Kinematics of unconstrained head movements in health and chronic neck pain

-Influence of muscle physiology and muscle activation patterns

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Summary

Background

Unconstrained movements of everyday life are often executed smoothly and are characterized by unimodal and relatively bell shaped velocity profiles. Smooth movements have been suggested to reflect coordinated and skilled movement performance. However, assessment of the kinematics of unconstrained head and neck movements in healthy subjects has been relatively limited. Neuromuscular factors determinant for peak performance of dynamic head and neck movements are also scarcely addressed in humans. The muscle fiber type proportions of the majority of cervical muscles in humans are unknown and neck muscle activation patterns have been predominantly studied during isometric muscle contractions. Another aspect contributing to peak movement velocity and acceleration is the displacement of movement, but it is not known whether measures of movement smoothness may vary systematically by kinematic factors such as movement displacement and velocity. In individuals with chronic neck pain after whiplash trauma (WAD) overall measures of neck movement performance i.e. peak displacement, velocity, acceleration and smoothness of movement are markedly reduced compared with healthy controls. Possible physiological mechanisms for the reductions in dynamic movement performance in chronic WAD, such as changes in neuromuscular activity, muscle fiber type proportions and possible contributing confounding kinematic factors have to a limited degree been explored.

Overall objective

The overall objective of this thesis was to examine the kinematics of simple, unconstrained head and neck movements and to compare the performance between healthy men and women and between participants with and without chronic WAD. Further, it was the aim to elucidate underlying physiological mechanisms for diversity in performance.

Methods

The morphology of the neck muscles sternocleidomastoid (SCM), scalenus medius and splenius and two reference muscles (trapezius and vastus lateralis) was examined by immunohistochemistry in a cross-sectional study consisting of muscle samples from each of 12 individuals in study I. In addition, three separate previously published datasets consisting in total of 40 different muscles and 37 individuals were re-analyzed. Study II was a case-control study in which the fiber type distribution of the SCM muscle was compared between 12 controls and 17 individuals with severe chronic neck pain. In study III, the peak isometric neck force and head movement kinematics were examined in the sagittal plane by means of a load cell and an electromagnetic position tracker. Four small and two large amplitude movements each accomplished at three different movement speeds were compared between healthy men (n = 12) and women (n = 14). Using a similar experimental setup, a case-control study (study IV) of 15 participants with chronic neck pain after whiplash and 15 healthy

participants was conducted for comparative examination of head movement kinematics and surface electromyographic (EMG) activity of the SCM and splenius muscles.

Results

The neck muscles were composed of more type 1 muscle fibers and smaller fiber cross-sectional area than the leg muscle vastus lateralis. Individuals that expressed high proportions of type 1 fibers in the leg muscle also displayed high proportions in the shoulder and neck muscles as well. The proportion of type 1 and type 2 fibers of the SCM muscle of individuals with severe chronic neck pain did not differ from the controls. Healthy men produced larger neck flexion and extension force normalized for head mass, greater acceleration and moved faster for a given displacement than women did. In healthy subjects the smoothness of head movements were strongly related to movement velocity and displacement. Peak head movement displacement, velocity, acceleration, smoothness of movement and neck muscle EMG amplitude were markedly reduced in the chronic WAD group. The differences between groups in peak velocity and acceleration persisted after controlling for displacement, while controlling for differences in velocity and displacement abolished the group differences in EMG amplitude and smoothness of movement.

Conclusion

Peak kinematic performance of head and neck movements is strongly influenced by sex and chronic neck pain. While the differences in peak movement velocity and acceleration between the sexes are likely to be mainly explained by overall cervical muscle sizes, the performance differences between subjects with and without chronic WAD do not seem to be caused by factors related to muscle physiology. The neural drive of the neck muscles in subjects with chronic WAD appears to be reduced which causes the movements to be slower and therefore less smooth. Yet, for a given movement velocity and displacement, unconstrained head and neck movements are accomplished equally smooth and with similar EMG amplitude in subjects with and without chronic WAD. It is therefore suggested that the difference in movement performance between subjects with and without chronic WAD is a result of reduced muscular activation and not changes in intrinsic muscle physiological properties.

