force transducer and the accelerometer were collected at a sample rate of 1000 samples per second and low-pass filtered at 15 Hz (4<sup>th</sup> order Butterworth) using MATLAB (The MathWorks, Inc.). Force data were expressed in Newtons and data of the accelerometer were expressed in ms<sup>-2</sup>.

The holding phase of each lift was defined as the 2-s window in the acceleration profile with the lowest standard deviation (Figure 2a). The mean force ( $F_{\text{MEAN}}$ ) during the holding phase was calculated (Figure 2b). The lifting phase was determined as the period of the lift from the initial force measured until the start of the holding phase. Both the maximum grip force ( $F_{\text{MAX}}$ ) and the maximum vertical acceleration ( $a_{\text{MAX}}$ ) in the lifting phase were determined. Moreover, a force ratio was calculated as the measured grip force divided by the load force after lift-off, in which the load force is the product of object mass and the sum of the measured vertical acceleration of the object and the gravitational acceleration. The maximum of the force ratio ( $F_{\text{RATIO}}$ ), which always occurred in the lifting phase, was determined.





**Figure 2a and 2b**

An example of the grip force (a) and acceleration profile (b) during one lift trial. Indicated are the lifting phase and the holding phase, the holding phase is defined as the 2-s window in the acceleration profile with the lowest standard deviation, the lifting phase is defined from the initial force measured until the start of the holding phase. The calculated dependent variables, i.e. mean force during the holding phase ( $F_{MEAN}$ ), maximum force during the lifting phase ( $F_{MAX}$ ) and maximum vertical acceleration during the lifting phase ( $a_{MAX}$ ) are shown in the figure.

## Statistical analysis

First of all, it was tested whether the subject groups differed with respect to age and gender. Differences in age were tested with one-way ANOVAs and differences in gender with Chi-square tests. Since age and gender were not different for the three main subject groups, i.e. subjects with pain, subjects with a history of pain and subjects without pain, and for the subgroups of “pain level” within the subjects with pain group, they were not included as covariates in further statistical analyses (for statistical results see Tables 1 and 2).

Differences in the dependent variables, i.e.  $F_{MEAN}$ ,  $F_{MAX}$ ,  $a_{MAX}$  and  $F_{RATIO}$ , between subjects with pain, subjects with a history of pain and subjects without pain, were tested using repeated measures ANOVAs with “subject group” as a between-subject factor and “lift trial” (1-5) as a within-subject factor. The interaction between “subject group” and “lift trial” was used to test whether the subject groups adapted grip force ( $F_{MEAN}$ ,  $F_{MAX}$  and  $F_{RATIO}$ ) differently over the five consecutive lift trials.

To test whether grip force control of subjects with pain could be distinguished on the basis of their pain level, similar ANOVAs for repeated measures as described above were carried out, with “subject group” being the subjects with a high level of pain

versus the subjects with a low level of pain.  $p$ -values smaller than 0.05 were considered to be statistically significant. Post-hoc testing was performed using Bonferroni corrections.

## Results

### Study population

In total 81 subjects with pain, 32 subjects with a history of pain and 39 subjects without pain participated in the study (see Table 1 for detailed subject information). For 3 subjects with pain, data on pain duration, location, and level, were missing. The subjects with pain in neck and upper extremity had this pain on average for 5 years and 0 months (SD = 4 years and 6 months, range = 1 month to 20 years). Fifty-six had pain in neck, shoulder, arm and hand, 12 only in the neck and shoulder and 10 subjects had pain in the arm and hand only. All experienced pain on the dominant side and the level of pain was rated on average 5.0 (SD = 2.2, range 1 to 9) on the 11-point numerical pain scale. The subjects with a history of pain were on average 1 year and 7 months (SD = 1 year and 4 months, range = 1 month to 5 years) free of pain.

**Table 1**

General subject information, i.e. age, gender, body height, body mass and handedness of the three main subject groups are given. Moreover, statistical results of the differences between groups as tested with a one-way ANOVA or a Chi-square are given.

Number of subjects	Age [year]	Gender % female	Body Height [cm]	Body mass [kg]	Handedness % right-handed
Subjects with pain	81 38.7 (SD = 11.2) range = 19 - 62	62.5	175.5 (SD = 10.2) range = 152 - 202	74.5 (SD = 15.0) range = 49 - 115	85.7
Subjects with a history of pain	32 40.7 (SD = 9.8) range = 23 - 58	53.1	175.7 (SD = 10.2) range = 159 - 200	73.0 (SD = 15.1) range = 49 - 108	90.3
Subjects without pain	39 35.2 (SD = 11.2) range = 18 - 62	59.0	174.6 (SD=9.0) range = 153 - 191	71.5 (SD = 11.2) range = 50 - 95	81.6
<b>Statistical test results</b>	$F_{(2,146)} = 2.402$ , $p = 0.094$	$X^2_{(2)} = 0.843$ , $p = 0.656$	$F_{(2,144)} = 0.158$ , $p = 0.854$	$F_{(2,144)} = 0.578$ , $p = 0.563$	$X^2_{(2)} = 1.061$ , $p = 0.588$

The cut-off point in “pain level” closest to the median led to a subgroup of 36 subjects with “low pain”, a pain score lower than or equal to 5, and a subgroup of 42 subjects with “high pain”, with a pain score of 6 or higher (Table 2).

**Table 2**

General subject information, i.e. age, gender, body height, body mass and handedness of the subgroups “high pain” and “low pain” in the subjects with neck and upper extremity pain are given. Moreover, statistical results of the differences between groups as tested with a one-way ANOVA or a Chi-square, are given.

Number of subjects	Age [year]	Gender % female	Body Height [cm]	Body mass [kg]	Handedness % right-handed
<b>Pain level</b>					
High pain	42 (53.8%) 36.8 (SD = 11.7) range = 19 - 61	61.9	173.8 (SD = 9.7) range = 152 - 195	73.6 (SD = 15.2) range = 49 - 115	83.3
Low pain	36 (46.2%) 41.0 (SD = 10.4) range = 19 - 62	63.9	175.4 (SD = 11.0) range = 158 - 202	75.7 (SD = 15.1) range = 50 - 108	83.3
<b>Statistical test results</b>	$F_{(1,75)} = 1.831$ $p = 0.180$	$X^2_{(1)} = 0.002$ $p = 0.966$	$F_{(1,74)} = 0.658$ $p = 0.420$	$F_{(1,74)} = 0.254$ $p = 0.616$	$X^2_{(1)} = 0.221$ $p = 0.638$

### Differences between subjects with pain, subjects with a history of pain and subjects without pain

ANOVA for repeated measures showed that there was a significant main effect of “subject group” for  $F_{\text{MEAN}}$ ,  $F_{\text{MAX}}$ , and  $F_{\text{RATIO}}$ . Bonferroni post-hoc analysis showed that  $F_{\text{MEAN}}$ ,  $F_{\text{MAX}}$ , and  $F_{\text{RATIO}}$  were significantly higher in the subjects with pain as compared to the subjects without pain (Table 3 and Figures 3 to 5). Moreover, the  $F_{\text{RATIO}}$  appeared to be significantly higher in the subjects with pain as compared to the subjects with a history of pain, whereas the latter group showed no significant differences, for any of the dependent variables, with the subjects without pain (Table 3 and Figure 5). There was no effect of “subject group” on  $a_{\text{MAX}}$  (Table 3 and Figure 6).

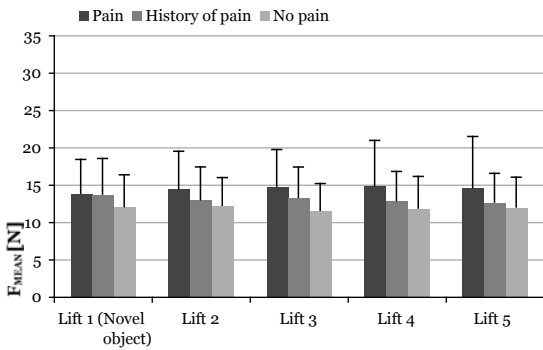
**Table 3**

Statistical results of the ANOVA repeated measures with “subject group” as a between-subject factor and “lift trial” as a within-subject factor on the dependent variables  $F_{\text{MEAN}}$ ,  $F_{\text{MAX}}$ ,  $a_{\text{MAX}}$  and  $F_{\text{RATIO}}$ .  $F$ -ratios and  $p$ -values of the between-subject effects, within-subjects effects and interaction effects are presented. An asterisk (\*) indicates significant differences at  $p < 0.05$ .

	Subject Group		Lift trial		Subject group * Lift trial	
$F_{\text{MEAN}}$	$F_{(2,149)} = 4.624$	$p = 0.011^*$	$F_{(4,596)} = 0.065$	$p = 0.992$	$F_{(8,596)} = 1.663$	$p = 0.157$
$F_{\text{MAX}}$	$F_{(2,149)} = 4.650$	$p = 0.011^*$	$F_{(4,596)} = 18.132$	$p < 0.001^*$	$F_{(8,596)} = 0.539$	$p = 0.746$
$a_{\text{MAX}}$	$F_{(2,149)} = 0.436$	$p = 0.648$	$F_{(4,596)} = 4.073$	$p = 0.004^*$	$F_{(8,596)} = 0.571$	$p = 0.782$
$F_{\text{RATIO}}$	$F_{(2,149)} = 6.284$	$p = 0.002^*$	$F_{(4,596)} = 13.346$	$p < 0.001^*$	$F_{(8,596)} = 0.337$	$p = 0.902$

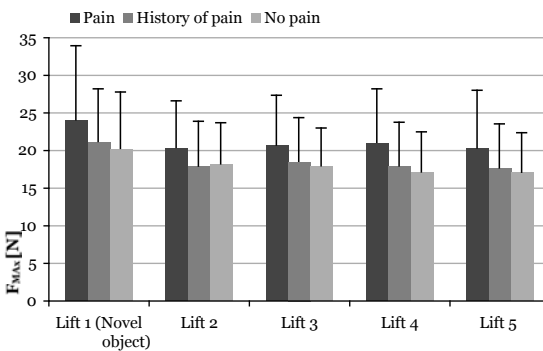
### Adaptation of grip force

$F_{\text{MAX}}$ ,  $a_{\text{MAX}}$  and  $F_{\text{RATIO}}$  were significantly affected by “lift trial” (Table 3). Bonferroni post-hoc testing showed that  $F_{\text{MAX}}$  and  $F_{\text{RATIO}}$  were both significantly larger in lift 1 as compared to the four consecutive lifts (Figures 4 and 5).  $a_{\text{MAX}}$  was significantly lower in lift 1 and lift 2 as compared to lift 5 (Figure 6). However, there was no significant interaction between “subject group” and “lift trial” for any of the dependent variables (Table 3).



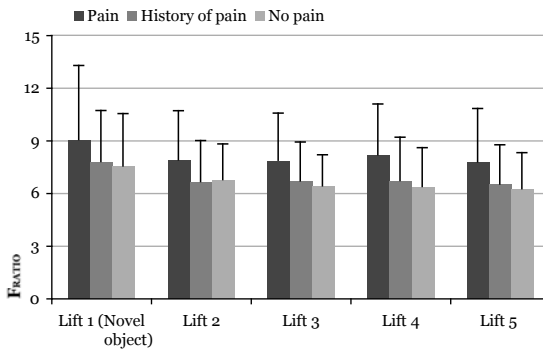
**Figure 3**

The mean force ( $F_{MEAN}$ ) in the holding phase for subjects with pain, subjects with a history of pain and subjects without pain for the five consecutive lift trials. Error bars indicate one standard deviation.



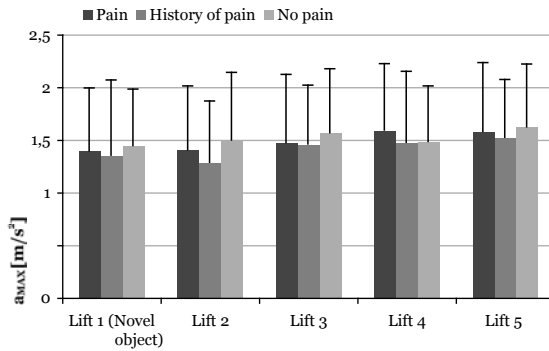
**Figure 4**

The maximum force ( $F_{MAX}$ ) in the lifting phase for subjects with pain, subjects with a history of pain and subjects without pain for the five consecutive lift trials. Error bars indicate one standard deviation.



**Figure 5**

The force ratio ( $F_{RATIO}$ ) in the lifting phase for subjects with pain, subjects with a history of pain and subjects without pain for the five consecutive lift trials. Error bars indicate one standard deviation.



**Figure 6**  
 The maximum acceleration ( $a_{MAX}$ ) in the lifting phase for subjects with pain, subjects with a history of pain and subjects without pain for the five consecutive lift trials. Error bars indicate one standard deviation.

### Differences between subgroups of subjects with pain

ANOVA for repeated measures showed no significant effect of subgroup “pain level” on  $F_{MEAN}$ ,  $F_{MAX}$  and  $a_{MAX}$  (Table 4). However, the  $F_{RATIO}$  was significantly larger in the “high pain group” as compared to the “low pain group” (Table 4). No interaction effects were found between “subgroup” and “lift trial” (Table 4).

**Table 4**

Statistical results of the ANOVA repeated measures with “subgroup” as a between-subject factor and “lift trial” as a within-subject factor on the dependent variables  $F_{MEAN}$ ,  $F_{MAX}$ ,  $a_{MAX}$  and  $F_{RATIO}$ . F-ratios and p-values of the between-subject effects, within-subjects effects and interaction effects are presented. An asterisk (\*) indicates significant differences at  $p < 0.05$ .

Subgroup “pain level”		
$F_{MEAN}$	$F_{(1,76)} = 0.944$	$p = 0.334$
$F_{MAX}$	$F_{(1,76)} = 3.278$	$p = 0.074$
$a_{MAX}$	$F_{(1,76)} = 0.337$	$p = 0.563$
$F_{RATIO}$	$F_{(1,76)} = 4.563$	$p = 0.036^*$

### Discussion

Subjects with pain in the neck and upper extremity used significantly higher grip forces, i.e.  $F_{MEAN}$ ,  $F_{MAX}$  and  $F_{RATIO}$ , as compared to subjects without pain. It is unlikely that these differences are caused by differences in lifting kinematics, since the acceleration during lifting was not different between groups. When the maximum grip force was corrected for the acceleration during lifting ( $F_{RATIO}$ ), grip force was also

significantly larger in subjects with pain as compared to subjects with a history of pain, whereas the latter group showed no differences with the subjects without pain. After the initial lift of the novel object, all subject groups adapted to the lifting task by lowering their  $F_{\text{MAX}}$  and  $F_{\text{RATIO}}$  in the second lift, to remain at a more or less constant level during the consecutive four lifts. None of the subject groups adapted their  $F_{\text{MEAN}}$  within the consecutive lifting trials. Despite the adaptation in  $F_{\text{MAX}}$  and  $F_{\text{RATIO}}$ , grip force levels were still significantly higher in the subjects with pain.

The subjects with pain in the present study were included without applying strict inclusion criteria, except for presence and duration of symptoms. This may have reduced the power of the study to detect effects, which were nevertheless found. Stricter inclusion criteria were not applied, since no specific diagnosis can be made in the majority of patients with neck and upper extremity symptoms (Sluiter et al. 2001). It is important to note that these non-specific symptoms nevertheless coincide with objectifiable changes in motor behaviour. The higher grip force found in the subjects with neck and upper extremity pain is in accordance with the higher grip force levels reported for more specific patient groups (Odergren et al. 1996; Schenk and Mai 2001; Hermsdorfer et al. 2003; Nowak et al. 2005; Nowak and Hermsdorfer 2006), for subjects with nerve dysfunctions (Thonnard et al. 1997; Lowe and Freivalds 1999), and for healthy subjects after digital cooling or anaesthesia (Johansson and Westling 1984; Nowak et al. 2001; Nowak and Hermsdorfer 2003a,b). Whereas in most of these studies grip force was measured after subjects practiced the lifting task and were familiar with the object, we studied the initial lift of a novel object, as well as the adaptation of the grip force over consecutive lifts. Subjects with neck and upper extremity pain showed comparable adaptation to the load as the subjects with a history of pain and subjects without pain, which is in line with what was previously reported for healthy subjects and subjects with focal hand dystonia (Nowak et al. 2005). The fact that subjects with pain adapted their grip forces after the initial lift indicates that there is no *general* deficit in sensory-motor integration (Nowak et al. 2005). On the other hand, after adaptation, grip force levels for subjects with pain were still higher than those for subjects without pain, which indicates that sensory-motor integration is affected. This could be caused by a deficit in the quality of sensory information, the processing of this information, in the generation of the motor output, or a combination of these factors.

The excessive grip forces observed in the present study might result from a general hyper-excitability. During other tasks, such as typing and graphical aiming, also higher force levels have been found in subjects with neck and upper extremity pain (Feuerstein et al. 1997; Bloemsaat et al. 2004), and in subjects with similar pain, such

as writer's cramp and CTS, during handling objects, writing and tool use (Lowe and Freivalds 1999; Schenk and Mai 2001). Whereas in subjects with writer's cramp indeed higher levels of co-contraction have been found (Hughes and McLellan 1985), in subjects with neck and upper extremity pain the empirical evidence for hyper-excitability, in terms of muscle activation levels, is inconclusive. Subjects with pain seem to react with either higher (Veiersted 1994; Holte and Westgaard 2002; Madeleine et al. 2003), equal (Westgaard et al. 2001; Holte and Westgaard 2002; Sjogaard et al. 2006) or lower (Sjogaard et al. 2006) levels of muscle activation as compared to healthy controls, depending on the specific task demands. Because no overall increase of muscle activity could be observed in these patients, a general hyper-excitability as an explanation for the higher grip force levels seems not likely. This suggests that the disturbance in the sensory motor integration is more likely to be the result of a sensory (processing) problem.

