SMI **Center for Sensory-Motor Interaction**

Modulations of the Human Trapezius Muscle H-Reflex Following Eccentric Exercise

AALBORG UNIVERSITY DENMARK

PhD Thesis by
Steffen Vangsgaard

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Aalborg, August 2014

Steffen Vangsgaard

Preface

The present studies were carried out at Center for Sensory-Motor Interaction (SMI), Aalborg University, Denmark, and at Neuroscience Research Australia (NeuRA), Sydney, Australia, in the period from 2010 to 2014. The current PhD stipend was funded by Aalborg University.
This dissertation is based on the following four peer-reviewed articles. In the text these are referred to as Study (I) to (IV) (full-length articles in Appendix).

Study (I): Vangsgaard S, Nørgaard LT, Madeleine P, Taylor JL. **Crossed responses found in human trapezius muscles are not H-reflexes.** *Muscle & Nerve*. 2014; 49(3):362-369.

Study (II): Vangsgaard S, Hansen EA, Madeleine P. **Between-day reliability of the trapezius muscle H-reflex**. *Submitted August 2014*.

Study (III): Vangsgaard S, Nørgaard LT, Korsholm Flaskager B, Søgaard K, Taylor JL, Madeleine P. **Eccentric exercise inhibits the H-reflex in the middle part of the trapezius muscle**. *European Journal of Applied Physiology*. 2013; 113(1):77-87.

Study (IV): Vangsgaard S, Taylor JL, Hansen EA, Madeleine P. **Changes in H-reflex and neuromechanical properties of the trapezius muscle after 5 weeks of eccentric training: a randomized controlled trial**. *Journal of Applied Physiology.* 2014; 116(12): 1623-1631

Contents

Summary

The trapezius muscles form very important parts of the neck-shoulder region and are commonly involved in musculoskeletal disorders. Interestingly, the motor and sensory innervation to trapezius is divided into the accessory nerve and the C3/4 cervical nerve, respectively. It is thereby possible to evoke H-reflexes in the trapezius muscle with minimal influence of M-waves which may allow special insight into the spinal mechanisms of this muscle. However, only a few studies exist on these responses and none have investigated the effects from muscle soreness or strength training.

When performed at a high intensity, eccentric contractions can lead to delayed onset muscle soreness. However, when the intensity is progressively increased, eccentric training has shown promising results with regards to strength training and rehabilitation. Still, knowledge on neural adaptations at the spinal level following eccentric exercise is lacking. The overall aim of this thesis was therefore to provide new insights into the spinal mechanisms of the human trapezius muscles and its response to eccentric exercises. For this purpose, four studies, all involving percutaneous electrical stimulation to elicit trapezius muscle H-reflexes and M-waves, were performed.

In Study (I), outcome measures of the trapezius muscle H-reflex were reported. In Study (II), the absolute and relative reliability of these measures were investigated and found to be good enabling the assessments of physical interventions. In Study (III), a single session of high-intensity eccentric exercises resulted in a decrease in the H-reflex most likely reflecting presynaptic inhibition of the α-motoneurons. On the contrary, five weeks of eccentric strength training resulted in an increase of the maximal amplitude of the trapezius muscle H-reflex, reflecting an increase in the net excitability of the α-motoneurons (Study (IV)).

The present findings confirmed the separated sensory and motor innervation of the trapezius muscle. Moreover, this series of studies investigated and documented for the first time changes in the trapezius muscle H-reflex in presence of muscle soreness and following eccentric strength training.

Dansk resumé (summary in danish)

Trapezius musklerne udgør meget vigtige dele af nakke/skulder-regionen og er ofte involveret i muskel-og skeletbesvær. Den motoriske og sensoriske innervation til trapezius er opdelt i henholdsvis nervus accessorius og den cervikale nerve C3/4. Det er derved muligt at fremkalde H-reflekser i trapezius musklen med minimal påvirkning af M-bølger. Dette muliggør undersøgelser, som kan give særlig indsigt i spinale mekanismer vedrørende denne muskel. Der eksisterer dog kun få undersøgelser vedrørende H-reflekser i trapezius musklen og ingen af disse har undersøgt effekten af muskelømhed eller styrketræning.

Excentrisk træning kan, når det udføres ved en høj intensitet, føre til forsinket muskelømhed. Når intensiteten derimod gradvist øges, har excentrisk træning vist lovende resultater med hensyn til både styrketræning og genoptræning. Tiltrods for dette mangler der viden om neurale tilpasninger på spinalt niveau efter excentrisk arbejde. Det overordnede formål for denne afhandling var derfor at undersøge de spinale mekanismer af trapezius musklerne samt disses tilpasning til excentrisk træning. Til dette formål blev fire studier udført, der alle involverede elektrisk stimulation for at fremkalde H-reflekser og M-bølger i trapezius musklen.

I studie (I) blev forskellige parametre relateret til trapezius musklens H-refleks undersøgt. I studie (II) blev den absolutte og relative pålidelighed af disse parametre undersøgt og vurderet til at være god, hvilket muliggør undersøgelser af fysiske interventioner. I studie (III) resulterede en enkelt session af høj-intensive excentriske øvelser i et fald i H-refleksen, hvilket sandsynligvis skyldes præsynaptisk inhibition af α-motorneuroner. Derimod resulterede fem ugers excentrisk styrketræning i en forøgelse af den maksimale amplitude af trapezius musklens H-refleks, hvilket afspejler en stigning i excitabiliteten af α-motorneuronerne (studie (IV)).

Resultaterne bekræfter den adskilte sensoriske og motoriske neurale innervation til trapezius musklen. Dette er desuden de første forsøg til at undersøge og dokumentere ændringer i trapezius musklens H-refleks som følge af muskelømhed eller excentrisk styrketræning.

List of Abbreviations

ANOVA : Analysis of Variance
DOMS : Delayed Onset Muscle Soreness
ECC : Eccentric Training Group
EMG : Electromyography
H-reflex : Hoffman Reflex
ICC : Intraclass correlation coefficient
MSD : Musculoskeletal disorders
MVC : Maximal Voluntary Contraction
M-wave : Motor wave
PPT : Pressure Pain Threshold
REF : Reference Group
RFD : Rate of force development
RMS : Root Mean Square
SD : Standard deviation
SEM : Standard error of measurement
SRD : Smallest real difference
VAS : Visual Analogue Scale

1 Introduction

This section presents a brief overview of the scope and background of the present thesis. The overall aim and the flow of the thesis are also presented.

1.1 Musculoskeletal neck-shoulder disorders

Musculoskeletal disorders (MSD) pose a significant health care problem in the western world today. A recent European survey shows that about 23 % of workers in European countries reported neck and shoulder pain and is now, second to back pain, the most common musculoskeletal disorder (1). In particular, computer work has been associated with neck-shoulder symptoms (2). This is a concerning issue not only because of the health effects on individuals, but also because of the socio-economic aspects, as the costs are estimated to be between 0.5 and 2 % of the Gross National Product in European Countries (3). Despite comprehensive attention, MSDs are still difficult to diagnose due to lack of clinical tests (1). A better understanding of the sensory-motor function in muscles of the neck-shoulder region may provide a better understanding of the mechanisms involved in both rehabilitation of MSD and exercise training in this region (4). Moreover, such information may provide new knowledge useful for the development of new diagnostic methods.

The trapezius muscles form very essential parts of the neck/shoulder region (6). Moreover, involvement of these muscles is common in MSDs (7) which are often associated with neck-shoulder pain and muscular hyperalgesia (8-10). The muscles extend longitudinally from the occipital bone to the lower thoracic vertebrae and laterally to the spines of the scapulae (see Figure 1). They are axially and bilaterally located and have a key role in supporting the body posture and in movements of the head and shoulders during a number of different tasks, e.g. stabilisation of the shoulder joint to allow precise manipulations with the arm and hand (11,12). Due to different fiber directions, the trapezius muscle is divided

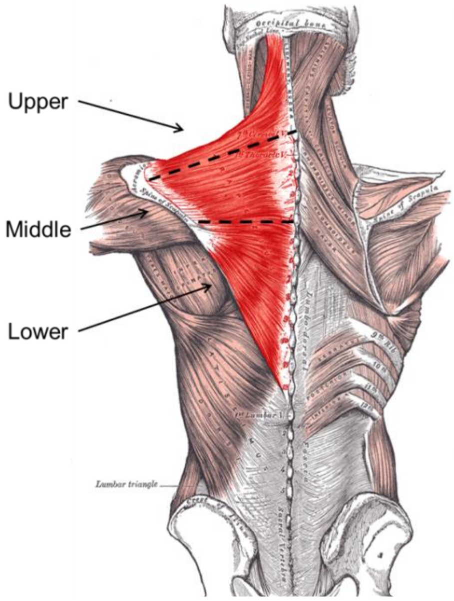

Figure 1: *The left trapezius muscle is marked with red colour. The three subdivisions are also illustrated. Modified from* (5).

into different anatomical and functional subdivisions (6). In the current project, the muscles are divided into three subdivisions: an upper, middle and a lower part (see Figure 1). Previously, the muscle has also been divided into four parts (13). Interestingly, the motor and sensory innervation to trapezius is divided into the accessory nerve and the C3/4 cervical nerve respectively (14-16). These nerves are located in the neck region and accessible by percutaneous electrical stimulation. Thus, it is possible to investigate spinal mechanisms by eliciting Hoffman reflexes.

1.2 The trapezius muscle Hoffman reflex

As described in a recent review by Millet et al. (2011), electrical stimulation is useful for investigating changes at the spinal level. In particular, Hoffmann (H-) reflexes, F-waves, and/or cervicomedullary motor-evoked potentials (CMEPs) are useful techniques for this purpose (see Figure 2). While H-reflexes and F-waves are evoked via electrical stimulation of a peripheral nerve, CMEPs are evoked via transcranial magnetic stimulation over the motor cortex. In the current thesis focus will only be on the H-reflex from the trapezius muscles.