List of papers

Paper I

Harald Vikne, Kristian Gundersen, Knut Liestøl, Jan Mæhlen and Nina Vøllestad. *Intermuscular relationship of human muscle fiber type proportions: Slow leg muscles predict slow neck muscles.* Muscle & Nerve. 2012; 45(4):527-535.

Paper II

Harald Vikne, Jan Mæhlen, Eva Sigrid Bakke and Nina Vøllestad. *Type 1 to type 2 neck muscle fibre proportion in persons with chronic neck pain and controls.* Submitted.

Paper III

Harald Vikne, Eva Sigrid Bakke, Knut Liestøl, Gunnar Sandbæk and Nina Vøllestad. *The smoothness of unconstrained head movements is velocity dependent.* Human Movement Science. 2013; 32(4):540-554.

Paper IV

Harald Vikne, Eva Sigrid Bakke, Knut Liestøl, Stian R. Engen and Nina Vøllestad. *Muscle activity and head kinematics in unconstrained movements in subjects with chronic neck pain; cervical motor dysfunction or low exertion motor output?* Re-submitted.

Abbreviations

ATPase	Adenosine triphosphatase
BA-D5	Monoclonal antibody against MyHC 1/β
BF-35	Monoclonal antibody against all non-2X MyHC
BMI	Body mass index
CSA	Cross-sectional area
C7	7^{th} cervical vertebrae
EBN	Extension back to neutral position
EF	Full extension from fully flexed position
EFN	Extension from neutral position
EMG	Electromyography
FABQ	Fear avoidance beliefs questionnaire
FBN	Flexion back to neutral position
FF	Full flexion from fully extended position
FFN	Flexion from neutral position
FITC	Fluorescein isothiocyanate
HGU/55P	Aviation helmet
HRQOL	Health-related quality of life
IARC7	Instantaneous axis of rotation C7
M	Maximum; referring to test speed condition
MRI	Magnetic resonance imaging
MVC	Maximum voluntary contractions
MyHC	Myosin heavy chain
NDI	Neck disability index, questionnaire
NJC	Normalized jerk cost
NP	Neutral position
P	Preferred; referring to test speed condition
PTFE	Polytetrafluoroethylene
RMS	Root mean square
S	Slow; referring to test speed condition
SCM	Sternocleidomastoid
SC-71	Monoclonal antibody against MyHC 2A
sEMG	Surface electromyography
SF-36	Short form 36, questionnaire
SIT	Silicon intensifier target
TRITC	Tetramethylrhodamine isothiocyanate
US	Ultrasound imaging
WAD	Whiplash-associated disorder
6H1	Monoclonal antibody against MyHC 2X

Introduction

In everyday life the head and neck are moved continuously for sensory communication with the external world. The head movements may be spatio-temporally constrained as for example when visually tracking a moving object or relatively unconstrained as while orientating the head obtaining visual overview. Unconstrained movements are usually performed smoothly by healthy people[1]**.** Smoothly executed movements are characterized by a bell-shaped velocity profile containing a single velocity peak and have been suggested to be a hallmark of coordinated and skilled movements[2]. Measures of movement execution, such as velocity, acceleration and smoothness of unconstrained head and neck movements have been given little attention in research. There is similarly limited empirical data on neuromuscular factors contributing to variation in dynamic movement performance of the head and neck such as neck muscle fiber type proportions and muscle activation.

The head and neck movements in subjects with long-term pain after whiplash injury (WAD) are executed with reduced displacement, velocity, acceleration and smoothness[3-5] as compared with healthy participants. Other measures of motor performance, such as peak isometric neck force and endurance are similarly reduced in chronic WAD[6-8]. However, the possible neuromuscular mechanisms for the reductions in the motor output of dynamic neck movements in persons with chronic WAD have been little addressed. It is for example not known whether the muscle fiber type proportions of cervical muscles in subjects with chronic neck pain differ from those of controls. The activation patterns within single and between multiple neck muscles in subjects with chronic WAD have almost exclusively been studied using isometric neck muscle contractions at low to moderate force or during movement of another body part[9-11], while studies examining neck muscle activation during dynamic unconstrained head movements are lacking.