Studies by Byl et al. (1996a,b) point to problems in sensory processing for subjects with neck and upper extremity pain. These authors suggest that with pain a plastic reorganisation occurs of the finger representation in the primary sensory cortex. In monkeys that performed highly repetitive movements, abnormal cortical finger representation was found with enlarged and overlapping tactile receptive fields. If stimuli to the digits are not processed as individual perceptions, serious sensory and motor confusion could occur (Byl et al. 1996b), which may require higher safety margins during lifting and holding an object. Insecurity about the processed sensory information could also result from a reduction in quality of the sensory information itself. The magnitudes of grip force increases seem to reflect a difference in the severity of tactile sensory dysfunction (Nowak and Hermsdorfer 2003b), with grip forces being 300% higher in a deafferented patient (Nowak et al. 2004), 100-200% higher when there is no tactile information whatsoever to grip forces being 30-50% higher in case sensibility is only partially affected (Thonnard et al. 1997; Lowe and Freivalds 1999; Nowak and Hermsdorfer 2003a). Indications for higher grip forces with diminished sensory information can also be found in the fact that grip force levels significantly increased with glove thickness (Kinoshita 1999), with graded compression at the median nerve (Cole et al. 2003) and as a result of a median nerve block (Dun et al. 2007). The 25% higher grip forces in subjects with pain found in the present study, may well be caused by reduced sensory function, since in subjects with upper extremity pain signs of peripheral nerve dysfunction, such as higher vibration thresholds, have been reported (Greening and Lynn 1998; Jensen et al. 2002; Torgen and Swerup 2002; Jepsen and Thomsen 2006; Laursen et al. 2006). Moreover, vibration perception thresholds were found to be significantly related to pain intensity (Jensen et al. 2002; Jepsen and Thomsen 2006), which could explain why grip force levels were even higher in subjects



with high levels of pain as compared to the subjects with low pain.

These sensory problems could be a direct result of pain. Stohler et al. (2001) have shown that induced muscle pain reduces cutaneous mechanosensitivity over and contralateral to the painful area. However, acute, induced muscle pain did not affect grip force control (Smith et al. 2006). Possibly, the increase in grip force in the chronic pain patients studied reflected an adaptation to reduced sensitivity that takes longer to develop or they did not directly result from the pain but rather from concomitant impairments of nerve function (Greening et al. 2005).

Unfortunately, in the present study, no data were collected on the sensory hand function of the subjects, and even though a decline of sensory function seems a plausible explanation for the higher grip force levels found in subjects with pain, no definitive conclusion can be drawn.

If the higher grip forces would be the result of an excessive motor output, a possible intervention would be to reduce grip force to “normal” levels under visual feedback, which has been shown to work for patients with writer’s cramp (Schenk and Mai 2001). The fact that the subjects with neck and upper extremity pain were capable of adjusting their grip force levels suggests that sensory input can also be used effectively in these patients. However, if higher grip forces are the result of sensory dysfunction, as was suggested, the higher grip force levels may be a functional adaptation. Then, the focus of the intervention should be at restoring sensory function, either by removing the underlying cause of the peripheral nerve dysfunction, e.g. external pressure on the nerve or tensile forces when working in non-neutral postures, or restoring the specificity of the receptive fields of the digits.

Instead of a consequence of pain or the underlying disorder, excessive motor output as reflected by the higher grip force levels could have been an individual characteristic preceding and playing a role in the onset and perpetuation of upper extremity pain. However, in this case high grip forces should have been found in the group with a history of pain as well. The fact that this group showed a significantly lower  $F_{\text{RATIO}}$  than subjects with pain and did not differ from the subjects without pain may suggest that the higher force levels are the result of pain. This would also explain why higher typing forces have been found in subjects with upper extremity pain (Feuerstein et al. 1997), while in a prospective cohort study typing force was not found to be a risk factor for pain (Marcus et al. 2002). However, it is also possible that subjects with a history of pain have learned to use smaller grip forces after e.g. (physical) therapy, which is often focused on muscle relaxation, while they recovered from their pain.

The threshold for the ratio between grip force and load force at which an object slips from between the fingers can differ substantially between subjects. Therefore, determination of each subject's slip threshold, by gradually reducing grip force until a slip starts, has been proposed (Johansson and Westling 1984). Symptoms of sympathetic hand dysfunction, among which sweaty hands, are common in patients with neck and upper extremity pain (Pascarelli and Hsu 2001; Greening et al. 2003). These symptoms might reduce friction between fingers and object and require higher grip forces in the patient group. Nevertheless, we did not refer grip force to individual slip thresholds, as determination of the slip threshold is time-consuming and its accuracy depends on the subject's motor skill, specifically the ability to gradually reduce grip force. This could have introduced a bias, as fine-motor skills are affected and specifically the ability to gradually reduce force is affected in this patient group (Bloemsaat 2006). Therefore, subjects wore a glove to eliminate differences in slip threshold. The glove is likely to reduce the acuity of tactile information obtained with the fingers and as such the novelty of the task was the combination of lifting this object for the first time and doing this wearing the glove. We assume that effects thereof are systematic and do not affect the between group comparisons made. Obviously, the use of gloves does limit generalisability to everyday tasks.

In conclusion, subjects with neck and upper extremity pain show elevated grip force levels as compared to healthy subjects during repetitively lifting and holding an object. Since subjects with pain adapt their grip force levels after the initial lift, like subjects without pain, it seems unlikely that the higher grip force levels are the result of a *general* deficit in sensory-motor integration. The higher grip force levels may be the result of a reduced quality of sensory information.

## Acknowledgements

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# Chapter **seven**

.....  
***Should office workers spend  
fewer hours at their computer?  
A systematic review of the  
literature***  
.....

*Stefan IJmker, Maaïke A Huysmans, Birgit M Blatter,  
Allard J van der Beek, Willem van Mechelen, Paulien M Bongers*  
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## Abstract

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*Worldwide, millions of office workers use a computer. Reports of adverse health effects due to computer use have received considerable media attention. This systematic review summarises the evidence for a relation between the duration of work time spent using the computer and the incidence of hand-arm and neck-shoulder symptoms and disorders. Several databases were systematically searched up to 6 November 2005. Two reviewers independently selected articles that presented a risk estimate for the duration of computer use, included an outcome measure related to hand-arm or neck-shoulder symptoms or disorders, and had a longitudinal study design. The strength of the evidence was based on methodological quality and consistency of the results. Nine relevant articles were identified, of which six were rated as high quality. Moderate evidence was concluded for a positive association between the duration of mouse use and hand-arm symptoms. For this association, indications for a dose-response relationship were found. Risk estimates were in general stronger for the hand-arm region than for the neck-shoulder region, and stronger for mouse use than for total computer use and keyboard use. A pathophysiological model focusing on the overuse of muscles during computer use supports these differences. Future studies are needed to improve our understanding of safe levels of computer use by measuring the duration of computer use in a more objective way, differentiating between total computer use, mouse use and keyboard use, attaining sufficient exposure contrast, and collecting data on disability caused by symptoms.*

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## Introduction

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The large-scale introduction of computers in the workplace has led to hundreds of millions of computer users worldwide (Andries et al. 2002; Freeman 2002). In many countries the widespread use of computers has led to considerable media attention concerning potential adverse health effects.

In the scientific literature, the rise and fall of an epidemic of “repetitive strain injuries” (i.e. workers reporting and claiming compensation for disorders of hand, arm, shoulder or neck) in Australia during the 1980s has been fuelling the debate whether computer use at work is a potential occupational hazard (Hall and Marrow 1988). Proponents stated that repetitive movements and static load due to constrained working postures caused the “injuries”. Critics focused on the absence of objective clinical signs among patients and the role of a liberal compensation system, offering large sums of money to workers who felt unable to work due to hand, arm, shoulder or neck symptoms (Bammer and Martin 1988). Some authors argued that lost lawsuits of workers against their employers were a main contributing factor to the decline of the epidemic (Szabo and King 2000). In 1988, Bammer and Martin (1988) concluded that the debate was characterised by a lack of empirical evidence to support many of the assertions made by both the proponents and the critics of the work-relatedness of repetitive strain injuries.

In this review, we will focus on the empirical evidence available for an association between the duration of work time spent using the computer (referred to as “duration of computer use”) and hand, arm, shoulder or neck symptoms and disorders. Previous reviews suggest that an association between the duration of computer use and disorders of hand, arm, shoulder or neck is present. In addition, computer use might be more strongly related to disorders of the hand and arm, than to disorders of the neck and shoulders (Punnett and Bergqvist 1997; Tittiranonda et al. 1999; Gerr et al. 2004; Wahlstrom 2005). However, the limitation of these reviews is that they are mainly based on cross-sectional studies (Punnett and Bergqvist 1997; Tittiranonda et al. 1999; Gerr et al. 2004). Cross-sectional studies cannot disentangle causes and effects and are therefore considered to be inferior to longitudinal studies (Rothman and Greenland 1998). The recent narrative review by Wahlstrom (2005) includes only part of the available longitudinal studies.

In order to get a more conclusive insight in the relationship between the duration of computer use and the incidence of hand-arm and neck-shoulder symptoms and disorders, a systematic review of longitudinal studies was performed. Since information on potential

dose-response relationships is lacking, specific attention will be paid to this issue.

## Methods

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### Search strategy

Publications were retrieved by a computerised search of the following databases: MEDLINE (from 1950 to November 2005), NIOSHTIC 2, CISDOC, HSELINE, MHIDAS, OSHLINE (all from 1985 to April 2005) and PSYCINFO (from 1967 to April 2005). The databases were searched for published articles up to 6 November 2005. The keywords included: retrospective, prospective, longitudinal, follow-up, computer, keyboard, mouse, office, display, VDU, VDT, terminal, neck, shoulder, elbow, wrist, hand, upper extremity, upper limb, musculoskeletal, pain, physical symptom, physical health. After inclusion of the articles based on the selection criteria, references were checked for additional articles. Finally, personal databases of the authors were searched for relevant articles.

### Selection criteria

Two reviewers (SIJ and MAH) independently selected relevant articles from the articles retrieved with the search strategy. The articles were selected based on the abstracts. If abstracts provided insufficient information, the full text of the articles was used. The selection criteria were: 1) the study population included computer workers, 2) the outcome included one or more syndromes, signs or symptoms related to pain or discomfort in hand, arm, shoulder or neck, 3) a risk estimate of the association between the duration of computer use, mouse use, or keyboard use and a relevant outcome measure (see 2) was presented, 4) the study had a longitudinal design (i.e. at least one follow-up measurement after baseline), and 5) the study was a full text, peer-reviewed article, written in English, Dutch or German. Experimental studies, letters and abstracts were excluded.

### Quality assessment

The articles that met the selection criteria were evaluated for methodological quality. We used a quality assessment list for prospective cohort studies, based on previous systematic reviews of risk factors for musculoskeletal disorders (Hoogendoorn et al. 1999; Ariens et al. 2000; Van der Windt et al. 2000; Hooftman et al. 2004). The full list of items is presented in Table 1.



Two reviewers (SIJ and MAH) independently assessed the quality of the studies. All items were scored as positive, negative or unclear (i.e. meaning that insufficient information was available). For each item, the scoring of the two reviewers was compared. In case of disagreement, consensus was reached during a meeting. If agreement could not be reached, a third reviewer (AvdB) decided in the matter. Subsequently, the first author of the included articles was contacted to provide an opportunity to discuss the quality assessment of their article(s). Methodological quality assessment was based on the percentage of positive items over the total number of items. A high quality study was defined as scoring positive on more than 50% of the items, which is in concordance with previously published systematic reviews (Hoogendoorn et al. 1999; Ariens et al. 2000; Van der Windt et al. 2000; Hooftman et al. 2004).

**Table 1**

*Quality assessment list for prospective cohort studies.*

<b>Study design</b>
1. Was the participation rate at baseline at least 80% OR, if participation rate was < 80%, not selective regarding exposure (i.e. duration of computer use) and potential confounders (i.e. at least for gender and age)?
2. Was the response at follow-up at least 80% OR, if the response was < 80%, not selective regarding exposure (i.e. duration of computer use), potential effect modifiers (i.e. at least gender and age) and outcome (i.e. hand, arm, shoulder and neck symptoms or disorders)?
<b>Exposure assessment</b>
3. Were the data on duration of computer use collected using standardised methods of acceptable quality? *
4. Were the data on ergonomic factors collected using standardised methods of acceptable quality? *
5. Were the data on psychosocial factors collected using standardised methods of acceptable quality? †
6. Were data on physical factors during leisure time collected and used in the analysis?
7. Were data on exposure change regarding the duration of computer use during the follow-up period (for example due to job change) collected and used in the analysis?
<b>Outcome assessment</b>
8. Were the data on outcome collected using standardised methods of acceptable quality? ‡
<b>Data analysis</b>
9. Was the statistical method used appropriate for the outcome studied and was a measure of association presented, including confidence intervals or <i>p</i> -value?
10. Was the statistical analysis tested for confounding by gender and age?
11. Was the number of subjects in the multivariate analysis at least 10 times the number of independent variables?
* ICC > 0.60 or Kappa > 0.40 for test-retest reliability or interobserver reliability. Additionally for self-reports: ICC > 0.60 or Kappa > 0.40 or $r > 0.75$ for agreement with observation or direct measurement.
† ICC > 0.60 or Kappa > 0.40 for test-retest reliability. Additionally for self-reports, in the case of using scales: Cronbachs alpha > 0.70 for the majority of scales used.
‡ ICC > 0.60 or Kappa > 0.40 or $r > 0.75$ for test-retest reliability or interobserver reliability, or if (modified) Nordic questionnaire was used. (Kuorinka et al. 1987; Baron et al. 1996; Palmer et al. 1999).

## Data extraction

Details on study population, exposure assessment, outcome assessment and data analysis were extracted from all articles. To examine the agreement between the two reviewers for the selection of articles and for the methodological quality assessment, Cohen's Kappa coefficients were calculated.

To evaluate the associations between the duration of computer use and hand, arm, shoulder and neck disorders, we decided to stratify according to the measure of computer use that was reported (total computer use, mouse use or keyboard use) and according to the location of the symptoms or disorders (i.e. neck-shoulder or hand-arm). Elbow symptoms were classified as hand-arm symptoms.

An association was scored as positive if the risk estimate (Odds Ratio, Rate Ratio or Hazard Ratio) was statistically significant, or if at least one of the presented exposure categories showed a point estimate larger than 2.0 (or smaller than 0.5).

## Levels of evidence

In order to summarise the results of the studies, we used levels of evidence.

*Strong evidence* was defined as consistent results for all tested associations, including at least two high quality studies. We anticipated that one article could present multiple associations for different case definitions and that multiple articles could present associations for the same cohort of workers. Therefore, multiple positive associations from the same cohort of workers were counted as one study. The criterion of consistent results was met if at least 75% of all tested associations for the risk factor were positive (i.e. provided a statistically significant risk estimate or a risk estimate larger than 2.0 or smaller than 0.5).

*Moderate evidence* was defined as consistent results for all tested associations (with a minimum of three associations tested) or consistent results for at least two high quality studies, irrespective of the findings from medium quality studies for that association.

*Insufficient evidence* was defined as inconsistent results for all tested associations, including the situation in which less than three associations were evaluated.

## Dose-response analysis

The dose-response relationship was evaluated if at least moderate evidence was available for an increased risk of developing hand-arm or neck-shoulder symptoms or disorders. We assessed dose-response qualitatively by plotting the point estimates against the exposure categories. Therefore, we extracted the point estimates for all

reported exposure categories. We used the middle value of the lower and upper limit to reflect the average duration of computer use for that exposure category. If there was no upper limit for the highest exposure category, we conservatively used the lower limit to reflect the duration of computer use. Some studies presented exposure categories as a percentage of working time. Based on the distribution of working hours at baseline, we estimated the average number of working hours for the whole population and multiplied this average with the percentage of computer use to calculate the average duration of computer use for each exposure category. A general increase of risk (i.e. higher point estimates) over increasing duration categories for most studies was considered as evidence for a dose-response relationship.

## Results

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### Search results

The search strategy resulted in 277 hits. Applying the selection criteria resulted in nine articles. We excluded the longitudinal study by Lindstrom et al. (1997), because cross-sectional analyses were performed. The two reviewers initially disagreed on the selection of one article, resulting in a kappa of 0.94. The references of the included articles provided one other article (Bergqvist et al. 1992). The final set of articles was based on five cohorts of workers: 1) the BIT-study (Jensen 2003), 2) the NUDATA study (Andersen et al. 2003; Kryger et al. 2003; Brandt et al. 2004; Lassen et al. 2004), 3) Bergqvist et al. (1992) 4) Marcus et al. (2002), and 5) Korhonen et al. (2003). See Table 2 for the characteristics and results of the included articles.

**Table 2**  
Characteristics and results of the included articles.

<b>Cohort</b>	<b>Assessment duration of computer use</b>	<b>Case definition(s)</b>	<b>Results</b>	<b>Results continued</b>
<b>First author Quality score</b>	<b>Study population</b>			
<b>BIT Jensen (2003)</b> 42%	Self-report "How much of your work time do you work with your computer (including overtime and working at home)" Response categories: Seldom; 25%; 50%; 75%; 100%	Self-reported symptoms for more than 7 days within the last year of the follow-up period.  Body regions studied: neck and hand-wrist	<b>Neck</b> Total computer use: - 0-25% of work time OR 1.5 (0.7-3.1) - 50% of work time OR 1.3 (0.6-2.7) - 75% of work time OR 1.6 (0.8-3.3) - 100% of work time OR 2.3 (1.2-4.3) <b>Mouse use:</b> - Seldom OR 1.3 (0.4-4.3) - 25% of work time OR 1.7 (0.5-5.7) - 50-100% of work time OR 4.0 (1.0-15.5)	<b>Hand-wrist</b> Total computer use: - 0-25% of work time OR 1.5 (0.7-2.4) - 50% of work time OR 1.3 (0.6-2.7) - 75% of work time OR 2.0 (1.1-3.9) - 100% of work time OR 2.3 (1.2-4.3) <b>Mouse use:</b> - Seldom OR 4.0 (1.1-14.4) - 25% of work time OR 1.7 (0.5-5.7) - 50-100% of work time OR 4.0 (1.0-15.5)
<b>BIT Juul-Kristensen et al. (2004)</b> 42%	See Jensen Analyses restricted to workers who held the same job during follow-up. N = 2002	<b>Duration outcome</b> Self-reported symptoms < 8 days in the past 12 months at baseline and > 7 days during follow-up <b>Intensity outcome</b> Self-reported symptom intensity < 4 (scale 0-9) during last 3 months at baseline and > = 4 during last 3 months at baseline + nonsymptomatic at both sides (left and right) and nonsymptomatic in nearby body regions  Body regions studied: elbow and shoulder	<b>Shoulder duration outcome</b> Total computer use: - 0-25% of work time OR 1.23 (0.63-2.40) - 50% of work time OR 1.00 (0.51-1.94) - Almost all work time OR 0.69 (0.34-1.39) <b>Shoulder intensity outcome</b> Total computer use: - 0-25% of work time OR 1.07 (0.60-1.90) - 50% of work time OR 0.95 (0.53-1.70) - Almost all work time OR 0.78 (0.43-1.43)	<b>Elbow duration outcome</b> Total computer use: - 50% of work time OR 1.11 (0.51-2.40) - 75% of work time OR 0.95 (0.43-2.10) - Almost all work time OR 1.08 (0.48-2.39) <b>Elbow intensity outcome</b> Total computer use: - 50% of work time OR 1.12 (0.58-2.18) - 75% of work time OR 0.90 (0.47-1.74) - Almost all work time OR 1.08 (0.48-2.39)