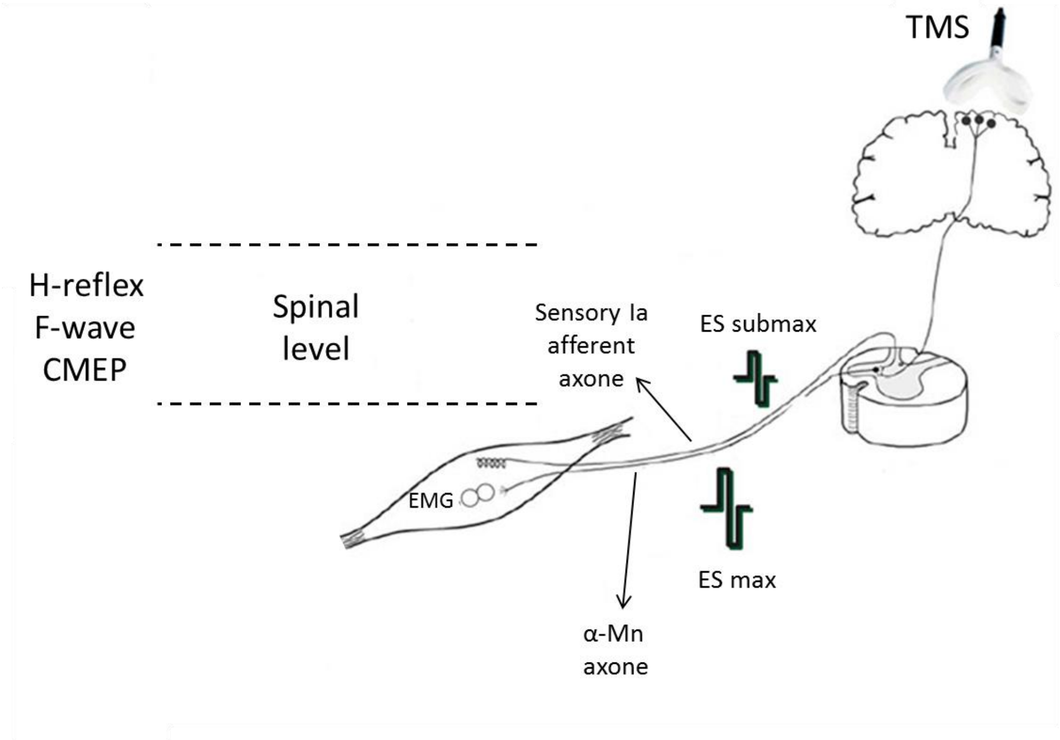

Figure 2: *Illustration of the different electrical and magnetic stimulation methods to investigate spinal mechanisms. α-Mn: Alpha-motoneurone;TMS: Transcranial magnetic stimulation; ES: Electrical stimulation. Modified from* (17) *and* (18)*.*

The H-reflex, originally described in 1918 in the soleus muscle by Paul Hoffman (19), is often used to investigate neurophysiological aspects of the central nervous system in able bodied persons as well as in patients suffering from e.g., radiculopathy and neuromuscular disorders (20-23). Briefly, the H-reflex represents the response evoked by submaximal percutaneous electrical stimulation of low-threshold muscle afferents which results in action potentials that travels along the afferent fibres until they reach the α-motoneurons and consecutively produce a response in the electromyograph (EMG) (see Figure 2) (24,25). The H-reflex is almost similar to the spinal stretch reflex which is mechanically induced by tapping the tendon. However, the major difference is that the H-reflex bypasses the muscle spindles by stimulating the afferent fibres at a superficial point (24).

Although the H-reflex is in theory possible to record in all superficial muscles with a nerve which can be accessed by percutaneous electrical stimulation, H-reflexes from muscles in the upper extremity are rarely investigated compared with H-reflexes muscles from the lower extremity (24) and only a few studies have been published regarding the H-reflex of the trapezius muscle (15,26,27). Interestingly, the findings from the study by Alexander and Harrison (2002) suggest that crossed reflexes are evoked in the contralateral trapezius by electrical stimulation of the C3/4 cervical nerves. These responses have a latency consistent with monosynaptic excitation by Ia afferents and were proposed to be H-reflexes. Such crossed reflexes would contribute to the close linkage between the two trapezii demanded by the bilateral tasks in which the two trapezii co-contract (15). Crossed facilitation of motoneurons by muscle spindle firing might also contribute to bilateral ongoing low level electromyographic (EMG) activity and spreading of pain (28,29).

As described in Section 1.1, the motor and sensory innervation to the trapezius muscles is separated into the accessory nerve and the C3/4 cervical nerves, respectively. Thus, it is possible to evoke trapezius muscle H-reflexes with minimal influence of M-waves which may allow special insight into the actions of Ia (muscle spindle) input on the motoneuron pool. In other muscles, like the soleus muscle, stimulation of a mixed nerve (i.e. containing both sensory and motor axons) causes the amplitude of the H-reflex to increase with stimulation intensity until a number of motor axons are also activated. Hereafter the amplitude decreases until it reaches zero. This is due to collision between action potentials of the evoked reflex response and antidromic action potentials in the motor axons from the electrical stimulation. Consequently, the use of the maximal H-reflex as a measure of reflex excitability is questionable (24). This is especially problematic in muscles with a low discrepancy between the threshold for activating Ia afferents and the threshold for activating motor axons (e.g. flexor carpi radialis and quadriceps). Therefore, studying the trapezius muscle H-reflex may allow special insight into the modulation of the monosynaptic circuit in different conditions, e.g. following strength training or in the presence of muscle soreness. To investigate these modulations it is of utmost importance to have a reliable method for measuring H-reflexes from the trapezius muscle between sessions. Only a few studies have examined the reliability of H-reflexes in the upper body and these have all focused on flexor carpi radialis (FCR) or extensor carpi radialis longus (ECRL) (30-33). Thus, knowledge on the between-sessions reliability of the trapezius muscle H-reflex is lacking.

1.3 Eccentric exercise - soreness and training

Physical exercise has been suggested as a treatment for musculoskeletal disorders in the neck-shoulder region (34-36). A recent study has shown that high-intensity specific strength training reduced pain intensity in neck muscle pain in women with trapezius myalgia (37). Even as little as two minutes of daily progressive resistance training resulted in clinical reductions of pain and tenderness (38). Other studies have also shown reduction of pain to some extent by strength training interventions (35,36,39). There is, however, no consensus as to which exercises are the most effective, and the spinal adaptations to eccentric exercise, which are characterised by lengthening of the muscle while a load is applied to it, have not been sufficiently evaluated (40). When performed at a high intensity, eccentric contractions can also lead to delayed onset muscle soreness (DOMS) and may therefore be used as a model to investigate muscle degeneration.

1.3.1 Eccentric exercise and muscle soreness

Physical activity involving repeated eccentric contractions at a high intensity can lead to damage in the active muscles as often seen in athletes (41). This has consequences for both muscle function and performance. The known principal markers of muscle tissue damage are prolonged strength loss, muscle contractures and an increased level in blood of muscle proteins (42). In addition, the damage may be accompanied by DOMS which peaks 24-72h after the exercise (43). DOMS is associated with muscle hyperalgesia, stiffness, decreased range of motion and altered surface electromyographic (EMG) activation (44,45). Many studies on DOMS have focused on e.g. tibialis anterior (46) and quadriceps muscles (47). However, the shoulder girdle has recently attracted more interest (44,48,49). DOMS is considered an endogenous pain model that can mimic aspects of the pain perceived by chronic neck-shoulder patients (48,50). Hence, several studies (48,51-53) have successfully evoked muscular hyperalgesia in the trapezius muscle in healthy subjects. Furthermore, patients with neck-shoulder pain show altered activity of trapezius although it is not clear whether this is a consequence of pain or a contributor to it (54). Investigation of the H-reflex from the trapezius muscle in the presence of DOMS may help to identify some of the mechanisms for this alteration.

Interestingly, resistance trained men are less susceptible to muscle damage induced by eccentric maximal exercise than untrained men (55). Moreover, light load eccentric exercise confers protection against subsequent bout of more demanding eccentric exercise (56). Recent results support the potential role of eccentric bouts in training regimens of the neck/shoulder region (51). In the study by Kawczynski et al. (2012) two subsequent sessions of eccentric exercise showed an adaption process in the second session indicating a protective role of eccentric training. Thus, eccentric contractions may be related to the prevention and eventually to the treatment of MSD. There is to date no available information about the extent of necessary eccentric work and how it should be applied (57).

1.3.2 Eccentric strength training

Recently, eccentric exercise has been reported to decrease pain intensity and increase function in patients with shoulder disorders (58-60). In line with this, eccentric training has also shown to decrease pain intensity in other injured tendons (e.g. the Achilles, Patellar, and elbow) (61-64).

Compared with concentric exercise, eccentric exercise is associated with a greater improvement in strength and requires lower levels of EMG activity to produce the same amount of force i.e., lower motor unit activation (65-67). Moreover, larger increases in surface electromyographic (EMG) activity have been observed after eccentric training compared to concentric training, indicating a greater neural flow in eccentrically trained muscles (68).

Even though several studies have examined the effects of strength training on pain intensity in the neck-shoulder region, no studies have investigated spinal mechanisms in relation to training in this region (69). In fact, neural adaptations at the spinal level have been rarely investigated following pure eccentric training and the results from these studies are not clear (70,71).Thus, knowledge about the effects of eccentric exercise on the neuromuscular system are needed (40). Investigation of the H-reflex may contribute information regarding the sites and mechanisms of neural adaptation at the spinal level to strength training (72)(69).

1.4 Aims of the Ph.D. project

The overall aim of this thesis was to provide new insights into the spinal mechanisms of the human trapezius muscles and its response to eccentric exercise training. For this purpose, percutaneous electrical stimulation of the C3/4 cervical nerve and the accessory nerve was used for eliciting trapezius muscle H-reflex and M-wave responses, respectively.

The specific aims of this Ph.D. project were:

1. To investigate the presence of crossed short-latency reflexes evoked in trapezius by stimulation of the C3/4 cervical nerves (**Study I**);
2. To estimate the absolute and relative between-day reliability of the trapezius muscle H-reflex and the corresponding M-wave (**Study II**);
3. To determine whether the H-reflex in trapezius was altered 24 hour after eccentric exercises in the presence of DOMS (**Study III**);
4. To investigate the neural adaptations induced by a 5-week strength training regimen, based solely on eccentric contractions of the shoulder muscles (**Study IV**).

To investigate these aims four research studies were performed. **Study (I)** acted as a methodological precursor to gain insight into the characteristics (i.e. the amplitude and latency) of the H-reflex and M-wave from all three parts of the trapezius muscles. Moreover, previously reported contralateral responses were recorded and investigated to determine whether these were H-reflexes or not. **Study (II)** followed the methods in the previous study to elicit H-reflexes and M-waves in the middle part of the trapezius muscle. The study was designed to investigate the between-day reliability of parameters extracted from the H-reflex and M-wave recruitment curves.