Unconstrained head movements may be accomplished with large interindividual variation in the measures of kinematics, such as displacement and velocity. While it is known that movement displacement is strongly related to movement velocity[12] and that both displacement and velocity influence EMG amplitude[13], it is unknown whether these kinematic factors may affect head movement smoothness. However, the impact of the variation in

movement execution on performance has not been empirically examined for head movements, neither for healthy men nor women nor in subjects with chronic WAD.

Patients with chronic neck pain constitute a diverse group with mainly unknown and possibly diverse etiologies. Of these, subjects with chronic WAD generally display larger impairment in physical functioning than subjects with neck pain of non-traumatic origin[7,14]. A whiplash injury is typically caused by a high velocity hyperextension – flexion of the neck due to rear-end motor vehicle accidents[15]. Symptoms and/or disabilities immediately following such an accident are commonly described as whiplash-associated disorders (WAD)[16]. The Quebec Task Force suggested a 5 point grading of severity of WAD[16] where subjects with WAD grade 0 display no complaints of the neck and no physical signs, grade 1 display pain but not musculoskeletal signs, grade 2 display pain and musculoskeletal signs, grade 3 in addition show neurological signs, while grade 4 include fracture or dislocation. The annual incidence of WAD in North America and the Western Europe is estimated to about 300 per 100 000 inhabitants[17]. A recent study from Northern Sweden found an overall yearly incidence of 235/100 000 across a ten year span and a yearly increase of 1 %[18]. Estimates predict that that up to 50 % of the individuals with acute WAD may develop long-term pain and disability exceeding one year of duration[19]. The main regions of pain in individuals with chronic WAD are the neck and head, but the prevalence of pain in the shoulders, upper and lower back is also high[20]. In addition to pain, the WAD-sufferers display a range of non-specific symptoms and signs[21], more subjective health complaints compared with the general population[20] and display reductions in functional ability in daily living such as driving, recreation, work and home activities and overall health related quality of life[22-24].

Aims of the thesis

The overall objective of this thesis was to examine the kinematics of simple, unconstrained head and neck movements and to compare the performance between healthy men and women and between participants with and without chronic WAD. Further, it was the aim to elucidate underlying physiological mechanisms for diversity in performance.

Specific aims of the thesis

Study I

1. To describe the fiber type proportion and fiber cross-sectional area of the cervical muscles sternocleidomastoid (SCM), splenius capitis and scalenus medius and to compare them with two reference muscles, the trapezius and vastus lateralis.
2. To examine whether some humans generally display fast muscles and others slow muscles.

Study II

3. To examine whether the type 1 to type 2 fiber proportion of the SCM muscle change as a result of long term neck pain.

Study III

4. To examine the kinematics of unconstrained head and neck movements across a large range in movement speed and amplitude and to compare healthy men and women by taking movement velocity and displacement into consideration[a].
5. To examine whether the smoothness and regularity of unconstrained head and neck movements is dependent upon movement displacement and velocity.

Study IV

6. To compare movement kinematics and neck muscle activation of unconstrained head and neck movements in subjects with and without chronic WAD at different movement speeds and loads and by taking movement velocity and displacement into consideration.

[a] The comparison of head kinematics between men and women in study III is not reported in paper III.

Background

Muscles and movement

Regulation of muscle force

Voluntary slow and fast dynamic movements in man are generated by the orderly activation of skeletal muscles. Thus everyday locomotion, chewing, breathing and talking would be impossible without the dynamic activity of skeletal muscles. Each muscle is composed of a few hundred and up to several hundred thousand muscle cells which are organized in smaller functional motor units consisting of some tenths to thousands of muscle cells innervated by a single α-motoneuron[25]. The muscle cells or fibers belonging to a given motor unit are intrinsically homogenous in that they all express similar cellular structures and biochemical apparatus and thus possess equal contractile and functional properties and are classified as distinct muscle fiber types[26].