Cohort	Study population	Assessment duration of computer use	Case definition(s)	Results
<p><b>NUDATA Andersen et al. (2003)</b> 50%</p>	<p>Employees from the Danish Association of Professional Technicians, i.e. technical assistants (draughtsmen) and machine technicians from 3527 public and private companies. Job tasks included technical drawing tasks, administrative and graphical tasks. N = 5658</p>	<p>Self-report Participants estimated their average hours per week doing specified work tasks during the past four weeks (separately for tasks using the computer and tasks not using the computer). Questions for keyboard use and mouse use separately. Computer use (=mouse use + keyboard use) not used in the analysis due to high correlation with mouse use.</p>	<p><b>Possible Carpal Tunnel Syndrome (CTS):</b> Self-reported tingling or numbness in the right hand at least once a week within the last 3 months, with no or minor tingling/numbness at baseline.  Body regions studied: wrist (possible CTS)</p>	<p><b>Wrist (possible CTS)</b> Mouse use: - 0 - &lt; 2.5 hrs/wk OR 1 - 2.5 - &lt; 5 hrs/wk OR 0.7 (0.3-1.9) - 5 - &lt; 10 hrs/wk OR 1.9 (0.9-4.0) - 10 - &lt; 15 hrs/wk OR 1.6 (0.8-3.3) - 15 - &lt; 20 hrs/wk OR 2.0 (0.9-4.2) - 20 - &lt; 25 hrs/wk OR 2.6 (1.2-5.5) - 25 - &lt; 30 hrs/wk OR 3.2 (1.3-7.9) Keyboard use: - 0 - &lt; 2.5 hrs/wk OR 1 - 2.5 - &lt; 5 hrs/wk OR 0.9 (0.4-1.8) - 5 - &lt; 10 hrs/wk OR 0.8 (0.4-1.5) - 10 - &lt; 15 hrs/wk OR 1.2 (0.6-2.5) - 15 - &lt; 20 hrs/wk OR 0.8 (0.4-1.5) - &gt; = 20 hrs/wk OR 1.4 (0.5-4.3)</p>
<p><b>NUDATA Kryger et al. (2003)</b> 42%</p>	<p>See Andersen</p>	<p>Self-report See Andersen</p>	<p>At least moderate to severe self-reported pain in the forearm within the past 7 days combined with quite a lot pain/discomfort during the past 12 months and at baseline none or less than moderate pain in the forearm in the past 7 days combined with less than "some" pain/tenderness during the past 12 months</p> <p>Body regions studied: forearm</p>	<p><b>Forearm</b> Mouse use: - 0-9 hrs/wk OR 1 - 10-19 hrs/wk OR 2.2 (1.0-4.7) - 20-29 hrs/wk OR 2.6 (1.0-6.6) - &gt; = 30 hrs/wk OR 8.4 (2.5-29) Keyboard use: - 0-4 hrs/wk OR 1 - 5-9 hrs/wk OR 1.2 (0.5-2.9) - 10-14 hrs/wk OR 1.3 (0.5-3.4) - &gt; = 15 hrs/wk OR 2.6 (0.9-7.3)</p>

\*hours per week

Cohort	Study population	Assessment duration of computer use	Case definition(s)	Results	Results continued
NUDATA Brandt et al. (2004) 42%	See Andersen	Self-report See Andersen	Self-reported pain in the last 7 days of at least moderate degree and pain during the last 12 months of follow-up that bothered at least quite a lot and no complaints in the region during the 12 months prior to the baseline examination and less than moderate pain in the regional area during the last 7 days at baseline	<p><b>Neck</b></p> <p>Mouse use:</p> <ul style="list-style-type: none"> <li>- 0-9 hrs/wk OR 1</li> <li>- 10-19 hrs/wk OR 1.1 (0.6-1.9)</li> <li>- 20-29 hrs/wk OR 0.9 (0.4-1.9)</li> <li>- &gt;= 30 hrs/wk OR 2.4 (0.8-6.8)</li> </ul> <p>Keyboard use:</p> <ul style="list-style-type: none"> <li>- 0-4 hrs/wk OR 1</li> <li>- 5-9 hrs/wk OR 1.1 (0.5-2.2)</li> <li>- 10-14 hrs/wk OR 1.0 (0.4-2.2)</li> <li>- &gt;= 15 hrs/wk OR 1.8 (0.8-3.9)</li> </ul>	<p><b>Shoulder</b></p> <p>Mouse use:</p> <ul style="list-style-type: none"> <li>- 0-9 hrs/wk OR 1</li> <li>- 10-19 hrs/wk OR 1.2 (0.7-2.1)</li> <li>- 20-29 hrs/wk OR 1.9 (1.0-3.5)</li> <li>- &gt;= 30 hrs/wk OR 3.3 (1.2-8.9)</li> </ul> <p>Keyboard use:</p> <ul style="list-style-type: none"> <li>- 0-4 hrs/wk OR 1</li> <li>- 5-9 hrs/wk OR 1.3 (0.7-2.6)</li> <li>- 10-14 hrs/wk OR 1.6 (0.8-3.3)</li> <li>- &gt;= 15 hrs/wk OR 2.2 (1.0-4.9)</li> </ul>
NUDATA Lassen et al. (2004) 42%	See Andersen	Self-report See Andersen	<p><b>Case</b></p> <p>Any self-reported pain or discomfort during the past 12 months, but not at baseline</p> <p><b>Severe case</b></p> <p>Self-reported pain or discomfort lasting for &gt; 30 days and causing at least "quite a lot of trouble" during the past 12 months at follow-up, but not at baseline</p> <p>Body region studied: elbow and hand-wrist</p>	<p><b>Elbow case</b></p> <p>Mouse use:</p> <ul style="list-style-type: none"> <li>- &lt; 2.5 hrs/wk OR 1</li> <li>- 2.5 - &lt; 5 hrs/wk OR 3.21 (2.03-5.17)</li> <li>- 5 - &lt; 10 hrs/wk OR 4.83 (2.79-8.40)</li> <li>- 10 - &lt; 15 hrs/wk OR 4.74 (2.51-8.95)</li> </ul> <p>Keyboard use:</p> <ul style="list-style-type: none"> <li>- 0 - &lt; 2.5 hrs/wk OR 1</li> <li>- 2.5 - &lt; 5 hrs/wk OR 1.04 (0.65-1.69)</li> <li>- 5 - &lt; 10 hrs/wk OR 1.47 (0.98-2.26)</li> <li>- 10 - &lt; 15 hrs/wk OR 1.33 (0.85-2.11)</li> <li>- &gt;= 15 hrs/wk OR 1.29 (0.78-2.17)</li> <li>- &gt;= 20 hrs/wk OR 1.98 (0.96-3.95)</li> </ul>	<p><b>Hand-wrist case</b></p> <p>Mouse use:</p> <ul style="list-style-type: none"> <li>- &lt; 2.5 hours/week OR 1</li> <li>- 2.5 - &lt; 5 hrs/wk OR 1.57 (0.99-2.51)</li> <li>- 5 - &lt; 10 hrs/wk OR 2.16 (1.46-3.22)</li> <li>- 10 - &lt; 15 hrs/wk OR 2.05 (1.37-3.07)</li> <li>- 15 - &lt; 20 hrs/wk OR 2.46 (1.65-3.72)</li> <li>- 20 - &lt; 25 hrs/wk OR 2.07 (1.32-3.26)</li> <li>- 25 - &lt; 30 hrs/wk OR 3.16 (1.82-5.46)</li> <li>- &gt;= 30 hrs/wk OR 3.05 (1.63-5.67)</li> </ul> <p>Keyboard use:</p> <ul style="list-style-type: none"> <li>- Increase of 10 hrs/wk OR 1.29 (1.06-1.57)</li> <li>- 0 - &lt; 2.5 hrs/wk OR 1</li> <li>- 2.5 - &lt; 5 hrs/wk OR 0.63 (0.41-0.98)</li> <li>- 5 - &lt; 10 hrs/wk OR 0.73 (0.50-1.07)</li> </ul>

Cohort	Study population	Assessment duration of computer use	Case definition(s)	Results	Results continued
NUDATA Lassen et al. (2004) Continued			<p><b>Hand-wrist case</b> Keyboard use (continued): - 10 - &lt; 15 hrs/week OR 0.80 (0.53-1.20) - 15 - &lt; 20 hrs/week OR 0.87 (0.55-1.38) - &gt; = 20 hrs/week OR 1.04 (0.51 -2.04)</p> <p><b>Severe elbow case</b> Mouse use: - &lt; 2.5 hrs/wk OR 1 - 2.5 - &lt; 5 hrs/wk OR 1.16 (0.34-3.54) - 5 - &lt; 10 hrs/wk OR 1.42 (0.58-3.64) - 10 - &lt; 15 hrs/wk OR 2.14 (0.93-5.32) - 15 - &lt; 20 hrs/wk OR 1.45 (0.59-3.78) - 20 to &lt; 25 hrs/wk OR 2.88 (1.18-7.54) - 25 to &lt; 30 hrs/wk OR 4.16 (1.45-12.13) - &gt; = 30 hrs/wk OR 6.91 (2.21-22.53)</p> <p>Keyboard use: - &lt; 2.5 hrs/wk OR 1 - 2.5 - &lt; 5 hrs/wk OR 1.09 (0.44-3.00) - 5 - &lt; 10 hrs/wk OR 1.58 (0.71-4.03) - 10 to &lt; 15 hrs/wk OR 2.49 (1.08-6.55) - 15 to &lt; 20 hrs/wk OR 2.86 (1.08-8.12) - &gt; = 20 hrs/wk OR 3.79 (0.91-14.11)</p>	<p><b>Hand-wrist case</b> Mouse use: - &lt; 2.5 hrs/week OR 1 - 2.5 - &lt; 5 hrs/wk OR 0.73 (0.23-2.01) - 5 - &lt; 10 hrs/wk OR 1.55 (0.74-3.34) - 10 - &lt; 15 hrs/wk OR 1.40 (0.68-3.01) - 15 - &lt; 20 hrs/wk OR 1.68 (0.82-3.58) - 20 to &lt; 25 hrs/wk OR 4.21 (2.12-8.85) - 25 to &lt; 30 hrs/wk OR 4.81 (2.18-10.99) - &gt; = 30 hrs/wk OR 2.30 (0.83-6.26)</p> <p>Keyboard use: - &lt; 2.5 hrs/wk OR 1 - 2.5 - &lt; 5 hrs/wk OR 1.14 (0.58-2.38) - 5 - &lt; 10 hrs/wk OR 0.99 (0.54-1.95) - 10 to &lt; 15 hrs/wk OR 1.46 (0.76-2.98) - 15 to &lt; 20 hrs/wk OR 1.89 (0.90-4.10) - &gt; = 20 hrs/wk OR 1.60 (0.43-4.94)</p>	
Bergqvist Bergqvist et al. (1992) 42%	Employees working for seven companies in Stockholm, Sweden: travel agencies, a newspaper production company, postal office, and an insurance company. Included employees worked at least 75% of a full time contract. N = 341	Self-report "How many hours per week did you work at the Visual Display Terminal?" Responses were categorized into three categories: no or occasional; < 30 hours/week; > 30 hours/week	Current self-reported pain or discomforts. Symptoms that occurred only occasionally and were of insignificant intensity were not taken into account.  Body regions studied: neck-shoulder; hand-wrist	<p><b>Neck-shoulder</b> Total computer use: - &gt; 30 hrs/wk versus no or occasional total computer use RR 1.25 (0.76-2.05) [univariate analysis]</p> <p><b>Hand-wrist</b> Total computer use: - &gt; 30 hrs/wk versus no or occasional total computer use RR 3.75 (0.89-15.81) [univariate analysis]</p>	



Assessment duration		Assessment duration	
Cohort	Study population	Case definition(s)	Results
<b>Marcus (2002)</b> 75%	Newly hired workers who 1) anticipated using a computer for at least 15 hrs/wk, and 2) anticipated using a computer keyboard for at least as many hrs/wk as in their previous job. Job sectors included insurance, finance, food production, health care, and education. N = 436 – 520	<b>Musculoskeletal symptoms</b> Self-reported discomfort in weekly diary which was present at least one day during previous week and pain score (VAS) > 6 or using medication for control of the discomfort. <b>Musculoskeletal disorders</b> Positive if case definition for musculoskeletal symptoms was met and physical examination was positive.	<b>Neck-shoulder symptoms</b> Total computer use: - Increase of 1 hr/wk HR 1.01 (0.99-1.03) - 35 hrs/wk versus 15 hrs/wk HR 1.22 (0.82 - 1.81) <b>Neck-shoulder disorders</b> Total computer use: - Increase of 1 hr/wk HR 1.01 (0.99-1.04) - 35 hrs/wk versus 15 hrs/wk HR 1.22 (0.82 - 2.19)
<b>Korhonen et al. (2003)</b> 50%	Full time working employees from three municipal administrative units. N = 138	Local or radiating self-reported neck pain at follow-up for at least 8 days during the last 12 months AND experiencing local or radiating neck pain < 8 days at baseline.  Body regions studied: neck	<b>Hand-arm symptoms</b> Total computer use: - Increase of 1 hr/wk HR 1.04 (1.02-1.06) - 35 hrs/wk versus 15 hrs/wk HR 2.19 (1.49 - 3.20) <b>Hand-arm disorders</b> Total computer use: - Increase of 1 hr/wk HR 1.04 (1.02-1.06) - 35 hrs/wk versus 15 hrs/wk HR 2.19 (1.49 - 3.20)
	Estimate how many percent of your working time during the preceding month you have used for each task of the following tasks (VDU work includes using keyboard or other input or control device, including short thinking periods and checking the results on the screen). Response categories: < 50%, > 50% of work time		<b>Neck</b> Total computer use: - < 50% of work time OR 1 - > = 50% of work time OR 1.0 (0.6-2.9) [univariate analysis]

## Methodological quality assessment

Methodological quality assessment of the articles is presented in Table 3. The kappa coefficient for the agreement between the ratings of the individual items (positive versus negative or unclear) of the two reviewers was 0.91 (disagreement on 5 out of 108 scored items). One item needed a decision of the third reviewer (AvdB); agreement on the other items was reached during the consensus meeting. Eight out of nine corresponding authors replied to our invitation to discuss the quality assessment. Based on the information, five unclear scores were replaced by positive scores. Six studies had a quality score exceeding 50%, which we considered as the cut-off point for high quality (Marcus et al. 2002; Andersen et al. 2003; Korhonen et al. 2003; Kryger et al. 2003; Brandt et al. 2004; Lassen et al. 2004).

**Table 3**

*Results of the methodological quality assessment.*

Cohort First Author	Study Design		Exposure and Outcome Assessment						Data Analysis			Score (%)
	1. Participation Rate	2. Response at Follow-up	3. Duration Computer Use	4. Ergonomic Factors	5. Psychosocial Factors	6. Physical Factors Leisure Time	7. Exposure Change	8. Outcome	9. Statistical Model	10. Confounding	11. Statistical Power	
<b>BIT</b>												
- Jensen et al. (2003)	?	?	?	?	?	-	+	+	+	+	+	<b>45</b>
- Juul-Kristensen et al. (2004)	?	?	?	?	?	-	+	+	+	+	+	<b>45</b>
<b>NUDATA</b>												
- Andersen et al. (2003)	?	+	?	?	?	+	+	+	+	+	+	<b>64</b>
- Kryger et al. (2003)	?	+	?	?	?	+	?	+	+	+	+	<b>55</b>
- Brandt et al. (2004)	?	+	?	?	?	+	?	+	+	+	+	<b>55</b>
- Lassen et al. (2004)	?	+	?	?	?	+	?	+	+	+	+	<b>55</b>
<b>Bergqvist</b>												
- Bergqvist et al. (1992)	+	+	?	?	?	?	+	?	+	-	+	<b>45</b>
<b>Marcus</b>												
- Marcus et al. (2002)	+	+	?	+	?	+	+	?	+	+	+	<b>73</b>
<b>Korhonen</b>												
- Korhonen et al. (2003)	+	?	?	?	?	+	?	+	+	+	+	<b>55</b>
<b>Positive (%)</b>	<b>33</b>	<b>67</b>	<b>0</b>	<b>11</b>	<b>0</b>	<b>67</b>	<b>56</b>	<b>78</b>	<b>100</b>	<b>89</b>	<b>100</b>	

\* the percentage of positive items over the total number of items

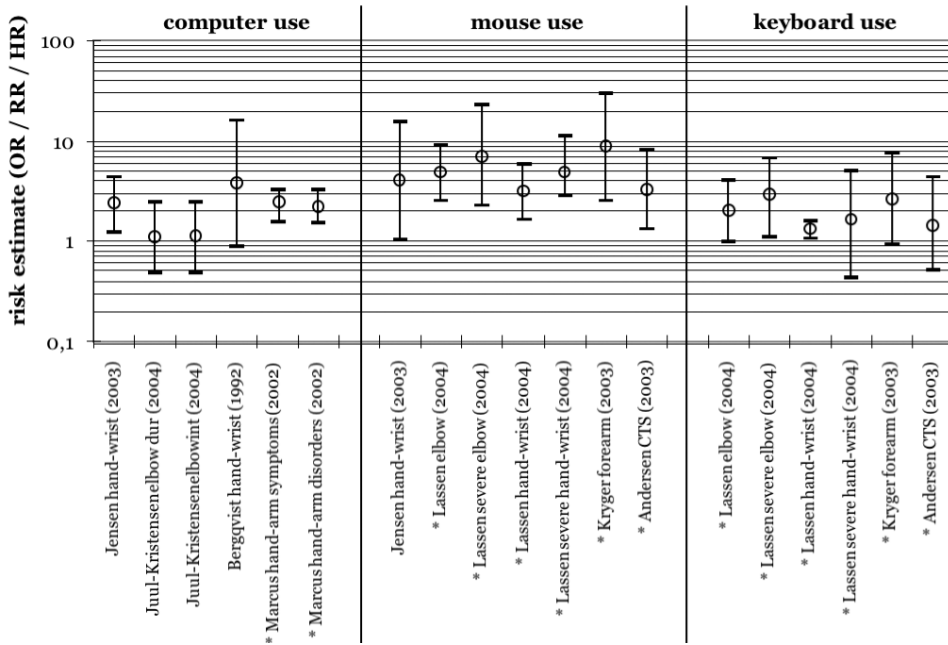
+ = positive, - = negative and ? = unclear (insufficient information available)

## Levels of evidence

Figures 1 and 2 present point estimates and 95% confidence intervals, derived from the original articles, for the associations between the duration of total computer use, mouse use and keyboard use and hand-arm and neck-shoulder symptoms and disorders, respectively. We excluded one of the associations studied by Bergqvist et al. (1992), because the case-definition involved anatomical locations from both the hand-arm and the neck-shoulder region. Risk estimates were in general larger for mouse use than for total computer use and keyboard use. For neck-shoulder symptoms and disorders, fewer associations were positive than for hand-arm symptoms and disorders.