Following up the evidence encountered in the previous research, two intervention studies were conducted. In **Study (III)** a single session of intensive eccentric neck-shoulder exercises was performed by the subjects in order to assess the effects from DOMS on the trapezius muscle H-reflex. **Study (IV)** was carried out as a randomised controlled trial (an eccentric training group and a reference group) where the training group followed a 5-week strength training regimen solely consisting of eccentric exercises identical to Study (III) but with a lower intensity. The flow of the thesis is illustrated in Figure 3.

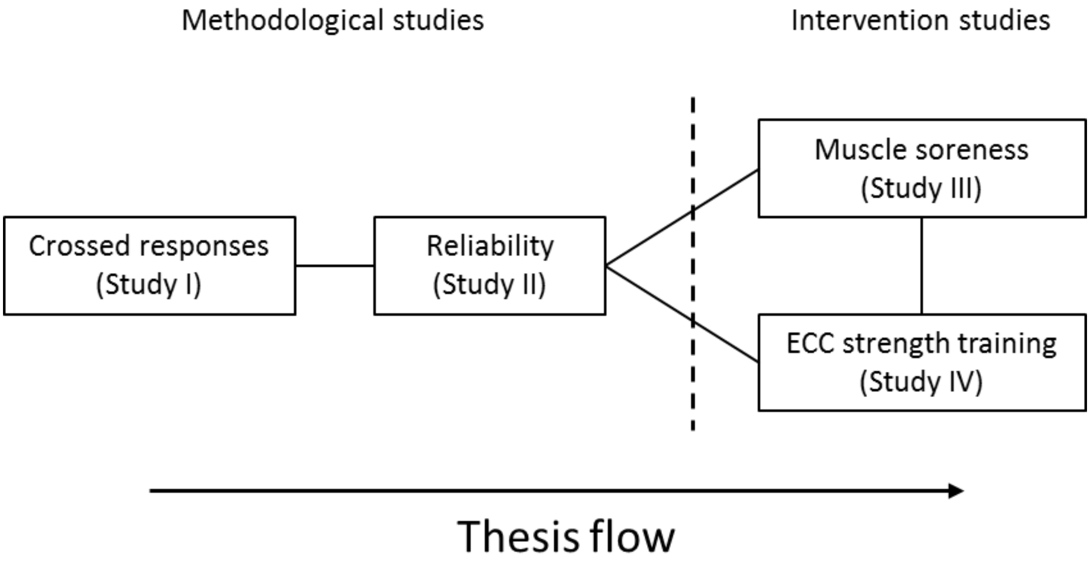

Figure 3: *Overview of the performed studies.*

2 Methods

The following section provides an overview of the methods used in the four studies.

2.1 Subjects

A total of 59 subjects participated in the four studies. The baseline anthropometrical measures, age and number of subjects of each study are shown in Table 1. All subjects were young healthy males and females with no history of previous neck-shoulder disorders. Furthermore, for Study (II), (III), and (IV), all subjects refrained from strenuous physical exercise and maintained normal daily activity during the course of the studies. All the studies were conducted according to the declaration of Helsinki and approved by the local ethical committees (HREC 08354; N-20070004; N-20120036). Moreover, Study (IV) was registered in the International Standard Randomized Controlled Trial Number Register (ISRCTN16080194). Informed consents were obtained from all participants.

Table 1: *Characteristics of the subjects in study (I) - (IV).*

	Study			
	(I) [A]	(II) [B]	(III)	(IV)
Number of subjects	21 (11 + 10)	16	13	29
Gender (M=males; F=females)	A: 6M + 5F B: 7M + 3F	9M + 7F	5M + 8F	10M + 19F
Age (years)	A: 27.1±4.0 B: 25.8±6.0	24.3±1.6	23.9±1.8	22.9±4.3
Body mass (kg)	-	71.1±13.9	64.8±9.1	62.9±10.4
Height (m)	-	1.77±0.09	1.71±0.1	1.71±0.07
Body mass index (kg/m^2)	-	22.5±2.9	21.5±2.2	21.5±2.5

[A] Study (I) consisted of a main experiment (A) and an additional experiment (B); [B] Ten of the participants in study (II) were also included in study (III).

In study (I) one subject was excluded from the main experiment, and two subjects were excluded from the additional experiment, because H-reflexes could be obtained with the hand-held cathode but not with the adhesive electrode. In study (III) two subjects was excluded due to lack of identifiable H-reflexes and one withdrew due to discomfort caused by the electrical stimulation. In study (IV) four subjects were excluded due to lack of identifiable H-reflexes. In addition, two subjects dropped out after the baseline test, Moreover, three subjects were excluded from the analysis involving M_{max} due to saturation of the signals.

An overview of the methods used in the studies is summarized in Table 2 and described in more detail below.

Table 2: *Overview of the methods used in study (I) – (IV).*

	Study			
	(I)	(II)	(III)	(IV)
Percutaneous stimulation	X	X	X	X
EMG recordings	X	X	X	X
Eccentric shoulder exercises			X	X
Force recordings			X	X
Visual Analogue Scale			X	X
Pressure algometry			X	

2.2 Percutaneous Electrical Stimulation (all studies)

All studies followed the recommendations for H-reflex recordings proposed by Brinkworth et al. (73) and Zehr (21): acquisition of full recruitment curves, normalization for the size of the reflex, as well as the use of a submaximal level of muscle activity. During all electrical stimulation, the subjects were seated on an office chair with feet on the floor and their right arm on a supporting bench with approximately 70° shoulder abduction and 90° of elbow flexion. As differences in body posture affect the H-reflex (49), the position of each subject was carefully noted. In study (II)-(IV), the level of muscle contraction was also controlled to ensure a similar level of motoneuron excitability across measures of H-reflexes (21). Therefore, prior to any stimulation maximal EMG was obtained from the middle part of the trapezius muscle over three trials of 3 s of isometric maximal shoulder abduction, by lifting the arm against a horizontal bar located just above the supporting bench. A target range of the maximal EMG was pre-set (see Table 3). When the target range was reached a trigger signal was sent to the stimulator (Digitimer DS7A, Digitimer Ltd, Hertfordshire, UK), allowing the next electrical stimulus to be delivered. Electrical pulses were delivered at intervals no faster than 5 s to minimize post-activation depression (8, 49). In studies (II)-(IV) H-reflexes were only recorded from the middle part of the trapezius muscle due to difficulties in measuring the H-reflex in upper trapezius (see study (I) and (15)) and limited effects of the eccentric exercises in the lower trapezius (48)).

Table 3: *Overview of the level of muscle contraction prior to stimulation used in study (I) – (IV).*

	Study			
	(I) [A]	(II)	(III)	(IV)
Level of muscle contraction	~5% MVC	15 ± 2% MVC	15 ± 2% MVC	20 ± 5% MVC

[A] In study (I) the level of muscle contraction was not controlled.

2.2.1 Electrical stimulation of the C3/4 cervical nerve

In studies (I) – (IV), percutaneous electrical stimulation was applied to the C3/4 cervical nerve to elicit trapezius muscle H-reflexes (see Figure 4). Single electrical pulses of 1 ms duration were delivered at intervals of no less than 5 s with the anode positioned just below the midpoint of the clavicle and the cathode fixed over the C3/4 cervical nerve. A hand-held electrode was used to determine the exact location for the cathode, which was placed where an H-reflex could most easily be elicited in the trapezius muscle. The search area was over the anterior surface of the upper fibers of trapezius above the clavicle. A self-adhesive Ag/AgCl surface electrode was stuck to the skin over the nerve once the location was found.

2.2.2 Electrical stimulation of the accessory nerve

In studies (I) – (IV), percutaneous electrical stimulation was applied to the accessory nerve to elicit trapezius muscle M-waves (see Figure 4). Single electrical pulses of 1 ms duration were delivered with the anode positioned over the mastoid process and the cathode fixed over the accessory nerve. The exact location for the cathode was determined using a hand-held electrode to find the location eliciting the largest M-wave in trapezius. The area of search was behind the sternocleidomastoid muscle and between the level of the jaw and the upper border of trapezius. A self-adhesive Ag/AgCl surface electrode was stuck to the skin over the nerve once the location was found.

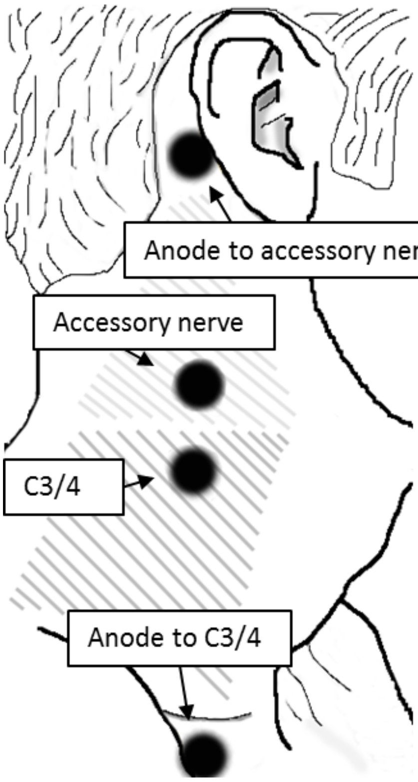

Figure 4: *Placement of anodes and cathodes for percutaneous electrical stimulation of the C3/4 cervical nerve and the accessory nerve [study III].*

2.3 Eccentric Shoulder Exercises (study III and IV)

In studies (III) and (IV), unilateral right-shoulder eccentric exercise was performed using a custom built dynamic shoulder dynamometer (Aalborg University, Aalborg, Denmark). For more details regarding the dynamometer, the reader is referred to Madeleine et al.(74). The subjects were seated in an upright position with back support and no foot support. The back support was adjusted to ensure correct positioning of the shoulder with regards to the shoulder pad of the dynamometer. The participants were equipped with a corselet to avoid lateral bending during exercise. The range of shoulder elevation was measured using the dynamometer prior to eccentric exercise. The subjects elevated both shoulders bilaterally as much as possible and then lowered their shoulders again as much as possible while position values of the dominant side were saved. During the eccentric exercise, the subjects acted against the dynamometer which moved from the highest to the lowest vertical shoulder position. Force feedback was provided using a monitor placed in front of the subjects. The shoulder pad moved with a constant speed of 5.4 mm/s. The subjects relaxed for ~3 seconds between contractions and ~2 minutes after each set. Table 4 summarizes the eccentric exercise regimes for study (III) and (IV).