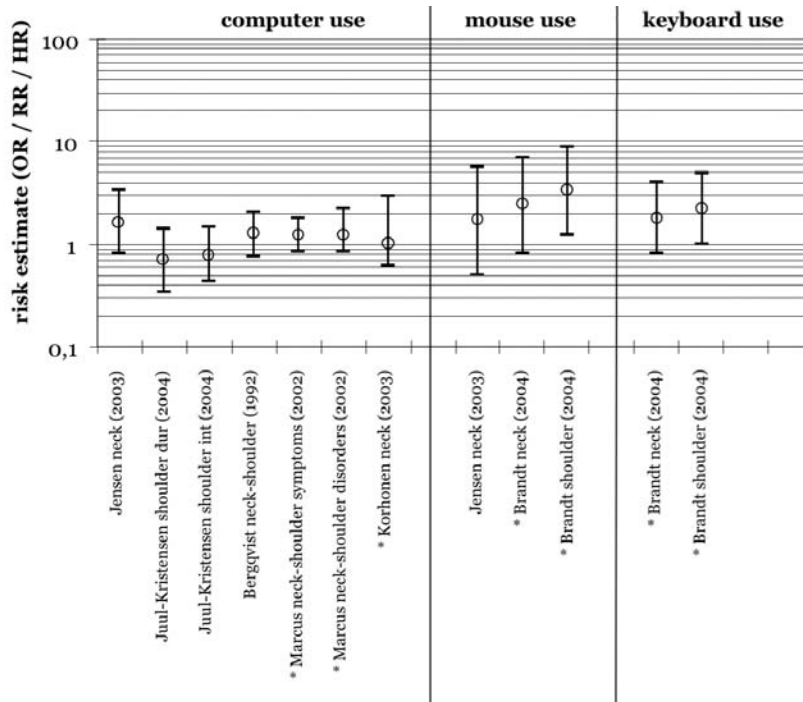
For hand-arm symptoms and disorders, moderate evidence was concluded for the association with duration of mouse use, since all studies showed a positive association, including three high quality studies based on the NUDATA cohort (Andersen et al. 2003; Kryger et al. 2003; Lassen et al. 2004). However, these were counted as one study. For the duration of total computer use and the duration of keyboard use insufficient evidence was concluded, since inconsistent results were found. For the duration of total computer use, associations from three cohorts were available. Only the NUDATA cohort investigated the duration of keyboard use.

For neck-shoulder symptoms and disorders, insufficient evidence was concluded for the duration of mouse use and the duration of keyboard use, since inconsistent results were found. For both mouse and keyboard use only the NUDATA cohort investigated the association with neck-shoulder symptoms and disorders. For the duration of total computer use, all tested associations failed to show a positive association. Four cohorts investigated total computer use, including two high quality studies (Marcus et al. 2002; Korhonen et al. 2003).



**Figure 1**

*Risk estimates for the association between duration of computer use and hand-arm symptoms and disorders. See the italic numbers in the results columns of Table 2 for exact values (\* = High quality study).*

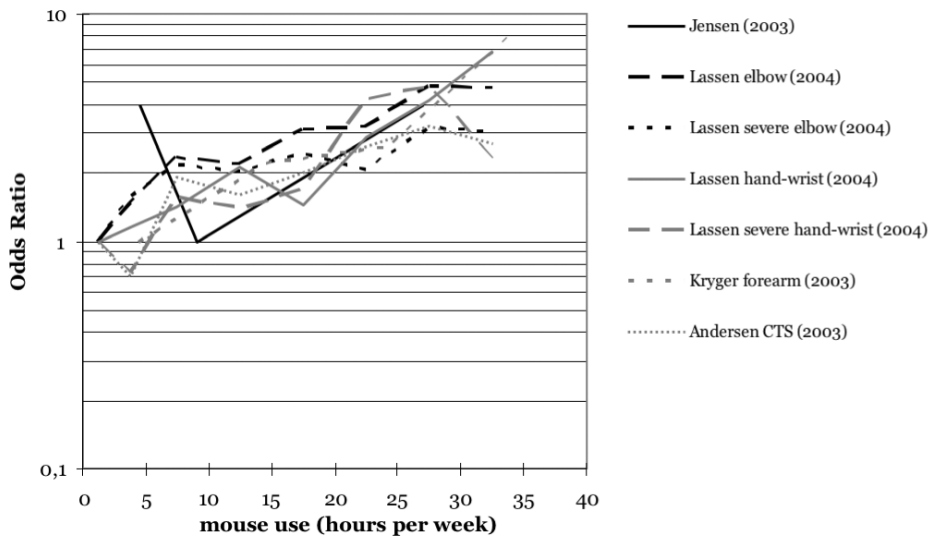


**Figure 2**

*Risk estimates for the association between duration of computer use and neck-shoulder symptoms and disorders. See the italic numbers in the results columns of Table 2 for exact values (\* = High quality study).*

### Dose-response analysis

Following the criteria set beforehand, we analysed the relationship between the duration of mouse use and the incidence of hand-arm symptoms. In general, an increase in risk over duration categories can be observed from Figure 3. However, the association between mouse use and hand-wrist symptoms reported by Jensen (2003) and the association between mouse use and “severe” hand wrist pain found by Lassen et al. (2004) did not show a clear increasing risk over duration categories (see Figure 3). Jensen (2003) reported an increased risk (OR 4.0) at a rather short duration of mouse use (i.e. approximately 4.5 hours per week), as well as an increased risk (OR 4.0) at a long duration of mouse use (i.e. approximately 27 hours per week). Lassen et al. (2004) presented a drop in risk from 4.8 to 2.3 for their highest exposure category (i.e. > 30 hours per week).



**Figure 3**  
 Odds Ratios for the association between the duration of mouse use and hand-arm symptoms.

## Discussion

The results of this review of longitudinal studies confirm the finding of previous reviews. The duration of computer use was more consistently associated with hand-arm than with neck-shoulder symptoms and disorders (Punnett and Bergqvist 1997; Wahlstrom 2005). In addition, our review adds to the existing literature the observation that the duration of mouse use was more strongly and more consistently associated with the incidence of hand-arm symptoms than the duration of total computer use and keyboard use.

## Methodological considerations

The studies included in this review all have substantial methodological quality, since they were based on longitudinal study designs and all but one scored positive on the quality items concerning statistical analysis. Still, the design of future studies might be improved by taking into account a number of methodological limitations that are present in the published studies.

First, all studies used self-report measurements to assess the duration of computer use. No study reported data on the test-retest reliability of these self-reports. Low test-retest reliability might be related to a poor validity of exposure measures. Moreover, several studies have shown that self-report measurements, on average, strongly overestimate the duration of computer use, resulting in misclassification (Heinrich et al. 2004; Lassen et al. 2005). Assuming that this misclassification is non-differential, this would lead to an underestimation of the true exposure-response relationship (Armstrong 1998). A recent development is the use of computer software to objectively measure the duration of computer use. Such software showed good agreement with observation (Blangsted et al. 2004), and has already been used in an epidemiological study (Lassen et al. 2005).

Second, most studies in this review solely measured the duration of total computer use. General measures of the duration of computer use might not be able to detect the variability in the duration of mouse and keyboard use. This might explain the stronger risk estimates for the duration of mouse use in comparison with those for the duration of total computer use. However, within the NUDATA cohort total computer use was not analysed since it was highly related to mouse use (Andersen et al. 2003).

Third, all included articles had study populations consisting solely of computer users. This might have led to a limited exposure contrast (i.e. only the contrast present within the group of computer users) and a limited power to explain the contributing factors to the incidence of hand, arm, shoulder and neck symptoms among computer users (Punnett and Bergqvist 1997).

Fourth, most case definitions were based on arbitrary cut-off points, based on the number of days on which pain or discomfort was experienced. In the NUDATA study (Brandt et al. 2004; Lassen et al. 2004) very few participants met the criteria for a clinical diagnosis during follow-up (i.e. less than 2% incidence for both neck-shoulder and hand-arm disorders). In addition, self-reports showed very mild disability. In contrast to the NUDATA study, the study by Gerr et al. (2002) showed a high incidence of clinical diagnoses (i.e. 35% incidence of neck-shoulder disorders and 21% incidence of hand-wrist disorders). One of the explanations for this difference between studies might be that the population studied by Gerr et al. (2002) consisted of newly hired workers. Newly hired workers might be more prone to health complaints, because they are not experienced with the physical and psychosocial exposures they have to deal with in the new job. The difference might also be attributed to selection effects within the NUDATA cohort: workers who are susceptible to or have suffered from hand, arm, shoulder or neck symptoms and disorders might have migrated to jobs with lower

durations of exposure or might have left the workforce. Kryger et al. (2003) indicated that the criteria used to establish a clinical diagnosis might be different between the NUDATA study and the one reported by Gerr et al. (2002). In addition, it should be noted that physical examination might not have sufficient inter-observer reliability (Salerno et al. 2000) and that information on validity is largely unknown (Marx et al. 1999).

Based on the limitations of physical examinations on the one hand, and the identical risk estimates for self-reported symptoms and clinically diagnosed disorders in the study by Marcus et al. (2002) on the other hand, self-reports of the degree of disability caused by symptoms might be preferred to grade the severity of symptoms in future epidemiological studies.

In order to estimate safe levels of the duration of computer use more precisely, more high quality studies are needed. These studies should focus on measuring the duration of computer use in a more objective way, differentiating between total computer use, mouse use and keyboard use, attaining sufficient exposure contrast, and collecting data on disability caused by symptoms.

### **Sensitivity analysis**

The levels of evidence proposed in this review might have been influenced by arbitrary decisions concerning the criteria used in the methodological quality assessment. The methodological quality score ranged between 45 and 73%, with seven out of nine studies scoring between 45 and 55%. Based on this distribution, our a priori cut-off point of > 50% might have influenced the levels of evidence and potentially the results of this review. Shifting the cut-off point from > 50% to > 40%, would have only changed the level of evidence for the combination mouse use and hand-arm symptoms and disorders. Strong evidence, instead of moderate evidence, would have been concluded. In contrast, shifting the cut-off point to > 60%, would not have influenced our levels of evidence at all.

Variation of exposure contrasts between studies might also have influenced the levels of evidence via the consistency of results. Studies analysing a limited exposure contrasts are less likely to find a positive association than studies analysing large exposure contrasts. Large variations in exposure contrast between studies were only available for the associations between the duration of total computer use and both hand-arm and neck-shoulder symptoms and disorders. However, variation in exposure contrast was not likely to influence the levels of evidence for these associations. For the



association between the duration of mouse use and neck-shoulder symptoms, a higher exposure contrast in the study by Jensen (2003) might have led to a positive association. In that case moderate evidence instead of insufficient evidence would have been concluded.

### **Dose-response analysis**

In general, the dose-response analysis for hand-arm symptoms showed an increase in point estimates over an increasing duration of mouse use. Jensen (2003) presented an increased risk at a rather low duration of mouse use and again at a high duration of mouse use. It is possible that residual confounding was present in their study, because subjects who had a low exposure to mouse use might have had a high exposure to keyboard use, leading to a long duration of total computer use and thus an increased risk.

Lassen et al. (2004) showed a decreased risk for developing severe hand-wrist pain at their highest exposure category (i.e. > 30 hours per week). A possible explanation is a saturation of biological pathways, or the presence of less susceptible workers at the highest exposure category due to selection in the past (Steenland and Deddens 2004).

To be able to explore a dose-response relationship we assumed that the relation between the point estimates of increasing exposure categories was linear. In addition, we had to estimate the average exposure within an exposure category. Both these factors might have biased our findings. However, these assumptions did not influence our general conclusion that the risk of developing hand-arm symptoms is higher at longer self-reported durations of mouse use.

### **Biological plausibility**

The studies in this review that investigated the effects of the same exposure contrast on both the hand-arm and the neck-shoulder region, generally showed stronger risk estimates for the hand-arm region than for the neck-shoulder region. Studies on muscle activity during computer use are in line with these findings, since they indicate a higher loading of the hand-arm region (extensors of the wrist) compared to the neck-shoulder region (trapezius muscle) (Bystrom et al. 2002; Jensen et al. 1998; Fernstrom and Ericson 1997). In addition, Laursen et al. (2002) found fewer EMG gaps in the extensor muscles of the wrist compared to the trapezius muscle during computer use, potentially indicating longer periods of continuous activation of local muscle fibres belonging to the same motor unit. The findings from both lines of research are supported by a hypothesis, which attributes a central role to the overuse of muscles and the

physiological consequences of this overuse in the pathophysiological mechanism underlying hand, arm, shoulder and neck symptoms and disorders (Visser and Van Dieen 2006).

Stronger risk estimates were found for mouse use than for keyboard use and total computer use. This difference can also be interpreted using the muscle overuse mechanism described above. Less variation in working postures during mouse use has been observed in comparison to keyboard work (Bystrom et al. 2002; Karlqvist et al. 1994), potentially leading to a longer duration of continuous muscle loading (Jensen et al. 1999).

Based on the above, it seems that evidence for a pathophysiological mechanism is available. However, caution is needed. The central role of muscles in the pathophysiological mechanism has been criticised (Knardahl, 2002). In addition, it should be borne in mind that the evidence found in this review for and against associations, was based on a limited number of studies. In addition, data for the effects of mouse and keyboard use are for the larger part derived from the NUDATA cohort. The possibility that a long duration of keyboard use can be a risk factor for developing hand, arm, shoulder or neck symptoms and disorders cannot be excluded, since only a limited range of exposures to keyboard use was available in the NUDATA cohort.

### **Limitations of this review**

The conclusions of this review are based on a rather low number of cohort studies. Therefore, it is possible that the conclusions might change when new studies will become available in the future.

A second limitation is that we compared studies with different case definitions. This might have influenced the results. Future research might indicate whether the associations between the duration of computer use and hand-arm or neck-shoulder symptoms are sensitive to these differences in case definition.

In addition, our review focused on only one contributing factor to the incidence of hand-arm and neck-shoulder symptoms and disorders among computer users (i.e. duration of computer use). This does not represent the general concept of a multifactorial origin of musculoskeletal disorders (Punnett and Bergqvist 1997). Moreover, it might be possible that other factors related to computer use (such as working postures or mental demands) act as effect modifiers of the association between the duration of computer use and hand-arm and neck-shoulder symptoms. A combination of, for example, high mental demands and long duration of computer use might lead to a higher incidence than a long duration of computer use per se. This might explain the

observed variation between study populations of the effect of a longer daily duration of computer use.

## **Conclusion**

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This review showed moderate evidence for an association between the duration of mouse use and the incidence of hand-arm symptoms. Indications for a dose-response relation were found. In addition, the neck-shoulder region seemed less susceptible to exposure to computer use than the hand-arm region. Both findings are supported by a pathophysiological mechanism based on the overuse of muscles during computer use. The low number of high quality studies prevents drawing a firm conclusion. More research is needed to confirm our findings.

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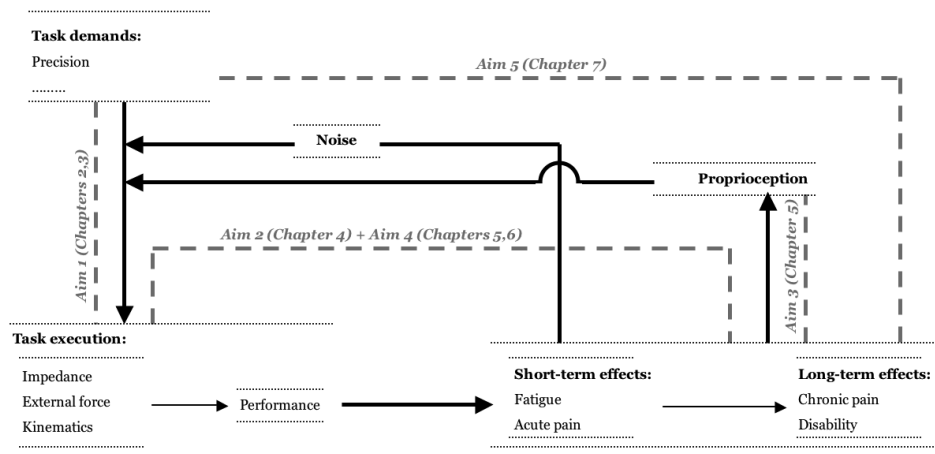


# *Chapter* ***eight***

*General Discussion  
and Conclusions*

## General Discussion

Despite a whole body of literature, the aetiology of neck and upper extremity pain, also referred to as RSI, repetitive strain injuries, is poorly understood. Besides static and awkward work postures and high forces, high precision demands in work tasks have been suggested as a physical risk factor for neck and upper extremity pain. In the introduction the Precision-Pain Model was introduced (see Figure 1), which predicts how precision demands could lead to neck and upper extremity pain. In this model, it is hypothesised that with higher precision demands in a task, endpoint impedance is increased, through increased co-contraction and higher friction with the substrate, and movement kinematics are changed in order to achieve the required task performance. If the task is performed for a long duration, the increased muscle activity will accelerate fatigue development. Fatigue has been shown to lead to impaired proprioception. Less accurate information on position and movement of body segments will make it more difficult to perform precise movements and a further increase in endpoint impedance is expected to be necessary to achieve the required task precision. This again will accelerate fatigue and close a vicious cycle. Continuation of this vicious cycle may lead to the development of chronic pain.



**Figure 1**

*The Precision-Pain Model proposed in the introduction which predicts how precision demands could lead to chronic neck and upper extremity pain*

The present thesis aimed to scientifically verify the following steps of the Precision-Pain Model described above:

1. Precision demands affect task execution (Chapters 2 and 3)
2. Fatigue affects task execution (Chapter 4)
3. Pain affects proprioception (Chapter 5)
4. Pain affects task execution (Chapters 5 and 6)
5. Precision demands are related to chronic pain (Chapter 7)

In the following paragraphs the evidence in favour of or against the Precision-Pain Model gathered in the present thesis in combination with results from the literature will be given. At the end of this chapter, the conclusions with respect to the principle aims of this thesis will be drawn.

## Evidence for the Precision-Pain Model

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### Precision demands affect task execution

On the basis of the Precision-Pain Model, it was expected that with increased precision demands muscle activity would increase in order to increase impedance to bring task performance at the required level. At the same time, it was predicted that alternative, less costly strategies, such as changing movement kinematics, would be applied, in response to increased precision demands.