In study (III), the eccentric exercise consisted of 5 bouts of 10 repetitions in line with previous studies (48,52,53,75).

In study (IV), 9 sessions of eccentric exercise were performed over a 5-week period (two training sessions per week for weeks 1, 2, 4, and 5, and one training session for week 3). This period was chosen as increased neural activation has been observed following 4-weeks of eccentric training (76). All training sessions were supervised by an investigator of the study to ensure 100% compliance. Prior to exercise, a 5-min warm-up of the shoulder region (rotation of the shoulder, shrugs and arm swings) was performed. The subjects acted against the dynamometer at a force equal to 60% (training sessions 1-3), 70% (training sessions 4-6) and 80% (training sessions 7-9) of the MVC force recorded at the PRE session.

Table 4: *Overview of the eccentric exercise regimes included in study (III) and (IV).*

	Study	
	(III)	(IV)^{A}
Sessions	1	9
Sets	5	3
Repetitions	10	10, 8, or 6
Intensity	100% MVC	60%, 70%, or 80% MVC

^{A} Study (IV) was performed over 5 weeks.

2.4 Electromyographic Recordings (all studies)

In study (I), EMG was recorded from the upper, middle, and lower sections of the trapezius on both sides via pair of pre-gelled surface electrodes placed on abraded and ethanol cleaned skin. In study (II), (III), and (IV) EMG was only recorded from the middle section of the trapezius muscle on the right side (see Section 2.2). For upper trapezius, one electrode was placed close to the midpoint between the C7 vertebra and the tip of the acromion, and the other electrode was placed 3 cm lateral. For middle trapezius, one electrode was placed close to the midpoint between the spine of the scapula and the T3 vertebra, and the other electrode was placed 3 cm medially.

For lower trapezius, one electrode was placed 3 cm lateral to the T6 vertebra, and the other was placed 3 cm lateral and superior on a line between T6 and the spine of the scapula. The reference electrode was placed on the C7 vertebra. An overview of the EMG specifications is summarized in Table 5.

Table 5: *Overview of the EMG specifications in study (I) – (IV).*

	Study			
	(I)	(II)	(III)	(IV)
Inter-electrode distance	30 mm	30 mm	30 mm	20 mm
Upper trapezius	X			
Middle trapezius	X	X	X	X
Lower trapezius	X			
Bilateral vs. unilateral	Bilateral	Unilateral	Unilateral	Unilateral
Analogue filter	16-1000 Hz	20-1000 Hz	20-1000 Hz	16-1000 Hz
Amplification	300-3000	300-1000	500	1000

2.5 Force Recordings (study III and IV)

In Studies (III) and (IV), the force was recorded with a load cell (SHBxR-200 Kg-C3-SC, Revere Transducers Europe, Hadsund, Denmark). The load cell signal was amplified with a strain gauge amplifier (LAU 73.1, Sensor Techniques Ltd., Cowbridge, UK). The force signal was sampled at 2 kHz and digitized via a 12-bit A/D converter (National Instrument PCI-MIO16-E4, Austin, TX, USA) using LabView (National Instrument, Austin, TX, USA) and digitally low-pass filtered at 5 Hz with a second order Butterworth filter.

2.6 Pain intensity (study III and IV)

In Studies (III) and (IV), muscle pain intensity in the neck–shoulder region was assessed using a visual analogue scale (VAS) score. The VAS consisted of a 10-cm line ranging from 0 (no pain) to 10 (worst pain imaginable). The subjects rated the pain intensity felt during daily life activity prior to the last session. In study (IV), pain intensity was considered as an adverse event.

2.7 Pressure algometry (study III)

In study (III), pressure pain threshold (PPT) was measured on the middle part of the dominant trapezius to investigate the effectiveness of the exercise to induce DOMS as indicated by lower PPT values (48). PPT from the middle part of the trapezius was measured above the midpoint between the spine of the scapula and the T3 vertebra. Additionally, PPT was measured on the right tibialis anterior as a control site. The PPT recordings were done using an electronic hand-held pressure algometer (Somedic Algometer type 2, Somedic AB, Hörby, Sweden).The tip was 1cm^{2}and was covered with 2mm thick rubber. The subject was seated against the backrest of a chair while pressure was applied perpendicularly to the skin with a constant rate of 30kPa/s. The subject pressed a hand-held button when the perception changed from pressure to pain. For each subject, all PPT measures were performed by the same investigator. Each recording was repeated three times and the mean value was used for statistical analysis. For points with a coefficient of variation equal to 0.2 or more, a fourth recording was made to reduce the intra-individual variance (48).

2.8 Data Analysis

An overview of the reported variables are summarized in Table 6 and further described below.

Table 6: *Overview of the reported variables in study (I) - (IV).*

	Study			
	(I)	(II)	(III)	(IV)
M_{max} (mV)	X	X	X	X
H_{max} (mV)	X	X	X	X
H_{max}/M_{max}	X	X	X	X
H_{slp}		X		X
Current at H_{TH} (mA)		X		X
Current at 50% H_{max} (mA)		X		X
Current at H_{max} (mA)		X	X	X
Current at M_{max} (mA)			X	
H_{I_TH}, normalized to M_{max}		X		X
H_{I_50}, normalized to M_{max}		X	X	X
H_{I_75}, normalized to M_{max}			X	
H_{I_Hmax}, normalized to M_{max}		X		X
H-reflex latency (ms)	X	X	X	
M-wave latency (ms)	X	X	X	
RMS_{max} (µV)				X
RMS EMG (µV)	X			
MVC force (N)				X
RFD (N/s)				X

2.8.1 H-reflex parameters

In all studies, maximal amplitudes of the H-reflexes and M-waves (H_{max} and M_{max}) were identified from the recruitment curves from each nerve. The latency was measured from the stimulus artefact to the first deflection from baseline. In studies (II), (III), and (IV) the ascending limb of each H-reflex recruitment curve was fitted using a general least square model of a custom three parameter sigmoid function (77). From the fitted curves the following H-reflex parameters were identified and analysed (see Figure 5):

1. Maximal amplitude of the normalized H-reflex (H_{I_Hmax});
2. 75% of the maximal normalized reflex amplitude (H_{I_75});
3. 50% of the maximal normalized reflex amplitude (H_{I_50});
4. normalized reflex amplitude at H_{TH} (H_{I_TH});
5. The current at H-reflex threshold (current at Hth);
6. The current at 50% of H_{max} (current at 50%H_{max});
7. The current at 75% of H_{max} (current at 75%H_{max});
8. The current at H_{max} (current at 100%H_{max});
9. The slope of the ascending limb of the recruitment curve at 50 % of the H_{max} value (Hslp).

As the stimulus intensities associated with the H-reflex parameters from the baseline sessions in studies (II)-(IV), were used as inputs to the equations describing the recruitment curves on day 2 (study (II) or following the interventions (studies (III) and (IV), (H_{I_TH}, H_{I_50}, and H_{I_Hmax}) the amplitudes of the H-reflex responses were compared on a basis of equal current intensities across sessions. Thus, the presence or absence of shifts in the recruitment curve at different stimulus intensities, delineating changes in H-reflex excitability, could be investigated (77,78).

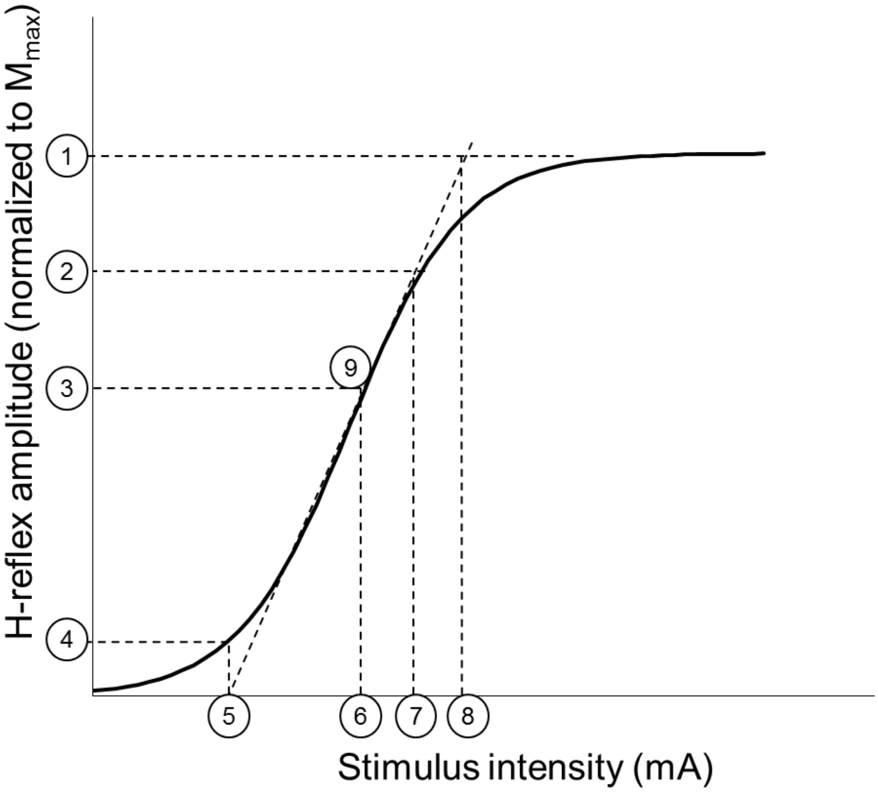

Figure 5: *H-reflex parameters of interest derived from the fitted curves. The analysed parameters were: maximal amplitude of the normalized H-reflex (*H_{l_Hmax}*, 1); 75% of the maximal normalized reflex amplitude (*H_{l_75}*, 2);50% of the maximal normalized reflex amplitude (*H_{l_50}*, 3); normalized reflex amplitude at* H_{TH} *(*H_{l_TH}*,4); current intensity at H-reflex threshold (current at* H_{TH}*, 5); current intensity at 50% of* H_{max} *(current at 50%* H_{max}*, 6); current intensity at 75% of* H_{max} *(current at 75%* H_{max}*, 7); current at the maximal normalized reflex response (current at* H_{max}*, 8); and the slope of the ascending limb (*H_{slp}*, 9). The solid line represents the fitted curve. Adapted from [Study (II)].*

2.8.2 Electromyography parameters

In study (I), root mean square (RMS) of the ongoing EMG (RMS EMG) was measured from individual traces over a 100-ms epoch before stimulation for all recordings. For EMG recorded over the left and right middle trapezius during left and right side contractions, respectively, RMS was also calculated over an epoch of approximately 50 ms after the elicited response. For each subject, this period was identified by visual inspection of traces from right middle trapezius recorded during right sided contractions and was set from the end of the H-reflex (ipsilateral to stimulation) to the end of the subsequent period of reduced EMG (silent period).

In study (IV), root mean square (RMS) values were estimated from the EMG for each MVC over overlapping 250-ms epochs moving in steps of 100 ms. The maximal RMS (RMS_{max}) was extracted from each MVC for the middle part of the trapezius muscle, as an index of efferent neural drive.

2.8.3 Muscle Force parameters

In study (IV), the MVC force was determined as the maximal value of the force-time curve for each MVC trial. The rate of force development (RFD) was also calculated from the force-time curve for each MVC trial, to investigate the early phase of the contraction (20). The RFD was calculated as the slope of the force-time curve (Δforce/Δtime) from contraction onset over an epoch of 500 ms (79). The contraction onset was set to the time point where the generated force exceeded 10 N. The time epoch was chosen as more than 500 ms from contraction onset was required to reach MVC force.

3 Results

This section presents a summary of the findings in the present Ph.D. project. For details, the reader is referred to the articles/manuscript (I)-(IV).

3.1 *H-reflex parameters (all studies)*

Below, findings regarding the trapezius muscle H-reflex from all studies are presented.

3.1.1 Baseline characteristics of the trapezius muscle H-reflex

In Table 7 the baseline characteristics of the H-reflexes and M-waves measured from the middle part of the trapezius muscle are presented.

Table 7: *Baseline characteristics of the H-reflexes and M-waves measured from the middle part of the trapezius muscle in study (I) – (IV).*

	Study			
	(I)	(II) ^{A}	(III)	(IV)^B
M_{max} (mV)	7.9 [3.8-10.7]	7.5 ± 3.7	5.4 ± 0.8	6.3 ± 2.4
H_{max} (mV)	1.7 [0.8-2.0]	1.7 ± 0.7	1.6 ± 0.6	2.5 ± 1.4
H_{max}/M_{max}	0.29 [0.15-0.31]	0.24 ± 0.12	0.30 ± 0.11	0.33 ± 0.11
H-reflex latency (ms)	9.1 [8.1-9.4]	9.2 ± 0.9	9.0 ± 0.5	-
M-wave latency (ms)	4.1 [3.8-4.5]	3.4 ± 0.5	3.1 ± 0.2	-

A: Ten subjects were also included in study (III); B: pooled data from both groups.

3.1.2 Crossed responses in the trapezius muscles

In study (I), ipsilateral responses increased and decreased significantly with increases and decreases in pre-stimulus electromyographic activity (EMG) in all ipsilateral parts of trapezius (Figure 6 A+B). Thus, they were considered H-reflexes. Contralaterally, much smaller responses with latencies corresponding to those observed ipsilaterally occurred in all parts of trapezius (Figure 6A). These responses which were recorded from the left trapezius increased significantly more with contraction of the right trapezius compared with contraction on the left side (Figure 6A+B). Moreover, they were also significantly smaller with increasing distance from the ipsilateral side (Figure 7).

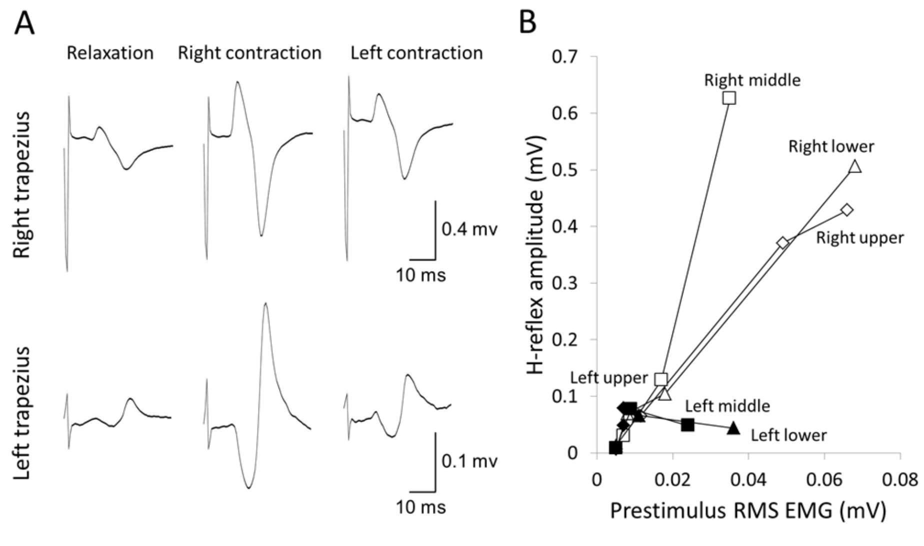

Figure 6: *A) Averaged reflexes evoked in the ipsilateral middle part of trapezius by electrical stimulation of the right cervical nerve of C3/4 in one subject during relaxation, contraction of right side, and contraction of left side, respectively. Bottom: The corresponding contralateral responses evoked by the same electrical stimulation and conditions. (B) Median amplitudes of H-reflexes increased with increasing median pre-stimulus RMS EMG for upper, middle, and lower parts of the right trapezius (white symbols). In contrast, responses recorded from the upper, middle and lower parts of left trapezius (black symbols), which was contralateral to the stimulation, did not increase monotonically with RMS EMG. [Study I]*

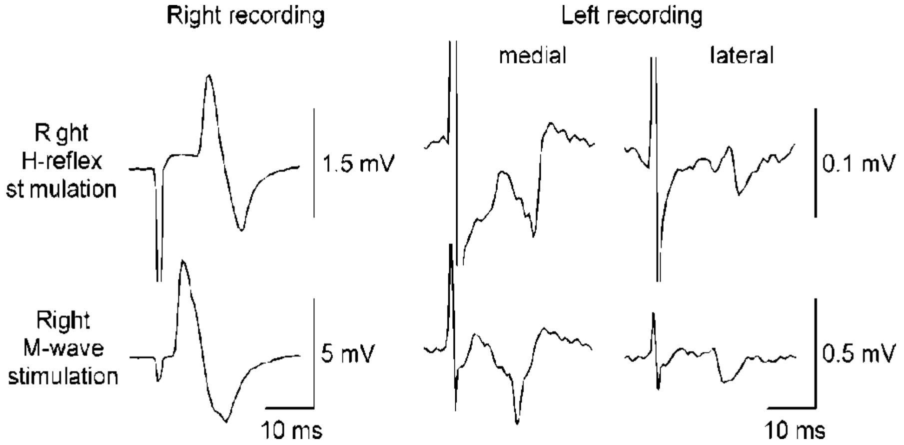

Figure 7: *Maximal H-reflex and maximal M-wave in the right middle part of trapezius in one subject. Left sided responses recorded at the same time through 2 sets of electrodes. Smaller responses were recorded through the more lateral set of electrodes. On average, lateral responses*

were 49% of medial with stimulation of the right accessory nerve, whereas with stimulation on the left side, lateral M-waves were 95% of medial. [Study I]

3.1.3 Reliability of the trapezius muscle H-reflex (study II and IV)

In study (II) the ICCs ranged from substantial to almost perfect agreement (0.70 – 0.99) except for H_{I_TH} (ICC = 0.31) according to the labels assigned by Landis and Koch (80). Similar results were observed in study (IV) where ICCs ranged from 0.58 to 0.87 except for H_{I_TH} (ICC = 0.07) (see Table 8). Moreover, no significant differences (P > 0.05) were observed between the two testing sessions for any of the variables.

In study (II), Bland-Altman plots showed that zero was included in the 95% confidence interval and no apparent systematic bias was present in the data for H_{max}, M_{max}, and H_{max}/M_{max}. Furthermore, the SEM% ranged from 1.4% to 78.2% and the SRD% ranged from 3.8% to 216.8% (see Table 9).

Table 8: *ICCs of the extracted H-reflex variables from study (II) and (IV).*

	$ICC_{2,1}$	
	Study (II)	Study (IV)^{A}
M_{max} (mV)	0.95	0.69
H_{max} (mV)	0.76	0.85
H_{max}/M_{max}	0.89	0.76
H_{slp}	0.71	0.72
Current at H_{TH} (mA)	0.79	0.87
Current at 50% H_{max} (mA)	0.83	0.78
Current at H_{max} (mA)	0.75	0.61
H_{I_TH}, normalized to M_{max}	0.31	0.07
H_{I_50}, normalized to M_{max}	0.70	0.58
H_{I_Hmax}, normalized to M_{max}	0.88	0.78
H-reflex latency (ms)	0.93	-
M-wave latency (ms)	0.99	-

A: ICCs were only calculated for the REF group.

Table 9: *Absolute and relative standard error of measurement (SEM and SEM%) and smallest real difference (SRD and SRD%).*

Parameter	SEM	SEM%	SRD	SRD%
H-reflex latency (ms)	0.22	2.4	0.62	6.7
M-wave latency (ms)	0.05	1.4	0.13	3.8
M_{max} (mV)	0.9	11.4	2.4	31.6
H_{max} (mV)	0.3	21.5	1.0	59.5
H_{max}/M_{max}	0.04	16.9	0.11	46.8
H_{slp}	0.04	34.8	0.12	96.5
Current at H_{TH} (mA)	0.3	27.7	0.9	76.8
Current at 50% H_{max} (mA)	0.3	14.3	0.9	39.5
Current at H_{max} (mA)	0.5	15.7	1.5	43.4
H_{I_TH}, normalized to M_{max}	0.03	78.2	0.08	216.8
H_{I_50}, normalized to M_{max}	0.04	33.7	0.12	93.3
H_{I_Hmax}, normalized to M_{max}	0.04	19.3	0.11	53.5

3.1.4 Eccentric exercises and the trapezius muscle H-reflex (study III + IV)

In study (III), a significant decrease in both H_{i_75}/M_{max} and H_{i_50}/M_{max} was observed 24 hour after eccentric exercise (Figure 8).