In **Chapter 2**, no evidence for increased muscular co-contraction in response to increased precision demands was found. Subjects instead moved slower when facing higher precision demands. However, when statistical power was increased by pooling data from the experienced crane drivers with data from inexperienced subjects (which was not reported in **Chapter 2**), increased muscle activity levels with increased precision demands were found ( $p = 0.042$ ), despite the fact that in both groups movement velocity was significantly decreased. In several studies in literature, with higher precision demands similar levels of muscle activity were found, most likely due to the significantly reduced movement times with higher precision (e.g. Birch et al. 2000a; Laursen et al. 1998).

In time-constrained aiming evidence for increased muscle activity with high precision demands has been reported (Van Gemmert and Van Galen 1997; Laursen et al. 1998; Van Galen and Van Huygevoort 2000; Gribble et al. 2003; Visser et al. 2004; Sandfeld and Jensen 2005; Van Roon et al. 2005; Selen et al. 2006a). However, even in

time-constrained reciprocal aiming movements, the distribution of velocity and acceleration over time can be and was altered (Mottet and Bootsma 1999). Subjects used higher accelerations in the first part of the aiming movement and decelerated when approaching the target (Mottet and Bootsma 1999). The homing-in phase (the last part of the aiming movement when close to target, in which the actual precision is required) was longer with smaller targets, because more corrective movements were made (Meyer et al. 1988).

The problem of interpreting EMG results with changes in movement velocity can partly be overcome by the use of tracking tasks, since in tracking movement velocity is imposed during the entire task. Therefore, tracking tasks may be more suitable to study the effects of precision demands on impedance. In **Chapter 3**, the effects of precision demands on endpoint impedance were studied in a multi-joint tracking task in which movement velocity was imposed. In line with the Precision-Pain Model, it was found that with higher precision demands endpoint impedance increased, as indicated by increased pen pressure and muscle activity. In the literature, different results have been reported. On the one hand, in a multi-directional tracking task performed with the computer mouse, Visser et al. (2004) did not find an effect of precision demands on muscle activity. On the other hand, in more constrained single joint tracking, direct estimates of elbow impedance were found to increase with increased precision demands (Selen et al. 2006b). The effect of precision demands on pen pressure has, to our knowledge, never been investigated before in tracking tasks. We only know of one study that investigated the effect of precision demands on pen pressure in aiming and that did not find an effect (Van Galen and Van HUYGEVOORT 2000). This could be due to the fact that in the study of Van Galen and Van HUYGEVOORT (2000) mean pen pressure was calculated over the whole aiming movement, while pen pressure may have been only increased in the (relatively short) positioning part of the aiming movement. This would be in line with the study of Osu et al. (2004) which showed that increased muscle activity was only found in the final stage of the aiming movement, where the actual positioning takes place.

However, in tracking tasks, in which movement velocity is imposed, changes in kinematics have also been shown in response to changes in target size (Selen et al. 2006b; **Chapter 3**). With smaller targets, sub-movements with larger amplitudes and a shorter duration were found, indicating less fluent movements. Subjects also spent a larger percentage of time behind the centre of target, although at a smaller mean distance to target (**Chapter 3**).

Since impedance control is energetically costly, if possible, other strategies, such as



reduction of movement velocity or changes in movement kinematics, appear to be preferred above or are used in combination with impedance control. However, in line with the Precision-Pain Model, it can be concluded that when movement velocity is imposed in the task, increased precision demands can lead to increased impedance, both when assessed with direct measures (in perturbation experiments), as with indirect measures (muscle activity and pen pressure).

### **Could increased impedance lead to fatigue and muscle pain?**

Another prediction of the Precision-Pain Model was that long duration of increased muscle activity, even in tasks with low intensities, leads to muscle fatigue and eventually to pain. Indications of fatigue have indeed been found in forearm muscles after a few hours of computer work (Jensen et al. 1999; Luttmann et al. 2005). The Cinderella hypothesis explains that even though the load for the whole muscle can be low, at the same time the load on certain motor units can be high (Hagg and Suurkula 1991). This is based on the neurophysiological concept of ordered recruitment of motor units with increasing force, i.e. the smaller motor units are recruited before the larger ones (Henneman and Olson 1965; Henneman et al. 1965). These earliest recruited and last de-recruited motor units could be overloaded, which may result in damage of muscles fibres (“ragged red fibres”) or in metabolic disturbances in these fibres. Evidence for the Cinderella hypothesis can be found in the studies of for example Zennaro et al. (2003) and Thorn et al. (2002) in which continuous activation of motor units was found during task execution. However, the Cinderella hypothesis does not include any statements on how the muscle fibre damage and metabolic disturbances are transferred into a pain sensation (Hagg and Suurkula 1991).

A possible mechanism for the pain sensation was suggested by Gissel (2000). The  $\text{Ca}^{2+}$  accumulation due to sustained motor unit activity may play a causative role in the development of muscle pain. In an electrostimulation study in rat muscles, it was found that during long-term low-frequency stimulation, intracellular concentrations of free  $\text{Ca}^{2+}$  were increased leading to calpain (i.e.  $\text{Ca}^{2+}$  sensitive neutral protease) activation and subsequent membrane leakages. Membrane leakage led to further influx of  $\text{Ca}^{2+}$  and further acceleration of membrane protein breakdown. Since the nociceptive system is designed to detect cellular damage, muscle activity that leads to membrane leakages is most likely to result in a sensation of pain. However, in the studies described by Gissel (2000) the damage was much larger in the EDL muscle, a mixed muscle with both fast and slow twitch fibres, as compared to the soleus, which mainly consists of slow twitch fibres. During muscle stimulation all motor units are activated and it could be that the damage only took place in the fast-twitch fibres of the soleus.

Therefore, it is possible that the Ca<sup>2+</sup> accumulation with sustained muscle activity applies only to the fast twitch fibres in the muscles and not to the slow twitch fibres, the Cinderella fibres, which are the only ones expected to be active during low-intensive computer work.

In conclusion, the evidence that sustained muscle activity at a low intensity could lead to muscle pain is still insufficient and needs further investigation.

### **Fatigue and pain affect proprioception**

The Precision-Pain Model predicts that with fatigue and pain proprioception will be diminished. The quality of proprioception is most often assessed by measuring movement sense or position sense acuity. In line with the Precision-Pain Model, movement and position sense acuity in the shoulder were found to be diminished with fatigue, not only by high-intensive contractions (Carpenter et al. 1998; Pedersen et al. 1999; Lee et al. 2003), but also by activity at a low intensities (Pedersen et al. 1999; Bjorklund et al. 2000). Similar results were also found for the effects of fatigue in other joints, such as the ankle and the knee joint (Lattanzio et al. 1997; Forestier et al. 2002). Studies on the effect of experimental muscle pain on position sense are scarce. In the study of Mattre et al. (2002), in which pain was induced by injecting hypertonic saline in the M. tibialis anterior muscle and the M. soleus muscle, no effect on ankle joint position sense was found. The influence of chronic muscle pain on proprioception was investigated in **Chapter 5**. In subjects with neck and upper extremity pain, position sense acuity was significantly diminished as compared to healthy controls, as was predicted by the Precision-Pain Model. In line with these findings, impaired position sense acuity was also reported for similar populations, such as for subjects with chronic neck pain (Revel et al. 1991), whiplash disorders (Loudon et al. 1997; Feipel et al. 2006; Sandlund et al. 2006), and lateral epicondylitis (Juul-Kristensen et al. 2006). However, in whiplash patients, Armstrong et al. (2005) found no position sense impairment for the head and neck, but this may have been due to the fact that the whiplash patients in this study were less severely affected than those in the studies of Feipel et al. (2006), Loudon et al. (1997) and Sandlund et al. (2006).

In the studies in which the effects of fatigue or experimental pain on proprioception were investigated, subjects acted as their own controls. Therefore, a causal relationship between fatigue or experimental pain and proprioception can be expected. For studies with subjects with chronic pain, it is less clear whether the pain is the cause or the effect of the impaired proprioception, because of the cross-sectional nature of these studies. In conclusion, whereas the evidence for the effects of experimental muscle

pain on proprioception is lacking, proprioception appears to be diminished with local muscle fatigue and in subjects with chronic pain.

### **Fatigue and pain affect task execution: kinematics and performance**

Based on the Precision-Pain Model, it was predicted that fatigue and pain would negatively influence task execution, because of the impaired proprioception and increased noise levels. With strict task demands, it was expected that, besides impedance control (which will be described in the next paragraph), movement kinematics would change, such as to minimise the effects on task performance.

In a 2-min computer tracking task, fatigue led to a diminished task performance, expressed as time on target, but only in the first half of the tracking task (**Chapter 4**). However, mean distance to target (MDT) and the standard deviation of this distance to target (SDDT) were significantly increased during the entire task. In single-joint tracking, time on target was unaffected by fatigue, and surprisingly the MDT was even lower with fatigue, while the SDDT was significantly larger (Selen et al. 2007a). The unchanged performance and smaller MDT were most likely due to the fact that subjects adopted a feed-forward strategy. Subjects moved closer towards the centre of target when fatigued, resulting in a smaller MDT (Selen et al. 2007a). This strategy was most likely not applied in **Chapter 4** because in this study an unpredictable target trajectory was used, in which a feed-forward strategy was not an option. In **Chapter 4**, we interpreted the increased SDDT, in combination with the increased peak muscle activity in the forearm extensor, as the result of a less fluent movement strategy, with larger corrective movements. However, in the study of Selen et al. (2007a) and in **Chapter 5** of the present thesis an increased SDDT was found without significant changes in sub-movement organisation. Therefore, our interpretation of the increased SDDT as the result of larger corrective movements in **Chapter 4** might be incorrect and the increased SDDT may be the direct effect of increased neuromotor noise.

Task performance in a precision aiming task was not reduced by experimental muscle pain induced in the extensor carpi ulnaris muscle and trapezius muscle (Birch et al. 2000b; 2001). Fine motor skills, as tested by the Purdue pegboard test, were also not affected by experimental muscle pain in the hand muscles (Smith et al. 2006). In subjects with neck and upper extremity pain, however, decreased positional precision was found as compared to control subjects (Brouwer et al. 2001; 2007). Jensen et al. (2002) found no differences between subjects with upper extremity pain and controls when tracing a pattern, but this could be due to lower movement speed in the pain subjects. When movement speed is not restricted, subjects with upper extremity pain

have often been reported to perform tasks slower (Madeleine et al. 1999; Smeulders et al. 2001; Madeleine et al. 2003; Harman and Ruyak 2005).

Following the Precision-Pain Model, the diminished performance in tracking was most likely the result from the impaired proprioception in subjects with neck and upper extremity pain. This would be in line with reports of Sainsburg et al. (1995), Cordo et al. (1995) and Miall (1996), who found larger positional errors in de-afferented subjects. In **Chapter 5**, we found indeed that performance in the tracking task was significantly correlated to performance in the position sense task. However, the explained variance of 25% was not high. It is likely that the visual feedback of the task performance in the tracking task, allows subjects to partially compensate the negative effects of impaired proprioception.

In line with the Precision-Pain Model, overall task performance seemed minimally affected by fatigue or pain. More sensitive measures of task execution, such as kinematic variability and tracking errors, were significantly affected by fatigue and chronic pain. The negative effects of fatigue are found to be compensated with changes in movement strategy, i.e. if allowed by the task. In subjects with chronic neck and upper extremity pain, no changes in kinematics to compensate for the decreased precision have been found. Even though it seems likely that the reduced task precision in fatigued subjects and subjects with chronic pain are the result of an impaired proprioception, because of the cross-sectional design of the studies on chronic pain patients it can not be concluded whether the impaired positional precision is the cause or the effect of the pain in this group. The fact that no evidence was found of effects of experimental muscle pain on task performance may be due to the fact that the performance measures used in these studies were not sensitive enough.

In conclusion, in line with the Precision-Pain model, overall task performance seemed minimally affected in fatigued subjects and subjects with neck and upper extremity pain, but more sensitive measures of task performance, such as positional precision, were significantly affected.

### **Fatigue and pain affect task execution: impedance and external force**

According to the Precision-Pain Model, fatigue and pain lead to increased muscle activity to achieve an increase in impedance. However, in **Chapter 4** no indications were found of a general increase in muscle activity with fatigue. Instead, a selective increase of peak muscle activity in the extensor muscle of the forearm was found. On the one hand, even though not predicted by the Precision-Pain Model, this increase in peak activity could

close the vicious cycle, because it could accelerate fatigue development. On the other hand, it could be that increased peak activity might facilitate a motor unit substitution process, and thus prevent fatigue (Wested et al. 2003). Direct estimates of impedance, as obtained by torque perturbations, were actually found to decrease with fatigue (Selen et al. 2007a). Unchanged or even lower levels of impedance with fatigue were most likely the result of changes in movement kinematics as described in the previous paragraph.

With experimental muscle pain, as induced by injecting hypertonic saline in the upper trapezius muscle, the EMG amplitude decreased in the painful upper part of the muscle and increased in the lower part of the trapezius (Madeleine et al. 2006; Falla et al. 2007), in the trapezius on the contra-lateral side (Falla et al. 2007), or in the synergistic infraspinatus muscle (Madeleine et al. 1999). However, this was all found in dynamic tasks requiring little precision. In precision tasks, reorganisation of muscle activity may be more limited. In a computer task performed with the mouse, Birch et al. (2000b) also found a decrease in muscle activity in the painful M. extensor carpi ulnaris when precision demands in the task were low. However, with high precision demands muscle activity remained unchanged in the painful muscle, relative to the non-painful control condition. Therefore, the use of the protective mechanism of reorganisation of activity within the muscle or within muscle synergies may be prevented with high precision demands.

In **Chapter 5**, no differences were found in muscle activity in forearm extensors, flexors and trapezius muscles between subjects with neck and upper extremity pain and healthy controls. In office workers the evidence for increased muscle activity with pain is inconsistent. Lower (Sjogaard et al. 2006), similar (Roe et al. 2001; Holte and Westgaard 2002; Goudy and McLean 2006) and higher trapezius muscle activity levels (Szeto et al. 2005) were found in subjects with pain, as compared to those without pain. In the forearm extensors, similar muscle activity levels (Roe et al. 2001) and in the neck extensors, lower muscle activity levels (Szeto et al. 2005) have been reported for symptomatic office workers. The large difference in study outcomes could be due to differences in normalising the data. In most of the above mentioned studies, EMG data were normalised to maximum values. Normalisation of the data to maximal values can be questioned, since lower muscle activity and forces have been reported for subjects with pain when performing a maximum voluntary contraction (e.g. Schulte et al. 2006; Sjogaard et al. 2006). This could be due to pain induced reflex inhibition or due to perceived anxiety to exacerbate the pain with maximal force exertion. Therefore, in the present thesis we deliberately chose not to normalise muscle activity outcomes to the values of maximal exertion in subjects with pain, which resulted in similar muscle activity levels for subjects with and without neck and upper extremity pain in **Chapter 5**. In the

same study subjects with pain also showed similar pen pressures as control subjects. Similar muscle activity levels for subjects with and without pain suggest that the vicious cycle proposed in the Precision-Pain Model did not occur. It should be noted that this may be due to the decreased performance in the subjects with pain, by which closure of the vicious cycle may be circumvented. In other tasks such as typing (Feuerstein et al. 1997), aiming (Bloemsaat et al. 2004) and lifting and holding small objects (**Chapter 6**) higher forces were reported for subjects with neck and upper extremity pain. These higher forces would imply higher muscle activity and acceleration of fatigue in subjects with pain, which would close the vicious cycle.

In conclusion, with fatigue alternative strategies seem to be preferred above the increase of impedance. In **Chapter 4** no general increase of impedance was found, but the selective increase of peak muscle activity with fatigue could also close the vicious cycle as proposed in the Precision-Pain Model. With experimental muscle pain no indication for increased muscle activity levels were found in literature. With lower precision levels in the task, muscle activity was even found to decrease in the painful muscle. Subjects with neck and upper extremity pain showed no increase of pen pressure or muscle activity in computer tracking tasks as compared to controls. However, in other tasks (e.g typing, lifting objects) external forces were found to be increased in the subjects with neck and upper extremity pain. Moreover, the absence of pain adaptation, which appears to be caused by high precision demands, may negatively affect prognosis in chronic pain. All in all, the evidence for the closure of the proposed vicious cycle is inconsistent.

### **Precision demands are related to chronic pain**

The Precision-Pain Model predicted that high precision demands can lead to neck and upper extremity pain. In line with this prediction, in the review in **Chapter 7** of longitudinal studies indications were found that long duration of self-reported computer mouse use was associated with the incidence of hand-arm pain. Moreover, indications for a dose-response relation were found. In contrast, for the total duration of computer use and the duration of keyboard use inconsistent evidence was found for an association with chronic hand-arm pain. This may be because precision demands in computer mouse work appear to be more stringent than in keyboard work. For chronic neck-shoulder pain, insufficient evidence was concluded for total duration of computer use, for duration of mouse use and for duration of keyboard use. Risk estimates for the hand-arm region were in general stronger than for the neck-shoulder region. The Precision-Pain Model does not differentiate between pain locations. Whether different onset mechanisms may apply for distal and more proximal pain will be discussed later.

The longitudinal studies in the review in **Chapter 7** only used self-reported computer work duration, and the use of objectively recorded computer use in future studies was recommended. Chang et al. (2007) and Andersen et al. (2007) found with objective measures of computer usage that total duration of computer use and duration of mouse and keyboard use predicted *acute* pain in the neck-shoulder region. However, a relation between duration of mouse and keyboard use and *chronic* neck-shoulder pain could not be found (Andersen et al. 2007). This would be in line with the suggestion in the review that duration of computer mouse use would be associated stronger with chronic hand-arm pain than with chronic neck-shoulder pain. Unfortunately, the association between objective measures of computer use and hand-arm pain has to our knowledge not been investigated yet. In conclusion, indications were found that computer mouse use, as a proxy for work with high precision demands, was associated with acute neck-shoulder pain and with the incidence of chronic hand-arm pain.

### **Summary of evidence for the Precision-Pain Model**

As predicted by the Precision-Pain Model indications were found that computer mouse use, as a proxy for work with high precision demands was associated with chronic pain in the hand-arm region. Moreover, evidence for increased impedance with increased precision demands was indeed found. However, since impedance control is energetically costly, it is likely that, if possible, other strategies will be used, such as reduction of movement velocity or changes in movement kinematics. Therefore, during less constrained, more natural tasks, impedance modulation will probably become less apparent and less important (Selen 2007b).

As predicted, proprioceptive acuity is reduced in subjects who are fatigued and in subjects with neck and upper extremity pain. Both in subjects with fatigue and in subjects with neck and upper extremity pain task performance in a computer tracking task was affected. Depending on the predictability of the task, indications for a feed-forward strategy were also found with fatigue, whereas in fatigued subjects and subjects with neck and upper extremity pain, sub-movement organisation was not changed.

With fatigue a selective increase of the peak muscle activity in the forearm extensor was found. Even though the increased P90 with fatigue does not support the increased co-contraction as predicted by the Precision-Pain Model, the increased P90 could close the vicious cycle by accelerating fatigue development. In subjects with neck and upper extremity pain, no effects on muscle activity or on pen pressure were found in the tracking task, but in other tasks, such as typing, aiming and lifting and holding a small object, increased external forces were found compared to healthy controls. Even

though evidence for a vicious cycle in case of pain is inconsistent, absence of pain adaptation (i.e. a reduction of muscle activity due to pain) appears to be caused by precision demands, which may negatively affect prognosis.

With the present data and results from literature, sufficient evidence for increased impedance with precision demands, and impaired proprioception and precision in subjects who are fatigued or have pain is present. However, the evidence for the development of a vicious cycle through increased impedance with pain and fatigue is inconsistent.

## **Reasons for inconsistent evidence of a vicious cycle**

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An important conclusion in the previous section is that the evidence for the closure of the vicious cycle through increased impedance is inconsistent. It may be that the vicious cycle does not exist or is circumvented by decreasing movement velocity or changing movement kinematics. However, it is also possible that a vicious cycle could not be demonstrated because of limitations of the methods used. Possible limitations will be discussed in the following paragraphs.

### **Were precision demands sufficiently imposed?**

The speed accuracy trade-off seems strong. If possible, movement speed will be reduced in response to increased precision demands in the task. In case movement speed is imposed, precision may be reduced or changes in movement kinematics may take place. In the tracking task used in the present thesis, both velocity and the level of precision were imposed. However, even though the time on target was similar for patients and controls, patients had a significantly larger distance from the centre of the target and showed larger kinematic variability. The task allowed this decrease in spatial accuracy, in the sense that it had no serious consequences (in terms of e.g. reward, punishment). The question remains, that if task failure (reduction of precision and/or movement time) would have had serious consequences, higher impedance would have been found in fatigued subjects and subjects with pain as compared to controls. In the lifting and holding task, in which the consequence would be that the cup would be dropped when grip forces would be too low, significantly higher grip forces were found for subjects with chronic pain.

However, all in all we believe that the precision demands in the tracking tasks used in



the present thesis were sufficiently enforced to investigate the effects of pain on task execution in precision tasks. Both subjects with pain and controls responded to the increased precision demands by changing task execution (e.g. their movement kinematics and impedance). A decrease in performance as shown in the tracking task by the subjects with neck and upper extremity pain as compared to healthy controls may reflect their behaviour in every day tasks, which likely impose precision or time even less strictly.

### **Were the appropriate EMG methods used?**

The Precision-Pain Model emphasises the importance of increased muscle activity levels in the development of pain. In terms of muscle fibre damage, it has been shown that long duration of sustained muscle activity may be of more importance than the absolute level of activity (Lexell et al. 1993). Hence, if muscle activity becomes more sustained when dealing with precision demands, then a vicious cycle could arise, because sustained activity will enhance fatigue.

In a prospective study of forest machine operators, the number of long periods of sustained low-level muscle activity in the trapezius muscle was positively correlated to the incidence of neck pain after one year (Ostensvik et al. 2007). In another prospective study of manual workers, future neck and shoulder pain patients showed fewer EMG gaps (periods of complete muscle relaxation) in the upper trapezius muscle (Veiersted et al. 1993). Also workers with previous episodes of complaints, but symptom free at the time of recording, had fewer EMG gaps than workers without such episodes (Veiersted et al. 1990). However, in cross-sectional studies on both office and industrial workers the relations between EMG gap occurrence and neck-shoulder disorders have been less consistent: both reduced (Hagg and Astrom 1997; Sandsjo et al. 2000) and similar (Jensen et al. 1993; Vasseljen and Westgaard 1995) numbers of EMG gaps have been reported for subjects with pain compared to controls. Thorn et al. (2007) showed that rest time showed a strong negative correlation with static muscle activity (P10). In the present study, P10 was measured, but this was not affected by neck and upper extremity pain. Nevertheless, indications have been found that sustained muscle activity plays a role in the onset of neck and upper extremity pain, and future studies could look at duration of muscle activity more specifically.

As the Cinderella hypothesis suggests, it may not be sustained activity of the muscle as a whole that is important, but sustained activity of specific individual motor units. Indications have been found that selective activation of motor units may be promoted by precision demands (Van Zuylen et al. 1988; Zijdwind et al. 1995; Visser et

al. 2003). Furthermore, precision demands may prevent protective strategies, such as reorganisation of muscle activity within the muscles or between synergists (Van Dieen et al. 2003). However, activity of single motor units could, unfortunately, not be investigated with the bipolar EMG measures used in the present thesis. For that, use of wire (needle) EMG or multiple electrode arrays is needed. For future research, it is recommended to investigate differences in muscle activity between cases and controls in precision tasks with these measures.

### **Different mechanisms for distal and proximal pain?**

Evidence for increased muscle activity with chronic neck and upper extremity pain is inconsistent in the literature. However, most of these studies only focused at muscles in the neck-shoulder region (trapezius), while muscles in the forearm are most often not investigated. In **Chapter 7**, indications were found that different mechanisms may apply for pain distally or more proximally. The relation between task demands (such as precision demands and time demands) and the development of chronic pain, as predicted in the Precision-Pain Model, may apply mainly for the development of pain in the hand-arm region, although both the Neuromotor Noise Theory and the Johansson Model, on which the Precision-Pain Model is based, do not distinguish between location of the chronic pain.

In **Chapter 7**, it was found that the association between pain and computer work, and specifically mouse use, was stronger for hand-arm pain than for neck-shoulder pain. This would be in line with studies during computer use, which indicate a higher and more continuous muscular loading of the hand-arm region than of the neck-shoulder region (trapezius muscle) (Bystrom et al. 2002; Jensen et al. 1998; Fernstrom and Ericson 1997; Laursen et al. 2002). Moreover, distal muscles seem to be more responsive to task demands (such as precision demands or time constraints) than proximal muscles (Bloemsaat et al. 2004). In **Chapter 3**, forearm muscle activity was significantly increased with higher precision demands in the task, while for the same number of subjects, no effect of precision was found on trapezius muscle activity. Moreover, in the study of Bloemsaat et al. (2004) muscle activity of the distal muscles was significantly increased during tapping at a higher pace, while the activity in the trapezius did not increase. A potential explanation for the lack of an effect of precision demands on trapezius muscle activity, within the framework of the Precision-Pain Model, might be that in the tasks studied the forearm is most often supported. Hence, only impedance of joints distal of the support would substantially affect endpoint impedance. Therefore, the Precision-Pain Model, which suggests high importance of tasks demands in the development of chronic pain may be more valid for hand-arm pain than for neck-shoulder pain.

## Conclusions

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In the introduction the Precision-Pain Model was proposed, which predicts how high precision demands in a task could lead to the development of neck and upper extremity pain. The Precision-Pain Model, which is a combination of the Neuromotor Noise Theory (Van Galen and De Jong 1995; Van Gemmert and Van Galen 1997; Van Galen and Van Huygevoort 2000) and the Johansson Model (Johansson et al. 2003), shows that with high precision demands in a task, endpoint impedance increases and movement kinematics change in order to achieve the required task performance. If the task is performed for a long duration, the higher muscle activity required to increase impedance will accelerate fatigue development. Fatigue, even when developed in tasks with low forces, has been shown to lead to impaired proprioception. Less accurate information on position and movement of body segments will make it more difficult to perform precise movements. In order to achieve the required tasks precision, this diminished positional precision is thought to be counteracted by a further increase in impedance. This again will accelerate fatigue and close the vicious cycle. Continuous duration of this vicious cycle may lead to the development of chronic pain.

The principle aims of this thesis were to investigate the relations implied by the Precision-Pain Model:

1. The effects of precision demands on task execution
2. The effects of fatigue on task execution
3. The effects of pain on proprioception
4. The effects of pain on task execution
5. The effects of precision demands on pain

### **1. Conclusions on the effects of precision demands on task execution**

In response to high precision demands in the task, impedance significantly increases. Since impedance control is energetically costly, it is likely that, if possible, other strategies, such as reduction of movement velocity or changes in movement kinematics, are preferred above or are used in combination with impedance control. Therefore, during less constrained, more natural tasks, impedance modulation most likely will be less apparent and less important, and the vicious cycle may be avoided.

### **2. Conclusions on the effects of fatigue on task execution**

With fatigue, task performance significantly decreases in a computer precision task, while movement kinematics do not change when tracking a target.

In contrast with the Precision-Pain Model, no general increase in co-contraction is found with fatigue, but a selective increase of peak muscle activity in the forearm extensor. Even though this does not suggest increased impedance, as predicted by the model, the increased peak activity could also close the vicious cycle by accelerating fatigue development.

### **3. Conclusions on the effects of pain on proprioception**

In subjects with neck and upper extremity pain position sense acuity is impaired, which indicates that proprioception is reduced. Because of the cross-sectional nature of the studies, it is not clear whether the impaired proprioception is the cause or the effect of the pain.

### **4. Conclusions on the effects of pain on task execution**

Subjects with neck and upper extremity pain show decreased task performance in a computer tracking task. This decreased task performance is most likely the result of impaired proprioception, since performance in the position sense task is significantly related to performance in the computer tracking task. Subjects with neck and upper extremity pain do not compensate for their reduced task performance, neither by increasing their endpoint impedance, nor by changing movement kinematics. External forces, measured as grip force during lifting and holding a small object, are significantly increased in subjects with neck and upper extremity pain. Whereas, no indications are found for closure of the vicious cycle through increased impedance in the computer tracking task, the increased external forces in the lift and hold task could accelerate fatigue and, thus, could close the vicious cycle.

### **5. Conclusions on the effects of precision demands on pain**

The proposed association between precision demands and neck and upper extremity pain was studied by taking computer work as a proxy for work with high precision demands. A positive association is found between long duration of computer mouse use and the incidence of hand-arm pain. Even indications for a dose-response relation are found. For neck-shoulder pain, the evidence for an association with total duration of computer use, duration of mouse use and for duration of keyboard use is insufficient.

## **Overall conclusion on the Precision-Pain Model**

On basis of the results from the present thesis in combination with results from literature it is concluded that there is evidence for a large part of the Precision-Pain Model.

In line with the Precision-Pain Model it is found that: 1) increased precision demands lead to increased impedance in combination with changes in movement kinematics, 2) proprioception and task performance in terms of positional precision are impaired in fatigued subjects and subjects with neck and upper extremity pain, and 3) precision demands could be associated with arm-hand pain. While a selective increase of peak muscle activity in fatigued subjects when performing precision tasks and the increased grip forces in a lift and hold task in subjects with neck and upper extremity pain could indicate closure of a vicious cycle, a general increase of impedance in computer tasks with high precision demands is not found in these subjects as compared to healthy controls. Therefore, the evidence for closing of the vicious cycle, as proposed by the Precision-Pain Model, is inconsistent.



# *Chapter* ***nine***

.....  
*Implications for Practice and*  
*Future Research Directions*  
.....

## **Implications for Practice and Future Research Directions**

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In the previous chapter the findings of this thesis were discussed and conclusions on the principle aims were drawn. Although the research in this thesis is fairly theoretical, the conclusions of this thesis may have implications for work settings in which high precision is demanded and in which the prevalence of neck and upper extremity pain is often high. These implications will be addressed in the following paragraph. Next, recommendations are given for future directions of research that may be explored in order to fill gaps that still exist in the theory on the underlying mechanisms of the development of neck and upper extremity pain in tasks with high precision demands.

### **Implications for practice: the optimisation of precision tasks**

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With high precision demands in the task, higher and probably more selective loading of the muscles seems to take place and protective mechanisms, such as reorganisation of muscle activity within the muscles or between synergists, may be prohibited. Moreover, the ability to work precisely seems to be reduced in subjects with fatigued muscles and in subjects with neck and upper extremity pain. This most likely leads to a decrease in task performance, i.e. longer movement times or a reduction in positional precision. If the task demands are very strict, both in timing and positional precision, then muscle activity may increase or subjects may fail to perform the task adequately. This may eventually contribute to disability. Even though the role of precision demands in the development of neck and upper extremity pain is not exactly clear, for the above stated reasons, it seems worthwhile to either strive to reduce precision demands in the task or to facilitate precision work. Different examples of how to achieve this are given below, in which the main focus will be on precision work performed with computer input devices.

#### **Expanding targets or cursors**

First of all, it is recommended to decrease, whenever possible, the precision demands required. In computer (mouse) work, this can be done by enlarging icons on the screen (Keyson 1997). However, the optimal size may be compromised because usually multiple icons have to be placed at the screen. Another option is the use of target expansion when the cursor approaches the target (McGuffin and Balakrishnan 2005). McGuffin and Balakrishnan (2005) found that users were able to take advantage of the



larger expanded target width even when expansion occurred after 90% of the distance to target had been travelled, which appears to be in line with the late modulation of impedance in aiming tasks (Osu et al. 2004; Selen et al. 2006). A good example of this is the expansion function of icons in the dock of the operating system of Apple computers (Figure 1). However, its advantage remains to be proven when multiple targets are located in close proximity (Balakrishnan 2004). Another option is to enlarge the cursor. This will make it easier to position the cursor over the target. Again problems may arise when targets are located closely together. That is why more advanced methods of enlarging the cursor have been suggested, such as the use of “bubble cursors”, which dynamically resize their activation area depending on the proximity of surrounding targets (icons) in such a way that only one target is selectable at a time. Results show that movement time is significantly shorter with the use of “bubble cursors” and that significantly fewer errors were made than with a point cursor (Grossman and Balakrishnan 2005).



**Figure 1**

*Expansion of icons when the cursor approaches the dock of the operating system of Apple computers*

## Display-control gain

The level of precision can also be changed by adjusting the display-control gain (DC gain) as was shown in **Chapter 2** in a simulated crane task. In operating a machine with joystick controls, DC gain is defined as the output of the machine element (speed) given a certain input of the joystick (position as defined by deflection). In computer work, the DC gain would be the movement of the cursor on the screen given the movement of the input device, such as the computer mouse. However, in most tasks, whether operated on a machine or a computer, precision demands are not constant, e.g. in an aiming task low precision is required during the movement towards the target and a high precision during the actual target acquisition. The optimal gain can be found by balancing the advantages of a relatively high gain (i.e. reduction of the

time to reach target) against the advantages of a relatively low gain (i.e. reduction of final corrective movements when close to target) (Buck 1980).

The effect of gain on performance has mainly been measured in computer tasks. A U-shaped relationship has been found between gain and movement time, where the minimum movement time represented the optimum gain (Lin et al. 1992). However, the gain value does not necessarily need to be a constant value. In computer work, examples of dynamic gain have been tested, such as increasing gain while approaching a target, and decreasing when within a target. In this way, the user must move the mouse further to escape the boundary of the icon, effectively making the icon larger in motor-space without using extra screen space. Such adaptive DC gains, also referred to as “sticky targets/icons”, have been shown to significantly decrease target acquisition times (Keyson 1997; Worden et al. 1997; Cockburn and Brewster 2005). Sticky targets were found to be particularly effective for older users in selecting small targets (Worden et al. 1997).

Also in machines operated with joystick controls, dynamic DC gains could have benefits, e.g. a low gain with a small deflection of the joystick and a higher gain at a large deflection. Dynamic gains are already applied in machines, but, the optimal gain is often determined by trial and error and rarely investigated in experimental studies. It should be kept in mind that the optimal gain both in computer and in machine work is very task specific.

### **Feedback mechanism in input devices**

Different mechanisms in input devices have been applied to help the user in target acquisition tasks by giving feedback when the cursor is positioned over the target, e.g. by auditory feedback (Cockburn and Brewster 2005), tactile vibratory feedback in the input device, or by force feedback, which is felt as a pulling force towards the centre of a target and as a counterforce when moving out of centre (Keyson 1997; Dennerlein and Yang 2001; Keuning 2003). Auditory feedback, tactile feedback by vibration and force feedback have all been shown to significantly reduce target acquisition time (Dennerlein and Yang 2001; Cockburn and Brewster 2005). Additionally, with force feedback perceived user discomfort and pain were significantly smaller (Dennerlein and Yang 2001). However, these feedback mechanisms seem to work especially with targets isolated from any surrounding “distracter” targets. When additional targets in close approximation of the target are given, as is often the case in more realistic work situations, e.g. in a scrolling menu, the benefits of feedback mechanisms often disappear (Cockburn and Brewster 2005; Dennerlein and Yang 2001). This problem could

be solved by using a prediction algorithm for the users intended target in combination with a force field around the intended target object (Keuning 2003).

### **Location of targets on the screen**

Movement time and movement precision in computer aiming tasks are also dependent on the location of the targets on the screen. Movements from left to right and from left lower corner to upper right corner are performed faster than movements up-down and from the upper left corner to the lower right corner when performed with pen on tablet, in subjects who are right hand dominant (Fernandez and Bootsma 2004). Brouwer et al. (2001; 2007) also showed that subjects had a lower accuracy when tracking a target in the lower right corner of the screen compared to other locations on the screen, mainly because working at this location with the cursor required extreme wrist flexion while moving the pen across the digitiser tablet. Frequently used icons could be put in locations allowing precise and fast target acquisition.

### **Changing physical characteristics of input devices**

Redesign of input devices could also have a positive effect on performance in precision tasks. In **Chapter 2**, it was shown that performance was positively influenced by the use of a joystick with a short handle. The physical load on the operator was found to be similar or even reduced with the small handle as compared to the large handle, most likely because the small muscles of the hand are more suitable for fine-motor movements than the larger muscles of the upper arm (Maier et al. 1995). For computer work also positive effects of re-design of a computer mouse were found on performance in precision tasks. On the underside of a conventional computer mouse 4 protruding legs were placed, which were designed to create a constant friction between mouse and mouse mat (Figure 2). In a study of Visser et al. (2007), this mouse was compared to a conventional mouse, which was, except for the protruding legs, identical to the experimental mouse. In an aiming task with the experimental mouse, the homing-in phase, i.e. the part of the movement where the precise positioning of the cursor over the target takes place, was significantly shorter than with the conventional mouse. In a tracking task, similar to the one used in this thesis (**Chapters 3, 4 and 5**), subjects spent significantly more time on target, were significantly closer with the cursor to the centre of target and tracked the target with smaller kinematic variability (i.e. smaller standard deviation of the distance to target) with the experimental mouse. Muscle activity was similar for the experimental mouse and the conventional computer mouse.



**Figure 2**

*The experimental mouse with 4 producing legs, designed to create a constant friction between mouse and mouse mat.*

## **In conclusion**

Most research on optimising precision work has been conducted in human-computer interaction, but most of the ergonomic solutions would also apply to other work tasks, in which input devices are used. It can be concluded that in order to make (computer) precision work easier, larger or expanding targets or cursors can be used and input devices can be supplied with feedback mechanisms. In addition, performance in precision tasks can be improved by optimising DC gain, the location of icons on the screen and physical characteristics of the input device.