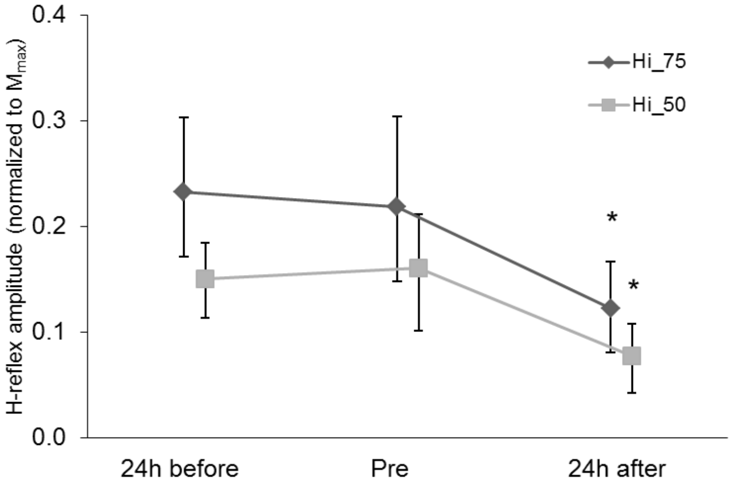

Figure 8: *Ratios of H-reflexes from the middle trapezius. Hi_75 and Hi_50 represented as mean values ± SD. Asterisk indicates a significant difference (P < 0.05). Modified from [Study III].*

The maximal H-reflex was not altered between sessions, but the H-reflex recruitment curve was shifted to the right (study (III), Figure 9).

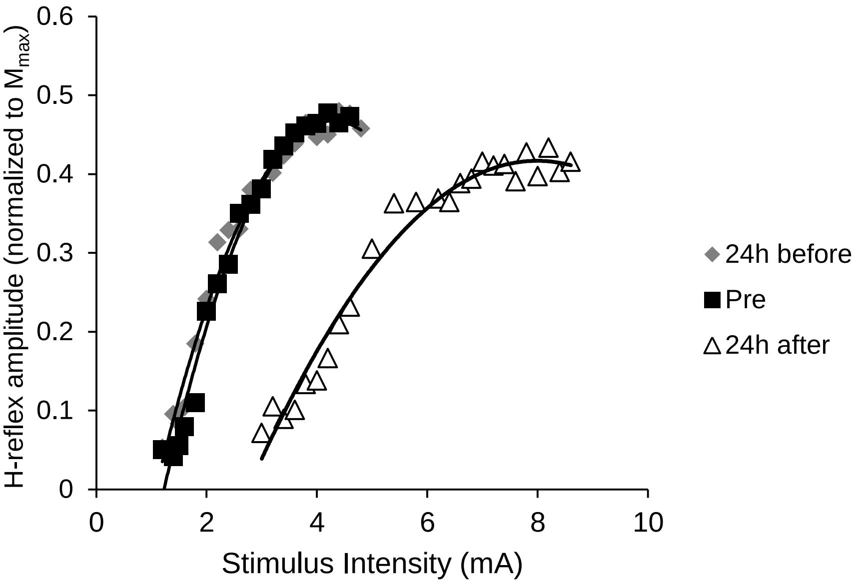

Figure 9: *Single subject (#5) normalized recruitment curves from all three sessions. Prior to curve fit all H-reflexes were normalized to the Mmax value from the corresponding session. Modified from [study III].*

Following 5 weeks of eccentric strength training, the amplitude of H_{max} increased significantly in the ECC group while no change was observed in the REF group (study (IV), Figure 10).

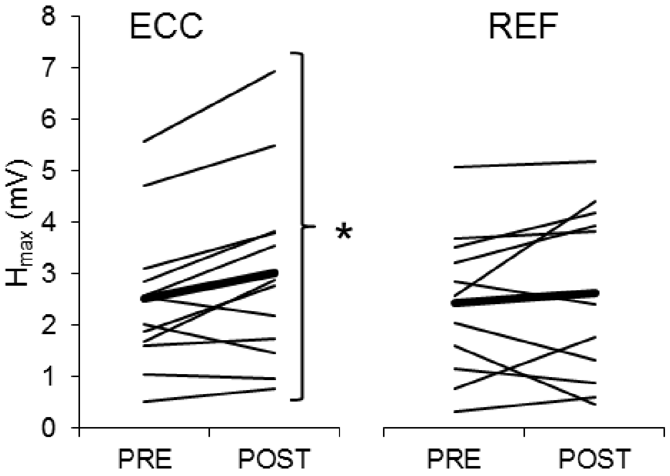

Figure 10: *H_{max} amplitude measured before (PRE) and after (POST) training in the ECC group and the REF group. Each line represents one subject. The thick black lines represent the average values. *P < 0.05, when comparing PRE to POST. [study IV]*

No significant changes were observed for any of the other H-reflex parameters. However, a tendency towards an increase in the H_{max}/M_{max} ratio was observed in ECC group (P=0.10, Figure 11).

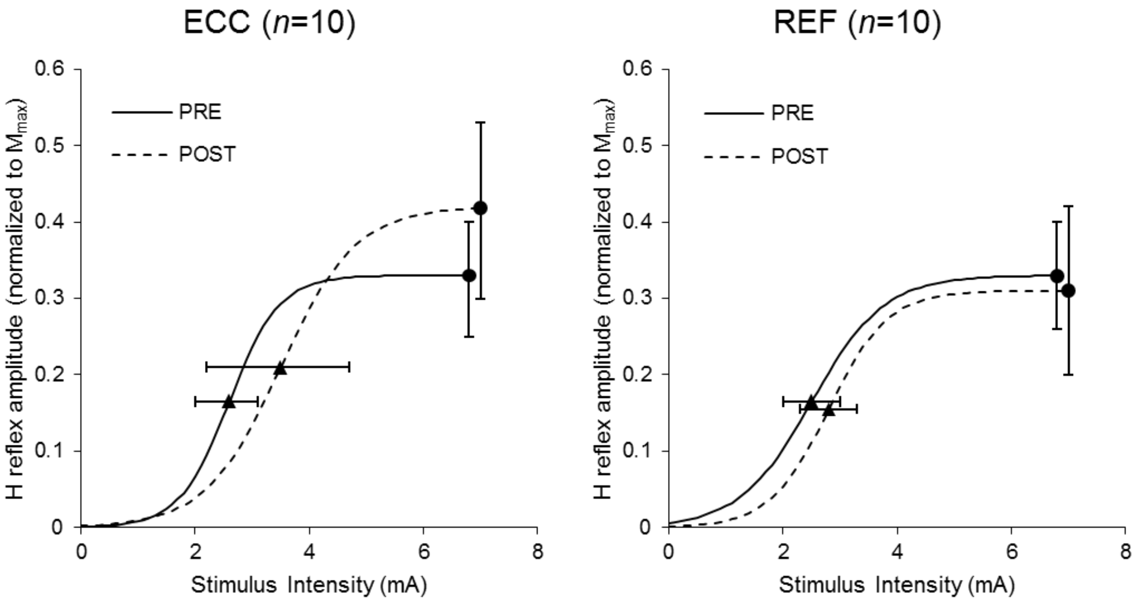

Figure 11: *Recruitment curves calculated from the average parameters obtained before (PRE) and after (POST) eccentric training. ●: Hmax/Mmax [95% CI]; ▲: current at 50%Hmax [95% CI]. [Study IV]*

3.2 Effects of eccentric exercise on electromyographic activity (study IV)

In contrast with the increase in MVC force and RFD, the RMSmax recorded during MVC did not significantly change in either group (P=0.12 and P=0.68 for respectively the ECC and REF group). Similarly, the relative change in EMG activity from PRE to POST between the groups (ECC group: 9.8 % [-1.9 - 21.5], REF group: 2.0 % [-13.9 - 17.9]) was not significantly different (P=0.41).
A significant positive correlation between the relative change in MVC force and relative change in RMSmax of the ECC group (r = 0.57, P=0.03) was found.

3.3 Effects of eccentric exercise on muscle soreness (study III + IV)

In study (III), VAS scores were as expected significantly higher at "Post" and "24h after" compared with "24h before" and "Pre" (P<0.05). Moreover, PPT was significantly lower at "24h after" compared with all other sessions (P<0.05).

In study (IV), no pain during daily life activity following training was reported by the subjects before the testing sessions (VAS was equal to 0).

3.4 Effects of eccentric exercise on muscle force (study IV)

3.4.1 MVC force

In study (IV), eccentric neck-shoulder training resulted in a significant increase in MVC force from PRE to POST test in the ECC group (P<0.01). No significant change in MVC force was found in the REF group (P=0.07). Furthermore, the relative change in muscle force from PRE to POST between the groups was significantly different (P<0.01).

3.4.2 Rate of force development

In accordance with the increase in force, the RFD increased significantly in the ECC group (P=0.025) after eccentric training and did not change in the REF group (P=0.37). However, the relative change in RFD from PRE to POST test between the groups was not significantly different (P=0.30).

4 Discussion

The overall aim of this project was to provide new insights into the spinal mechanisms of the human trapezius muscles and its modulation to eccentric exercise. Four studies, all including percutaneous electrical stimulation of the C3/4 cervical nerve and the accessory nerve, were performed to investigate this. The main findings of the studies were: (1) H-reflexes and M-waves can be obtained in all three parts of the trapezius muscle by electrical stimulation of the C3/4 cervical nerve and the accessory nerve, respectively (all studies); (2) The contralateral responses observed in the trapezius muscles are not H-reflexes (Study I); (3) The trapezius muscle H-reflex can be reliably measured between days (study II) and between weeks (study IV); (4) A single session of high-intensity eccentric exercises decreases the trapezius muscle H-reflex (study III); and (5) five weeks of eccentric strength training increases the amplitude of the maximal H-reflex in the trapezius muscle (study IV). Below, these findings are discussed in more details as well as the limitations and perspectives of the current thesis.

4.1 General description of the trapezius muscle H-reflex (all studies)

In study (I), stimulation of the accessory nerve elicited M-waves in all 3 parts of trapezius on the ipsilateral side, whereas H-reflexes were evoked in each part of trapezius by stimulation of the C3/4 cervical nerves during weak voluntary contractions. In the other studies, M-waves and H-reflexes were only evoked in the middle part of the ipsilateral trapezius. However, H-reflexes could not be obtained in 15.3 % of the tested subjects with the self-adhesive electrode. Recruitment curves showed that the H-reflexes, like the M-waves became larger with increasing stimulation intensity. In most subjects, H-reflex amplitude appeared to reach a plateau and did not decrease with increased stimulus intensity after reaching Hmax. Small M-waves were often observed with the highest levels of cervical nerve stimulation. This may represent spread of the stimulus to the accessory nerve at high intensities. Another explanation may be variable innervation of the trapezius muscle by some motor axons in the C3/4 cervical nerves in some subjects (14).

The latencies and amplitudes of the H-reflex were comparable between the four studies. In general, the sizes of the Hmax/Mmax ratios found in the studies (0.08 for the upper, 0.24-0.33 for the middle, and 0.09 for the lower trapezius) are small compared to ratios found in other muscles in which H-reflexes are commonly measured. Maffiuletti et al.(81) found Hmax/Mmax ratios in the soleus muscle in trained athletes to be 0.37 to 0.67. Jaberzadeh et al.(82) found Hmax/Mmax ratios in the flexor carpi radialis in healthy subjects to be 0.42. In a range of upper limb muscles, mean Hmax/Mmax ratios during contraction are reported to be 0.14-0.28 (83). The results from this thesis put trapezius at the lower end of this range and suggest that facilitation by muscle spindle input is not very strong to the motoneurons of the trapezius muscle compared to other muscles despite the relatively high number of spindles in trapezius (84).

4.1.1 Crossed responses in the trapezius muscle are not H-reflexes (study I)

In study (I), responses in the muscle ipsilateral to the stimulation became bigger during voluntary activation of the muscles from which they were recorded which is expected for H-reflexes (85). Compared to relaxation, the responses were larger during contralateral contraction, which also resulted in some ipsilateral EMG, but were largest during ipsilateral contraction. This corresponds with the normal behaviour of H-reflexes. Facilitation of the motoneuron pool through descending drive results in more motoneurons being close to threshold and therefore, more are activated by the Ia volley evoked by the H-reflex stimulus (85). In addition, the ipsilateral H-reflex was followed by a brief period of reduced EMG activity. This is also expected for H-reflexes due to spinal mechanisms, such as synchronisation of motor unit firing, Ib inhibition, and recurrent inhibition (86-88).

The responses on the side contralateral to stimulation, (i.e. in left trapezius) became larger compared to relaxation during contraction of the homonymous muscle but became largest during contraction of right trapezius. Alexander and Harrison (2001) previously reported bilateral responses in trapezius with cervical nerve stimulation. These had an average latency of 11.9 ± 1.5 ms in the lower trapezius and an average latency of 12.2 ± 1.7 ms in the upper trapezius. Furthermore the responses on both sides increased in amplitude with voluntary activity of the muscle on the side of stimulation. This corresponds with the findings in study (I). However, in study (I) voluntary contraction of the contralateral muscle was also performed, but this showed no further increase in the contralateral response as would be expected if these responses were H-reflexes (85). The lack of increase in amplitude of the contralateral response when contracting the homonymous muscle strongly suggests that the responses are not crossed reflexes. Rather, the responses follow the size of the ipsilateral reflex. They increased when the ipsilateral responses increased and decreased when the ipsilateral responses decreased. In addition, no difference was observed between the RMS values of the ongoing EMG and the period following the observed response. Thus, no silent period was present after the contralateral response. These observations suggest that the responses are likely to be crosstalk (far-field EMG) instead of a contralateral reflex.

Crosstalk refers to a signal recorded over 1 muscle that is actually generated by a nearby muscle and conducted through the intervening volume to the recording muscle (89). This interpretation is supported by the occurrence of responses in the contralateral trapezius with stimulation of the accessory nerve, which evoked ipsilateral M-waves. Similarly, contralateral responses occurred with stimulation of C3/4 cervical nerves, which evoked ipsilateral H-reflexes. When Mmax was evoked on the ipsilateral side, the contralateral responses remained very small in upper trapezius (approximately 1% Mmax). However, responses were more substantial in the middle (14% Mmax) and lower (6% Mmax) trapezeii, where the contralateral recording electrodes were much closer to the ipsilateral muscle. Moreover, the additional experiment confirmed a decrease in the contralateral response with increasing distance from the ipsilateral side by showing that the amplitude of the contralateral response recorded over the lateral part of the left middle trapezius was smaller than that recorded medially. On the contrary, responses of similar amplitude were seen from the 2 recording sites over the left middle trapezius with stimulation of the nerves on the left side. As contralateral responses to C3/4 stimulation were also smaller more laterally, it suggests that these proposed reflexes actually come from a signal propagated from the right trapezius.

The lack of crossed short-latency reflexes further suggests that there is not strong muscle spindle facilitation of the trapezius motoneuron pool from the contralateral muscle even though trapezius is axial and is often engaged in bilateral postural tasks. This has important implications, as spinal and/or supraspinal mechanisms have been suggested to mediate the spread of motor effects to heteronymous or contralateral muscles via reflex mediated pathways (28,29,45). However, one should keep in mind that this study only investigated the relatively strong and direct pathway for Ia contralateral input, and other spinal mechanisms involved in the spread of pain are likely to exist. Alexander and Harrison (2002) reported contralateral reflexes after tapping of the lower fibres of the trapezius. Such crossed stretch reflexes have also been found in the abdominal muscles (90) and in paraspinal muscles (91). The primary difference between the H-reflex and the spinal stretch reflex is that the H-reflex bypasses the muscle spindle (25). To explain the neural mechanisms underlying chronic musculoskeletal pain a ‘vicious circle’ hypothesis has been proposed (92). This model propose that group III and IV afferents have excitatory actions on γ-motoneurons which increase the background firing of the muscle spindles and/or increase the sensitivity of the muscle spindles to stretch. This may lead to increased activation level of the homonymous α-motoneuron pool and accumulation of metabolites. Johansson and Sojka (1991) also propose that secondary muscle spindle afferents affects γ-motoneurones projecting to both the homonymous and heteronymous muscles and hereby spread the pain. Such a connection does not involve Ia afferents and is, thus, not conflicting with the present findings. An increased muscle spindle sensitivity as a result of muscle pain has previously been reported by Matre et al. (93) who showed that experimental muscle pain increase the sensitivity of the muscle spindles without any effects on the α-motoneuron excitability. In addition, the trapezius muscles are rich in muscle spindles which seem to be associated with chronic musculoskeletal pain (92).

4.1.2 Reliability of the trapezius muscle H-reflex (study II and IV)

Brinkworth et al. (2007) have previously reported the difficulty in measuring reliable H-reflexes between days, and have shown day-to-day and trial-to-trial variability in recruitment curves in all trials. Thus, to enable a sound interpretation of changes in H-reflex in the trapezius muscle, e.g. following an intervention, it is important to investigate the reproducibility of the H-reflex to exclude methodological issues due to H-reflex variability between days.

Reliability studies should both report absolute and relative reliability of the extracted parameters (94). Consequently, the ICCs were used as an index of relative reliability while the SEM and SRD served as indexes of absolute reliability. The ICCs reported for the latencies in study (II) showed excellent reliability (80) and were in line with previous findings in muscles of the upper extremity (30,31). For H-reflex and M-wave amplitudes, the ICCs for study (II) showed substantial to excellent reliability. In particular, the maximum responses (H_{max}, M_{max}, and H_{max}/M_{max}) showed high reliability (ICC = 0.76, 0.95, and 0.89, respectively). Similar results were obtained in study (IV) with ICCs equal to 0.85, 0.69, and 0.76 for H_{max}, M_{max}, and H_{max}/M_{max}, respectively. In other muscles of the upper extremity, similar ICCs for H_{max}/M_{max} are reported, i.e., 0.94 and 0.99 for the extensor carpi radialis (ECR) and flexor carpi radialis (FCR), respectively (32). For the FCR, lower ICCs of 0.68, 0.84, and 0.66 for H_{max}, M_{max}, and H_{max}/M_{max}, respectively, have been reported (31).

Still, the ICCs reported in the present project are at the lower end of ICC values reported for H_{max} in muscles of the lower body. For the soleus, peroneal and tibialis anterior muscles, Palmieri et al. found ICCs to be 0.99, 0.99, and 0.86, respectively (95). For the quadriceps muscle, Hopkins and Wagie reported an ICC of 0.79 between days (96). The absolute reliability of the H_{max}/M_{max} ratio, reflected in the SEM and SRD values, is in agreement with findings from the FCR reported by Phadke et al. (33).

4.2 *Alteration in the trapezius muscle H-reflex following eccentric exercises (study III + IV)*

In studies (III) and (IV) the trapezius muscle H-reflex was altered following the eccentric exercise. In study (III) a decrease was observed for H_{i_50} and H_{i_75} 24 hour after the high-intensity eccentric exercise. On the contrary, an increase was observed in H_{max} in study (IV) following 5 weeks of eccentric strength training. These changes are larger than the corresponding SEMs found in study (II). This indicates that the changes due to DOMS or eccentric strength training most likely were caused by genuine modulation of the excitability of the H-reflex and not due to error in the measurement (97). Still, the modulations were smaller than the SRD for the variables found in study (II). However, as described by Lexel and Downham (2005), clinically or experimentally relevant changes are often defined arbitrarily. Thus, reliability indicators should be reported together with significant findings.

Alteration in the size of the H-reflex may reflect changes in the net excitation to the trapezius motoneurons and/or changes in the excitability of the subliminal fringe motoneurons (20,69,98). Moreover, changes in the muscle fibre action potential due to changed membrane properties could affect the size of the H-reflex. Changes in net excitation may arise from (i) altered excitatory input, i.e. more/less group Ia (or group II) input, and/or (ii) changes in inhibitory input (disynaptic inhibition). In study (III) and (IV) all H-reflexes were collected with a controlled background level of EMG, which was set at 15% (study III) or 20% (study IV) of the maximal EMG in each session. This attempt to control motoneuron output should minimize changes in the excitability of the motoneurons (99). Changes in the muscle fibre action potential were accounted for by normalization to M_{max}. Hence, changes in the afferent limb of the reflex provide the more likely explanation for the altered reflex responses. However, the mechanisms may differ between the studies.