## **Future research directions**

On the basis of the present thesis it is not clear whether the impaired proprioception, impaired performance in tracking, and increased grip forces in subjects with neck and upper extremity pain are the cause or the effect of pain. To gain further insight in the mechanisms of the development of pain, the applied methods of this thesis as in **Chapters 3, 4 and 5** could be applied in epidemiological studies with a longitudinal design. Such a study should preferably be undertaken in office workers, since especially in this group the mechanisms of the development of neck and upper extremity pain are unclear. When in the same study measures on sensory function would be added, it could also be investigated whether changes in grip forces are the cause or effect of sensory deficits.

High quality epidemiological studies (longitudinal cohort or RCT studies) are required to determine whether precision is actually an independent risk factor for the development

of neck and upper extremity pain. Indications were found that high sensory demands as measured in a questionnaire, could be related to neck and hand-wrist pain in women (Christensen et al. 2003). However, the underlying mechanism was not clear and objective measures of precision demands have to our knowledge never been associated with neck and upper extremity pain. For computer work it would be possible to quantify precision with objective measures of daily mouse use with computer software. Specific tasks and actions in keyboard use and mouse use could be defined that are associated with different levels of precision and their relationship with either neck-shoulder or hand-arm pain could be determined.

The role of increased muscle activity in the development of neck and upper extremity pain was doubted in the present thesis, but could not be ruled out because activity of individual motor units and reorganisation of muscle activity within or between muscles were not measured. Besides applying methods for the assessment of individual motor units and reorganisation of muscle activity in experimental (laboratory) settings it is advised to apply EMG methods in longitudinal cohort studies. Moreover, it is recommended to use measures of sustained activity and activity of individual motor units, not only in the muscles of interest, but also in their synergists. This interest should not be limited to the trapezius muscle, but also muscles in the forearm should be included. Before starting up a longitudinal study the EMG measures that distinguish between cases and controls should be determined in cross-sectional or case-control studies. Assessment of EMG measures in epidemiological studies might enable the development of a measure of internal load that might be related to the development of neck-shoulder or hand-arm pain. Knowledge of such an association makes it possible to determine whether tasks in other work settings can be considered risk-full without setting up another epidemiological study.

No effect of experimental pain on task performance was found in the literature. However, the outcome measures from the pegboard test and aiming tasks may not have been sensitive enough to find an effect. To test whether the pain sensation in chronic pain is responsible for the negative effects on proprioception and task precision, the effects of induced pain in the forearm extensor and trapezius could be tested in a similar experimental set-up as used in **Chapter 5**. Research questions of interest would be if induced pain leads to similar impairments in proprioception and in tracking performance as in chronic pain patients, and whether subjects respond differently to pain induced in the distal muscles as compared to proximal muscles. Moreover, in **Chapter 4**, detailed analysis of movement kinematics was not possible, and therefore, we could not draw a conclusion on whether local muscle fatigue led to changes in movement kinematics. Therefore, it would be recommended to replicate

the experimental set-up of **Chapter 5** to test for the effects of local muscle fatigue on task performance and kinematics. This will also allow comparison of the effects of local muscle fatigue, experimental pain and chronic pain, and how these physical states relate to each other. Besides it would be interesting to test the effects of fatigue induced by actual computer work.

In the aging population similar physical changes have been found as in subjects with neck and upper extremity pain, such as impaired proprioception, impaired positional precision, reduced quality of sensory information, loss of muscle strength and reduced reaction times (Pai et al. 1997; Smith et al. 1999a; 1999b; Goodpastar et al. 2001; Laursen et al. 2001; Enoka et al. 2003; Romero et al. 2003). Moreover, elderly have been shown to respond with increased co-contraction levels to increased precision demands (Seidler-Dobrin et al. 1998). It seems of interest to investigate if age, and more specifically the capacity of elderly, could act as a disabling factor in performing precision tasks, especially since nowadays employees are expected to participate in the working process until an older age.

Several ergonomic solutions to improve performance in precision tasks have been described in the first paragraph of this chapter, of which the effects on performance in precision tasks seem promising. However, most studies tested the effects on precision in very simplified tasks, e.g. pointing at one single target at a screen, without surrounding targets. Moreover, in most studies only measures of performance were taken and the effects on physical load of the operator were neglected. In future studies it is recommended to test the effects of these solutions, not only on performance, but also on kinematics and physical load. Moreover, the optimal solution is most likely very task specific. Therefore, the effects should be tested in realistic tasks.



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# *Summary*

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*From precision demands to  
neck and upper extremity pain*

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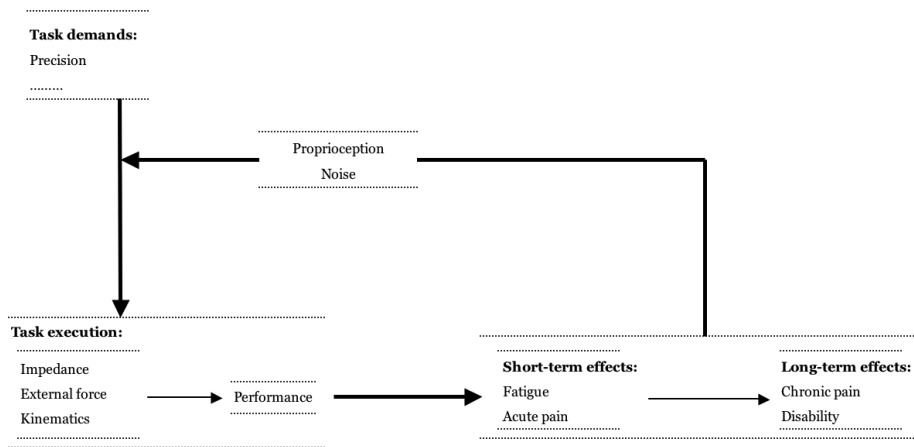
## **From precision demands to neck and upper extremity pain**

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### **Summary**

Despite a whole body of literature, the aetiology of neck and upper extremity pain, also referred to as RSI, Repetitive Strain Injury, is poorly understood. Besides repetitive movements, working in the same (awkward) posture for long periods of time and exerting high forces, working with high precision has been suggested as a risk factor for neck and upper extremity pain. In the introduction of this thesis a Precision-Pain Model (Figure 1) is proposed which hypothesises how precision demands could lead to neck and upper extremity pain. In the Precision-Pain Model it is hypothesised that with higher precision demands in a task, endpoint impedance (i.e. resistance against imposed motion) is increased through increased co-contraction and/or higher friction with the underlying substrate. According to the model, if the task is performed for a long duration, the higher muscle activity required to increase impedance will accelerate fatigue development. Fatigue has been shown to lead to impaired proprioception, i.e. the accuracy of perception of movement or position of body parts, and to increased force variability (= noise). Less accurate information on position and movement of body segments and increased noise will make it more difficult to perform precise movements and a further increase in impedance is expected to be necessary to achieve the required task precision. Increasing impedance is not the only way to deal with high precision demands. In addition, kinematics can be altered and higher external forces may be applied in case proprioceptive information provides insufficient guidance, such as excessive forces in keying or in handling small objects. Higher muscle activity to increase impedance and to generate higher external forces again will accelerate fatigue and close a vicious cycle. This vicious cycle may lead to the development of chronic pain, which may be accompanied by disability.





**Figure 1**  
*Precision-Pain Model*

The present thesis aimed to scientifically verify the following steps of the Precision-Pain Model described above:

1. Precision demands affect task execution (Chapters 2 and 3)
2. Fatigue affects task execution (Chapter 4)
3. Pain affects proprioception (Chapter 5)
4. Pain affects task execution (Chapters 5 and 6)
5. Precision demands are related to chronic pain (Chapter 7)

### Precision demands affect task execution

The study in **Chapter 2** was designed to determine the effect of precision demands on task performance and muscle activity in crane operators during a simulated crane task performed with a joystick. Furthermore, it was investigated whether joystick handle size and display-control gain could positively affect performance, muscle activity and wrist posture. Eight experienced crane operators performed a crane task in which they had to virtually move a load with the crane from one container into another on a computer screen by operating the joystick. The results of the study showed that higher task precision, i.e. using smaller containers, was associated with lower task performance (less repetitions were performed). The number of errors made remained the same. Muscle activity and wrist posture were not affected by task precision. Task performance improved when using a joystick with a short handle and when working at a higher display-control gain, while muscle activity was unaffected. The results of the study appear to contradict the Precision-Pain Model, since precision demands did not affect muscle activity in the simulated crane task. This could be explained by a change

in the kinematics of the task, involving a decrease in task performance (productivity) in line with the speed-accuracy trade-off. Based on the results from this study we recommend a joystick with a short handle to practice. Furthermore, it is advised to optimise display-control gain settings of the machine in relation to the task constraints observed in practice.

In **Chapter 3** we investigated how task performance, kinematics, defined by organisation of sub-movements, and impedance, in terms of muscle activity and pen pressure, were affected by target size in a 2D tracking task performed with a pen on a digitiser tablet. Tracking does not allow a decrease in movement velocity to accommodate precision demands as was possible in the task studied in Chapter 2. Twenty-six healthy subjects performed the tracking task in which either a small or a large target was tracked, while it moved quasi-randomly across the computer screen. With the small target, mean distance to target and the standard deviation of this distance to target were significantly smaller and subjects trailed more behind the centre of target compared to tracking the large target. Subjects also changed pen kinematics, with larger velocity fluctuations of shorter duration, and increased pen pressure and co-contraction of forearm muscles with a smaller target. We concluded that increased precision demands are accommodated by a different organisation of sub-movements and an increased impedance.

### **Fatigue affects task execution**

In **Chapter 4**, the same tracking task as in Chapter 3 was used to study the effects of local muscle fatigue on task performance and on muscle activity in the extensor muscle of the forearm. Eleven female participants performed a tracking task with a computer mouse, before and immediately after a fatigue protocol (wrist extension). After the fatigue protocol percentage time on target was significantly lower in the first half of the tracking task, but was unaffected in the latter half of the task. Mean distance to target and the standard deviation of the distance to target were both significantly larger after the fatigue protocol. The lower task performance was accompanied by higher peak amplitudes of muscle activity in the M. extensor carpi radialis, whereas the static and the median muscle activity levels were not affected. The results of this study showed that task execution was affected by fatigue. Contrary to what is hypothesised in the Precision-Pain Model, the negative effects of fatigue on task performance, i.e. positional precision, are not counteracted by an overall higher muscle activity, but lead to a selective increase in peak muscle activity levels of the forearm extensor muscle.

## **Pain affects proprioception and task execution**

In the study of **Chapter 5**, twenty-three subjects with neck and upper extremity pain and twenty-six healthy control subjects participated in a 2D pointing task to investigate whether position sense acuity (as a measure for the quality of proprioception) differed between these groups. Furthermore, it was investigated whether task performance, kinematics (organisation of sub-movements), impedance (muscle activity and pen pressure) and perceived exertion are affected by neck and upper extremity pain in the 2D tracking task. In the pointing task, subjects were instructed to point at targets, without vision of their arm and hand. The tracking task was the same as used in Chapters 3 and 4 and was performed with a pen on a digitiser tablet. The results showed that position sense acuity and tracking performance were impaired in subjects with neck and upper extremity pain as compared to healthy controls. No differences were found in kinematics and muscle activity and pen pressure as indicators of impedance during tracking. Subjects with neck and upper extremity pain perceived the tracking task as physically more demanding than the healthy controls, whereas mental exertion was perceived similarly. Position sense acuity and tracking performance were correlated, implying that reduced proprioception underlies the reduced tracking performance in subjects with neck and upper extremity pain.

**Chapter 6** concerns the effect of pain on the execution of a gripping task. Grip force control and adaptation of grip force were measured in eighty-one subjects with pain in neck and upper extremity, thirty-two subjects with a history of pain, and thirty-nine subjects without pain. The participants had to lift and hold an object (cup of 300 gram) five times with the dominant hand. Subjects with pain used significantly higher grip forces than subjects without pain, both during lifting and holding the object, while the vertical acceleration of the object during lifting was not different. After the initial lift, all subjects significantly reduced the maximum grip force during lifting, to keep it at a more or less constant level during the consecutive lifts, though grip force levels were still higher in the subjects with pain. The fact that subjects with pain adapted their grip forces after the initial lift indicates that there is no general deficit in sensory-motor integration. The higher grip forces observed in the subjects with pain seem more likely the consequence of reduced acuity of tactile information, which like proprioceptive information is used to guide motor behaviour and appears affected in people that report pain in the neck and upper extremity.

## **Precision demands are related to chronic pain**

In **Chapter 7**, a systematic review was conducted to investigate the evidence for a relation between the duration of computer use, as an example of work requiring high

precision, and the incidence of hand-arm and neck-shoulder pain. In the systematic review only articles were included that presented a risk estimate for the duration of computer use, included an outcome measure related to hand-arm or neck-shoulder symptoms or disorders, and had a longitudinal study design. Nine relevant articles were identified, of which six were rated as high quality. It was concluded that moderate evidence exists for a positive association between the duration of mouse use and hand-arm symptoms. For this association, indications of a dose-response relationship were found. For neck-shoulder pain, insufficient evidence is concluded for total duration of computer use, for duration of mouse use and for duration of keyboard use. Risk estimates are in general stronger for the hand-arm region than for the neck-shoulder region, and stronger for mouse use than for total computer use and keyboard use.

## Conclusions

On basis of the results from the present thesis in combination with results from literature it is concluded that only partial support is found for the Precision-Pain Model. In line with the Precision-Pain Model, it is concluded that: 1) higher precision demands lead to higher impedance in combination with changes in kinematics, 2) proprioception and task performance in terms of positional precision are impaired in fatigued subjects and in subjects with neck and upper extremity pain, and 3) precision demands could be associated with arm-hand pain. The selective increase of peak muscle activity in fatigued subjects when performing precision tasks and the increased grip forces in a lift and hold task in subjects with neck and upper extremity pain could indicate the closure of a vicious cycle, as proposed by the Precision-Pain Model. However, a general increase of impedance in computer tasks with high precision demands was not found for these subject populations as compared to healthy controls. Therefore, the evidence for a vicious cycle is still inconsistent.

## Implications for practice

Even though the role of precision demands in the development of neck and upper extremity pain is not exactly clear, it seems worthwhile to either strive to reduce precision demands in the task or to facilitate precision work. In **Chapter 9** several solutions to improve performance in precision tasks are given, most of which apply to human-computer interaction, but are also applicable in other work tasks in which input devices are used. For instance, in order to make (computer) precision work easier, larger or expanding targets or cursors can be used and input devices can be supplied with feedback mechanisms. In addition, performance in precision tasks can

*Summary*

be improved by optimising display-control gain, the location of icons on the screen and physical characteristics of the input device.



# *Samenvatting*

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*Kunnen hoge precisie-eisen  
in het werk leiden tot RSI?*

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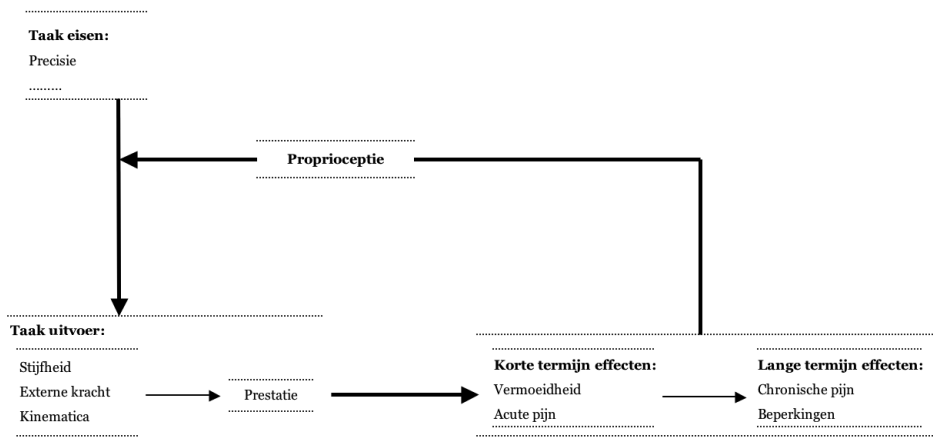
## Kunnen hoge precisie-eisen in het werk leiden tot RSI?

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### Samenvatting

Er zijn aanwijzingen dat het uitvoeren van fijn-motorische hand-arm taken, ofwel taken met hoge precisie-eisen, één van de mogelijke oorzaken is van klachten aan de nek, schouders, armen en/of handen, in de volksmond ook wel RSI genoemd. Hoe hoge precisie-eisen in (werk-) taken tot het ontstaan van RSI zouden kunnen leiden beschrijft het Precisie-Pijn Model, dat centraal staat in dit proefschrift (zie figuur 1 en hoofdstuk 1). Het Precisie-Pijn Model veronderstelt dat bij hoge precisie-eisen, de stijfheid (weerstand tegen bewegen) in het eindpunt, bijvoorbeeld een pen of computermuis die wordt vastgehouden, verhoogd moet worden om de nauwkeurigheid van werken te verhogen. Dit kan gedaan worden door spieren aan weerszijde van de gewrichten gelijktijdig harder aan te spannen (co-contractie) of door de wrijving met de ondergrond te verhogen, bijvoorbeeld door tijdens schrijven harder op de pen te drukken. Als de taak voor langere tijd moet worden uitgevoerd, kan de toegenomen spieractiviteit ervoor zorgen dat vermoeidheid of acute pijn ontstaat. Vermoeidheid heeft een verminderde proprioceptie – het gevoel van positie en beweging van onze ledematen zonder dat we ernaar hoeven te kijken – tot gevolg. Hierdoor is het nog moeilijker nauwkeurig te werken en zal de stijfheid verder moeten toenemen. Verhogen van de stijfheid is niet de enige manier om aan hogere precisie-eisen te voldoen. Hogere precisie-eisen kunnen ook zorgen voor een andere bewegingsuitvoering (kinematica) en het is mogelijk dat taken met verhoogde krachten worden uitgevoerd als de proprioceptieve informatie ontoereikend is om de beweging te sturen. Hogere spieractiviteit voor het verhogen van de stijfheid en om de hogere krachten te kunnen leveren zouden opnieuw de vermoeidheid kunnen versnellen en een vicieuze cirkel kunnen veroorzaken. Het voortduren van deze vicieuze cirkel zou kunnen leiden tot chronische pijn, wat de nodige beperkingen met zich mee kan brengen.