4.2.1 Effect of muscle soreness on the trapezius muscle H-reflex (study III)

Twenty-four hours after the eccentric exercise in study (III), the pressure pain threshold measured over the middle trapezius was significantly lower and pain was reported in presence of DOMS during daily life activities in line with previous studies (52,53). These findings confirm that DOMS was induced in the dominant trapezius muscle. Muscle hyperalgesia evoked 24 h after high level eccentric contractions could stem from acute damage to the muscle fibres during exercise, causing a mechanical disruption of the ultra-structural elements within the muscle fibres and extracellular matrix (43,100,101). Acute inflammation in response to the initial injury may also sensitize the muscle nociceptors and lower their threshold to mechanical stimuli (102). Further, DOMS is associated with an increase in interstitial inflammatory mediators that will activate group III and IV afferents (100). The onset of muscle swelling is usually delayed two to four days (103), thus muscle swelling during DOMS was unlikely to explain the changes in H-reflex. Although pre-synaptic inhibition of Ia afferents by the firing of group III and IV afferents could therefore occur during DOMS, study (III) did not find a direct relationship between participants' pain scores and H-reflex depression. This could be due to the low pain intensity and the difference in pain perception experienced by the participants. Bulbulian & Bowles (1992) and Avela et al. (1999) reported no change in H_{max}/M_{max} ratios 24h after eccentric exercise. The results of H_{max}/M_{max} in study (III) were similar, but the use of submaximal stimulus intensities, as well as measurement of the stimulus intensity required to elicit H_{max}, enabled the detection of differences with DOMS. Further, in study (III) the H-reflex was measured during contraction in contrast to the relaxed conditions in the former studies (104,105). Since the sensation of DOMS is mainly present during muscle activity (106), there may be limited soreness/pain and limited discharge of nociceptive afferents during muscle relaxation. Thus, a conditioning contraction may be necessary for the modulation of the H-reflex by DOMS.

4.2.2 Effect of eccentric training on the trapezius muscle H-reflex (study IV)

In study (IV), the maximal H-reflex amplitude (H_{max}) increased following 5 weeks of eccentric strength training, suggesting that neural adaptations occur in the initial phase of a strength training program focused on the shoulder region (18,69). The finding of an increase in H_{max} following strength training is in line with most previous findings (18,69,70,107). Additionally, an increase in H-reflex amplitude of the soleus and medial gastrocnemius muscles has previously been observed following pure eccentric strength training as investigated in study (IV) (70).

No alterations were observed in threshold or slope of the H-reflex recruitment curve. This possibly argues against (i) a change in the recruitment gain of the motoneuron pool and hence, a change in the excitability of motoneurons in the subliminal fringe, and (ii) a blanket increase in excitatory input at all stimulus intensities, as might be expected if presynaptic inhibition of the Ia fibers was reduced. Thus, a differential effect on higher threshold motoneurons or their inputs, or a change in the balance of excitatory and inhibitory inputs as additional afferents are activated with higher stimulus intensities, are postulated to explain the observed increase in maximal H-reflex amplitude. The sensory Ib afferents from the Golgi tendon organs have previously been suggested to inhibit muscle activity at high force levels in order to preserve muscles and connective tissues from injury (66,108). Strength training has previously been proposed to reduce the neural inhibition and thereby increase the generated MVC (66). Interestingly, Hortobagyi et al. (68) suggested that eccentric training downscaled inhibition more effectively than concentric training. However, as no experimental data yet supports this idea it has been considered speculative (109). Here, neural modulation following eccentric exercise was only observed at H_{max} suggesting a change in the recruitment of the higher threshold motoneurons or the balance of input from higher threshold afferents. Thus, it may be possible that the increased H-reflex observed in the current study is mediated by decreased inhibition from Ib afferents, and hence, an altered balance between Ia input (monosynaptic excitation) and Ib input (disynaptic inhibition).

Only two previous studies have investigated changes in the entire H-reflex recruitment curve following strength training (78,110). In contrast to the findings from the present thesis, Vila-Chã et al. (110) reported a decrease in the current intensity to elicit a threshold H-reflex of the plantar flexors, suggesting that the excitability only changed for the low-threshold motor units. Similar results have been presented by Dragert and Zehr (78), who reported an increase in amplitude of the threshold H-reflex following high-intensity isometric training of the dorsiflexors. However, this was accompanied with a decrease of the maximal H-reflex. The conflicting results may be explained by the different methodologies applied to record the H-reflexes (e.g. differences in the level of contraction) and/or the differences in training modalities. However, it might also be possible that different neural adaptations to training are present in upper and lower limbs as differences in neural activation have been suggested (111,112).

4.3 Methodological considerations

This thesis has focused on H-reflex responses from the human trapezius muscles. Only a few studies have previously investigated these responses and none of these have investigated the effect of physical exercises or muscle soreness (15,26,27). Therefore, among the strengths of this project is the investigation of the trapezius muscle H-reflex in relation to strength training and DOMS. Moreover, the high reliability found for the investigated parameters, the use of a randomized-controlled design in study (IV), and the session "24h before" in study (III) suggests that it was possible to assess genuine effects of the interventions.

When interpreting the results, it should be taken into account that the H-reflex is affected by several factors and should not solely be taken as an estimate of the alpha-motoneuron excitability (20,21,24,113). In particular, the H-reflex is modulated by presynaptic inhibition which is affected by e.g. afferent feedback from peripheral receptors (21). Therefore, it is of utmost importance that the H-reflex is evoked in identical conditions between sessions. In particular, the input to the alpha motoneurons should remain the same (17). In muscles like soleus and tibialis anterior, the M-wave accompanying the H-reflex is typically used to control for constant axonal stimulation and hence, constant synaptic input to the alpha motoneurons (21,25). However, as the motor and sensory innervations are divided into the accessory nerve and the C3/4 cervical nerves, respectively, this is not possible for the trapezius muscle. Similarly, normalization of the stimulation intensity with respect to the stimulation intensity used for M_{max} (78,110) is rendered impossible for the trapezius muscle. In the present thesis, the background EMG activity was controlled in order to have constant motoneuron output between sessions and thereby minimize changes in the excitability of the motoneurons.

Although the results of this thesis suggest that DOMS and strength training affects the trapezius muscle H-reflex, indicating spinal changes, the exact mechanisms for these changes could not be identified. Thus, another limitation of the study may be that only measures of the H-reflex were investigated. To investigate the neural changes during DOMS or following strength training more thoroughly, different methods could be included in future studies. By using cervicomedullary motor-evoked potentials (CMEPs) and/or F waves in combination with H-reflexes would allow a comparison between cortical and spinal changes (17,114). However, the separated neural innervation to the trapezius muscles, and thereby the lack of the antidromic effect, makes it impossible to elicit F-waves in the trapezius muscle. Interestingly, a recent study suggests that strength training increases MEPs in the trapezius muscle (115).

Another limitation of this project is that only slim healthy young adults were included. H-reflexes may vary with aging (116) and in patient populations (23,33). Thus, it will be necessary to perform further studies in order to extrapolate the present findings to other populations. Investigations of the trapezius muscle H-reflex could provide information in neurophysiological changes at the C4 level of the spinal cord. Interestingly, previous studies on patients with chronic low back pain report a modulation of the soleus muscle H-reflex similar to the results obtained in study (III), i.e. a shift of the recruitment curve to the right (23,117). Likewise, the H-reflex of the trapezius muscle is altered in subjects with non-traumatic shoulder instability compared with a healthy group (27). The present findings confirm the potential of neural assessments in relation to musculoskeletal pain. This calls for future randomised controlled trials on H-reflexes in patients with neck-shoulder disorders.

5 Conclusions

The overall aim of this thesis was to provide new insight into the spinal mechanisms of the human trapezius muscles and its adaptation to eccentric exercises of the neck-shoulder region. To meet this purpose, percutaneous electrical stimulation was applied to elicit H-reflexes and M-waves in the trapezius muscle. The findings from the present project confirm that H-reflexes can be evoked in the upper, middle, and lower part of the ipsilateral trapezius through electrical stimulation of the C3/4 cervical nerve, whereas motor innervation to each part of the muscle is mainly through the accessory nerve. Thus, the afferent and motor supplies to trapezius are largely separated. This separation makes H-reflexes in the trapezius muscle unique. While responses were also observed in the contralateral muscle, the present results suggest that these crossed responses in trapezius are not H-reflexes but are more likely to be cross-talk. For the middle part of the trapezius muscle, the amplitude and latency of the H-reflexes was found to be reliable across sessions in healthy young subjects. During DOMS, a decrease in the H-reflex was observed, most likely due to pre-synaptic inhibition the Ia afferents. On the contrary, 5 weeks of eccentric strength training increased the net excitability of the H-reflex pathway. This was accompanied by increases in MVC and RFD and may be explained by decreased inhibition of Ib afferents. The two latter studies were the first to investigate and document changes in trapezius muscle H-reflex during muscle soreness and following strength training. Altogether, this thesis provides valuable knowledge on spinal mechanisms of the human trapezius muscles, which may act as a starting point for future investigations of the neck-shoulder region in patients suffering from neck-shoulder disorders.

6 Thesis at a glance

Title of study	Primary aim	Method	Main findings
Study I:			
The crossed responses found in human trapezius muscles are not H-reflexes	To investigate the presence of crossed short-latency reflexes evoked in trapezius by stimulation of the C3/4 cervical nerves.	Eliciting trapezius muscle H-reflexes and M-waves by percutaneous stimulation of the C3/4 cervical nerve and the accessory nerve, respectively. EMG measurements.	H-reflexes can be obtained in all parts of the trapezius muscle. Crossed responses are not H-reflexes.
Study II:			
Between-day reliability of the trapezius muscle H-reflex and M-wave	To estimate the absolute and relative between-day reliability of the trapezius muscle H-reflex and the corresponding M-wave	H-reflexes, M-waves	Trapezius muscle H-reflexes and M-waves can be reliable measured between days.
Study III:			
Eccentric exercise inhibits the H reflex in the middle part of the trapezius muscle	To determine whether the H-reflex in trapezius was altered 24 hour after eccentric exercises	H-reflexes, M-waves. PPT, pain intensity. Intervention: High-intensity eccentric exercises of the neck-shoulder region.	DOMS inhibits the trapezius muscle H-reflex.
Study IV:			
Changes in H reflex and neuromechanical properties of the trapezius muscle after 5 weeks of eccentric training: a randomized controlled trial	To investigate the neural adaptations induced by a 5-week strength training regimen, based solely on eccentric contractions of the shoulder muscles	H-reflexes, M-waves. MVC, RFD, EMG. Intervention: 5 weeks of eccentric strength training of the neck-shoulder region.	Eccentric strength training increases the excitability of the trapezius muscle H-reflex.

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Appendix I

Appendix II

Appendix III

Appendix IV

Changes in H reflex and neuromechanical properties of the trapezius muscle after 5 weeks of eccentric training: a randomized controlled trial

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