**Figuur 1**

*Het Precisie-Pijn Model.*

In dit proefschrift zijn enkele stappen in het Precisie-Pijn Model onderzocht. Hierbij stonden de volgende onderzoeksvragen centraal:

- Leidt een verhoging van de precisie-eisen tot een aangepaste kinematica en tot een verhoogde stijfheid?
- Leidt vermoeidheid tot een verminderde nauwkeurigheid van werken?
- Hebben mensen met RSI een verminderde proprioceptie en werken ze minder nauwkeurig dan mensen zonder RSI?
- Voeren mensen met RSI taken met hoge precisie-eisen uit met een verhoogde stijfheid of meer kracht?
- Kan langdurig werken met hoge precisie-eisen gerelateerd worden aan het ontstaan van RSI?

Om antwoord te kunnen geven op de onderzoeksvragen zijn verschillende experimentele studies uitgevoerd.

## **Bij hoge precisie-eisen wordt de kinematica aangepast en de stijfheid verhoogd**

Allereerst is in **hoofdstuk 2** onderzocht wat het effect is van hoge precisie-eisen op de taakprestatie en spieractiviteit in de nek, schouder en arm tijdens het uitvoeren van een gesimuleerde kraantaak met een joystick. Bovendien is onderzocht of het aanpassen van de grootte van het handvat van de joystick en de overbrengingverhouding tussen de joystick en de beweging van de kraan (display-control gain; een hoge display-control gain wil zeggen dat een kleine beweging van de joystick een grote beweging van de kraan tot gevolg heeft) een positief effect hebben op de prestatie en spieractiviteit

van de kraanmachinist. Acht gezonde ervaren kraanmachinisten bestuurden met een joystick een kraan die zichtbaar was op een beeldscherm en kregen de opdracht met de kraan zo snel en zo nauwkeurig mogelijk een last tussen twee containers heen en weer te verplaatsen (Figuur 2). Bij hoge precisie-eisen, waarbij de last in kleinere containers geplaatst moest worden, werd de last minder vaak verplaatst, terwijl het aantal gemaakte fouten gelijk bleef. Wanneer met een joystick met een kleiner handvat werd gewerkt of wanneer met een hogere display-control gain werd gewerkt was de prestatie op de taak hoger, dat wil zeggen de last werd vaker verplaatst, terwijl de spieractiviteit niet hoger was. Precisie-eisen hebben in de gesimuleerde kraantaak dus geen effect op spieractiviteit, in tegenstelling tot wat op basis van het Precisie-Pijn Model verwacht wordt. Dit is waarschijnlijk het directe gevolg van het feit dat bij hoge precisie-eisen de taak langzamer uitgevoerd wordt. Geadviseerd wordt om in de praktijk een joystick met een klein handvat te gebruiken en de display-control gain te optimaliseren naar de precisie-eisen in het werk.

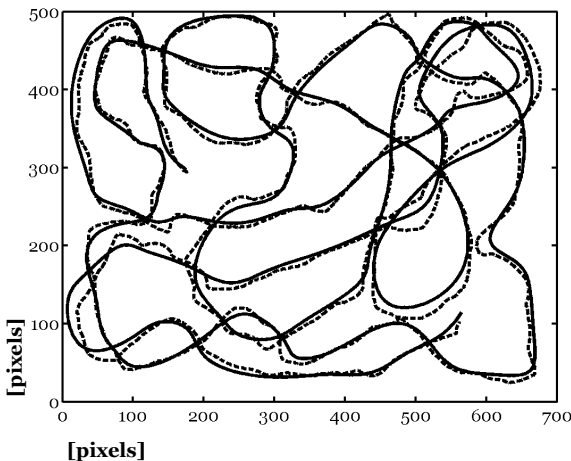


**Figuur 2**

*De onderzoekopstelling zoals gebruikt in de studie van hoofdstuk 2. De kraanmachinist voert een gesimuleerde kraantaak uit met een joystick.*

In **hoofdstuk 3** is het effect van precisie onderzocht op taakprestatie, kinematica en stijfheid in een volgtaak op de computer. In de volgtaak werd met de cursor, die aangestuurd kon worden door met een pen over een tablet te bewegen, een doel gevolgd, terwijl het doel met een constante snelheid op een voor de proefpersoon onvoorspelbaar traject over het beeldscherm bewoog (Figuren 3 en 4). Tijdens het volgen van het doel bewegen proefpersonen nooit met een constante snelheid met de pen, maar fluctueert de snelheid van bewegen. Als maat voor de kinematica is in deze studie de grootte en de duur van deze snelheidsfluctuaties berekend. Als maat voor de stijfheid is de spieractiviteit in de onderarm en de druk van de pen op het tablet gemeten. Zesentwintig gezonde proefpersonen voerden de volgtaak uit waarin zowel een groot als een

klein doel gevolgd werd. Tijdens het volgen van het kleine doel waren de gemiddelde afstand tot het doel en de standaard deviatie van deze afstand significant kleiner dan bij het grote doel en de proefpersonen bleven meer achter het midden van het doel “hangen”. Ook de kinematica was anders bij het volgen van het kleine doel, met grotere snelheidsfluctuaties van een kortere duur en waren zowel de druk op de pen en de co-contractie in de onderarm toegenomen. Deze verhoogde co-contractie trad niet alleen op in de arm waarmee de taak werd uitgevoerd, maar ook in de arm die tijdens de taak ogenschijnlijk rustig naast het tablet op tafel lag. De conclusie is dat bij hogere precisie-eisen de kinematica aangepast wordt en de stijfheid in de arm verhoogd wordt.



**Figuur 3**

Voorbeeld van de volgtaak; met de doorgetrokken lijn het traject van het doel en de stippellijn het traject van de cursor van een willekeurige proefpersoon.

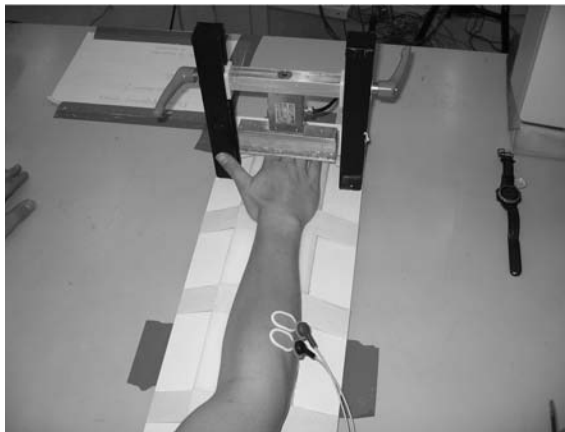


**Figuur 4**

De onderzoekopstelling zoals gebruikt in hoofdstukken 3 en 5. De proefpersoon voert een volgtaak uit op de computer met een pen en een tablet.

### **Bij lokale spier-vermoeidheid wordt minder nauwkeurig gewerkt**

In **hoofdstuk 4** is gebruik gemaakt van dezelfde volgtaak als in hoofdstuk 3 om het effect van lokale spierversmoeidheid op taakprestatie en spieractiviteit in de onderarm te onderzoeken. Elf gezonde vrouwelijke proefpersonen voerden de volgtaak uit met een computermuis, één keer voor en één keer direct na een vermoeidheidsprotocol waarbij de strekkers van de pols vermoeid werden (Figuur 5). Na het vermoeidheidsprotocol bleek het percentage van de tijd dat de cursor op het doel is in de eerste helft van de volgtaak significant lager, maar in de tweede helft van de taak hetzelfde als voor het vermoeidheidsprotocol. De gemiddelde afstand tot het doel en de standaarddeviatie van deze afstand waren beide significant groter na het vermoeidheidsprotocol. De verminderde taakprestatie ging gepaard met hogere pieken in de spieractiviteit in de strekker van de pols (*M. extensor carpi radialis*), terwijl het statische en mediane niveau niet aangedaan waren. De resultaten van deze studie laten zien, dat als gevolg van lokale spierversmoeidheid minder nauwkeurig gewerkt kan worden. In tegenstelling tot wat verwacht wordt op basis van het Precisie-Pijn Model, worden de negatieve effecten van vermoeidheid op de taakprestatie niet gecompenseerd door een algehele toename van de spieractiviteit, maar vindt een selectieve toename van de piek spieractiviteit in de onderarm extensor spier plaats.



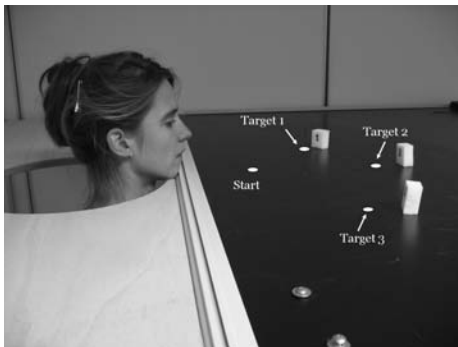
**Figuur 5**

*De opstelling voor het vermoeidheidsprotocol in hoofdstuk 4, waarin de strekkers van de onderarm vermoeid worden.*

### **Mensen met RSI voeren een taak met hoge precisie-eisen minder nauwkeurig uit vermoedelijk als gevolg van een verminderde proprioceptie. De kinematica en de stijfheid zijn vergelijkbaar als bij mensen zonder RSI.**

In de studie in **hoofdstuk 5** hebben drieëntwintig proefpersonen met RSI en zesentwintig gezonde proefpersonen een 2D aanwijkstraak uitgevoerd om te onderzoeken of

de nauwkeurigheid van het positiegevoel (als indirecte maat voor proprioceptie) bij mensen met RSI verschilt van mensen zonder RSI. Voor de aanwijkstraak werden de proefpersonen geïnstrueerd om doelen die bovenop een plaat zichtbaar waren aan de onderzijde van de plaat aan te wijzen, zonder dat ze hierbij hun arm en hand konden zien (Figuur 6). Bovendien voerden beide groepen proefpersonen dezelfde volgtaak uit als in hoofdstukken 3 en 4 gebruikt werd met een pen op een tablet. Met deze volgtaak is onderzocht of taakprestatie, kinematica (grootte en duur van snelheidsfluctuaties), stijfheid (spieractiviteit en pendruk) en ervaren belasting veranderd zijn in mensen met RSI. De nauwkeurigheid van het positiegevoel en de prestatie op de volgtaak bleken verminderd bij mensen met RSI in vergelijking tot de mensen zonder RSI, terwijl de kinematica, de spieractiviteit en de pendruk in de volgtaak hetzelfde waren voor beide groepen. De mensen met RSI ervoeren de taak wel als fysiek inspannender, terwijl de mentale inspanning door beide groepen hetzelfde ervaren werd. De nauwkeurigheid van positiegevoel en de prestatie op de volgtaak waren gecorreleerd, wat impliceert dat een verminderde proprioceptie de onderliggende reden is van de afgenomen prestatie op de volgtaak bij de mensen met RSI. Mensen met RSI blijken echter niet te compenseren voor deze verminderde taakprestatie door het aanpassen van de kinematica of door het verhogen van de stijfheid.



**Figuur 6**

*De opstelling van de 2D aanwijkstraak, zoals gebruikt in hoofdstuk 5, waarmee de nauwkeurigheid van het positiegevoel getoetst wordt.*

## **Tijdens het optillen van een beker gebruiken mensen met RSI grotere knijpkrachten**

In **hoofdstuk 6** is onderzocht wat het effect is van RSI op de knijpkracht en het aanpassen van de knijpkracht tijdens het optillen en het vasthouden van een voorwerp met de voorkeurshand. Eenentachtig mensen met RSI, tweeëndertig mensen die

RSI hebben gehad maar klachtenvrij zijn op het moment van meten en negenendertig mensen zonder RSI tilden vijf keer een voorwerp op (beker van 300 gram) en hielden deze gedurende vijf seconden vast (Figuur 7). Mensen met RSI gebruikten een significant hogere knijpkracht dan mensen zonder RSI tijdens zowel het optillen als het vasthouden van de beker, terwijl de verticale versnelling tijdens het optillen gelijk was. Na de eerste poging pasten alle proefpersonen hun maximale knijpkracht aan en gebruikten tijdens de volgende pogingen minder kracht, hoewel de knijpkracht wel steeds significant hoger was bij de mensen met RSI. De hogere knijpkrachten van de mensen met RSI lijken het meest waarschijnlijk het gevolg van een verminderde nauwkeurigheid van tactiele informatie.



**Figuur 7**

*Knijpkracht en aanpassing van de knijpkracht zijn gemeten tijdens het optillen en vasthouden van een beker in hoofdstuk 6.*

## **Werk met hoge precisie-eisen kan gerelateerd worden aan het ontstaan van hand-arm klachten**

Computerwerk kan gezien worden als werk met hoge precisie-eisen. Om te kijken of het veelvuldig uitvoeren van werk met hoge precisie-eisen gerelateerd kan worden aan het ontstaan van RSI is gekeken of de duur van computerwerk gerelateerd kon worden aan het ontstaan van hand-arm en nek-schouder klachten. In **hoofdstuk 7** is hiertoe een systematisch literatuuronderzoek uitgevoerd. Er is systematisch gezocht naar artikelen met een risicoschatter voor de duur van computer gebruik, met een uitkomstmaat gerelateerd aan hand-arm en nek-schouder klachten en een longitudinaal design. Negen relevante artikelen werden geselecteerd, waarvan zes beoordeeld werden als

kwalitatief hoogstaand. Matig bewijs is gevonden voor een positieve associatie tussen de duur van muisgebruik en hand-arm klachten. Voor deze associatie is een indicatie voor een dosis-respons relatie gevonden, dat wil zeggen dat bij langer muisgebruik steeds meer klachten worden gerapporteerd. Voor nek-schouder klachten is de conclusie dat er onvoldoende bewijs is voor de associatie met totale duur computergebruik, duur muisgebruik en duur toetsenbordgebruik. Risicoschatters zijn over het algemeen sterker voor de hand-arm regio dan voor de nek-schouder regio, en sterker voor duur muisgebruik dan voor duur totaal computergebruik of duur toetsenbordgebruik.

## Conclusies

Op basis van de resultaten van dit proefschrift in combinatie met gegevens uit de literatuur kan geconcludeerd worden dat voor een deel van het Precisie-Pijn Model bewijs is gevonden. In overeenstemming met het Precision-Pain Model is gevonden dat:

- 1) hogere precisie-eisen leiden tot een hogere stijfheid (hogere spieractiviteit) in combinatie met veranderingen in de kinematica;
- 2) proprioceptie en het vermogen nauwkeurig te werken (taakprestatie op taken met hoge precisie-eisen) zijn verminderd bij mensen met vermoeide armspieren en mensen met RSI;
- 3) hoge precisie-eisen geassocieerd kunnen worden met hand-arm klachten.

De selectieve toename van de piek spieractiviteit in proefpersonen met vermoeide armspieren bij het uitvoeren van taken met hoge precisie-eisen en de toegenomen knijpkracht tijdens het optillen van een voorwerp zouden de vicieuze cirkel in het Precisie-Pijn Model kunnen sluiten. Echter, een algemene toename van stijfheid in (computer) taken met hoge precisie-eisen is niet gevonden bij mensen met RSI in vergelijking met mensen zonder RSI zoals door het Precisie-Pijn Model verondersteld wordt. Daarom kan geconcludeerd worden dat het bewijs voor het sluiten van de vicieuze cirkel, zoals voorgesteld in het Precisie-Pijn Model beperkt is.

## Wat betekenen de resultaten van het onderzoek voor de praktijk?

Mensen met RSI voeren taken met hoge precisie-eisen minder nauwkeurigheid uit. Als een vermindering van de nauwkeurigheid in taken niet wordt toegelaten, is het waarschijnlijk dat mensen met RSI taken langzamer uitvoeren. Zowel minder nauwkeurig als langzamer werken kan leiden tot een verminderde inzetbaarheid en geschiktheid van mensen met RSI in arbeidstaken met hoge precisie-eisen. Ook mensen die vermoeid zijn laten een verminderde nauwkeurigheid op taken met hogeprecisie-eisen zien. Dit betekent dat ook het ontstaan van vermoeidheid bij het uitvoeren van deze taken moet worden voorkomen omdat anders de prestatie op de taak vermindert.

Kortom, reden genoeg om te trachten de precisie-eisen in werktaken naar beneden te brengen of het uitvoeren van deze taken te vergemakkelijken. Daartoe zijn in **hoofdstuk 9** aanbevelingen gedaan. De meeste oplossingen zijn onderzocht voor de interactie met computers, maar zijn ook toepasbaar voor andersoortige taken waarin invoermiddelen worden gebruikt, zoals het gebruik van joysticks op kranen. (Computer) werk met hoge precisie-eisen kan gemakkelijker gemaakt worden door iconen of cursors te gebruiken die vergroten als ze in elkaars nabijheid zijn, door het gebruik van invoermiddelen met feedback mechanismen die bijvoorbeeld gaan trillen of geluid maken als de cursor bij het doel is. Bovendien kan de prestatie op taken met hoge precisie-eisen verbeterd worden door het optimaliseren van de display-control gain, de optimale locatie van iconen op het scherm vast te stellen en het optimaliseren van de fysieke eigenschappen van het invoermiddel. Een voorbeeld van het laatste is dat met een joystick met een klein handvat een taak met hoge precisie-eisen sneller uitgevoerd kan worden dan met een joystick met een groot handvat, zoals in hoofdstuk 2 van dit proefschrift geconcludeerd werd.

a



b



**Figuur 8**

*Met een joystick met een klein handvat (a) kan een taak met hoge precisie-eisen sneller uitgevoerd worden dan met een joystick met een groot handvat (b).*







# About the Author



Maaike Huysmans was born on September 3rd 1974 in Enschede, the Netherlands. After completing secondary school at the Jacobus College in Enschede in 1992, she worked one year in London as an au-pair. In 1993 she started to study Human Kinetic Technology at the The Hague University of Applied Sciences in The Hague. After graduating in 1997 she started studying at the Faculty of Human Movement Sciences at the VU University Amsterdam. In 2001 she graduated cum laude with a specialisation in Ergonomics. From June 2001 to December 2002 she worked as a consultant in ergonomics for VHP Ergonomics in The Hague. In January 2003 she started with a PhD project, of which the results are presented in this thesis, at the Faculty of Human Movement Sciences at the VU University Amsterdam. The project was part of Body@Work, Research Centre on Physical Activity, Work and Health, which is a joint initiative of the Institute for Research in Extramural Medicine of the VU University Medical Centre (EMGO-institute) and TNO Quality of Life. During the first three years of her PhD project she worked one day a week as a researcher/consultant in ergonomics for TNO Quality of Life in Hoofddorp. In January 2008 she started her current position as a post doctoral fellow at Body@Work, VU Medical Centre, where she will continue to do research in the area of work and health.

**Contact:**

[m.huysmans@vumc.nl](mailto:m.huysmans@vumc.nl)

[maaikehuysmans@hotmail.com](mailto:maaikehuysmans@hotmail.com)

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