The motor output of skeletal muscles is regulated by two main mechanisms; *rate coding* and *recruitment*. The contraction force of the muscle fibers belonging to a single motor unit is controlled by the frequency of impulses sent by the motoneuron known as rate coding[27,28]. At low force demands, the motoneurons discharge at a low firing frequency and at high force demands the firing frequency increases. To raise the voluntary activated contraction force of a whole muscle, increasingly more motor units are activated or recruited to match the force demand at hand[29,30]. This recruitment of motor units is accomplished sequentially in a relatively fixed order. Small motor units consisting of relatively few muscle fibers are recruited first and thereafter larger motor units consisting of increasingly more fibers depending on the force needed[30,31]. In everyday living movements across a joint are normally accomplished by activation of several agonistic muscles shortening across the joint(s). While the agonistic muscles create forces in the intended movement direction, antagonistic muscles are activated concurrently, but to a lesser degree, in order to keep the joint movements stable[32,33]. For human neck movements, the force created of the agonistic neck muscles is therefore strongly related to the degree of activation as recorded by surface electromyography (sEMG)[34].

Muscle fiber types and force-velocity properties

In human trunk, spine and extremity muscles, most muscle fibers come in three different main types termed 1, 2A and 2X(D)[b] classified after what type of myosin heavy chain (MyHC) it express[37]. Two hybrid muscle fiber types termed 1/2A(C) and 2A/X co-express respectively both type 1 and 2A MyHC and type 2A and 2X MyHC. In addition to the three main fiber types, humans have muscle fibers that express at least six other MyHCs, but the expression of these seems to be restricted to specialized muscle cells in the myocardium, extraocular muscles, jaw and larynx[38-40] or during muscle development and regeneration[41].

The basics of the dynamic performance of a maximum activated single muscle fiber is described by its force-velocity relationship[42] in which each sarcomere operates at approximately optimal lengths for cross-bridge development to create force. The relationship simply describe that a muscle shortens slowly and creates high force if the load opposing the shortening is heavy. Conversely, if the load is light the muscle shortens fast and creates low force. At the low-force, high-velocity portion of the relationship, the peak shortening velocity of a single muscle fiber is largely dependent upon the myosin heavy chain (MyHC) it express[41]. On average, the type 1 single fibers display lower myofibrillar ATPase activity[43], unloaded and maximum shortening velocity[44-48] and normalized maximum power (force*velocity)[45,47,49] than 2X and 2A fibers of the same length and CSA. The type 1 fibers are often termed "slow". The type 2X display properties on the opposite end of the continuum while the type 2A fibers have intermediate properties. The type 2 fibers are commonly referred to as "fast" fibers. The hybrid fibers display intermediate properties of that of the two "nearest neighbor" fiber types.

At the high-force, zero-velocity portion of the force-velocity relationship, i.e. isometric contractions, the peak force of a single muscle fiber is dependent upon the total number of cross-bridges in parallel and thus, its overall size and cross-sectional area (CSA)[47,50]. There are some conflicting results whether the specific isometric force (force/size) is higher in type 2 than type 1 fibers[44-48,51]. For these intrinsic contractile properties of the muscle fibers, previous research indicates that there is no effect of sex at the adult age[50]. The following generalizations can therefore be made concerning the force-velocity relationship of

[b] Historically this novel type 2 MyHC was identified about simultaneously of two separate research groups using two different methods; immunohistochemistry and SDS-gel electrophoresis[35,36] and was termed 2X and 2D respectively. In the following I will refer to this MyHC as 2X.

single muscle fibers; a type 2 fiber produce higher peak shortening velocity and larger force at a given shortening velocity than a type 1 fiber of the same dimension. A fiber with large CSA produces larger peak isometric force and larger force at a given shortening velocity than a smaller fiber of the same type. Figure 1 illustrates the force-velocity, velocity-power and force-CSA relationships for single human muscle fibers.

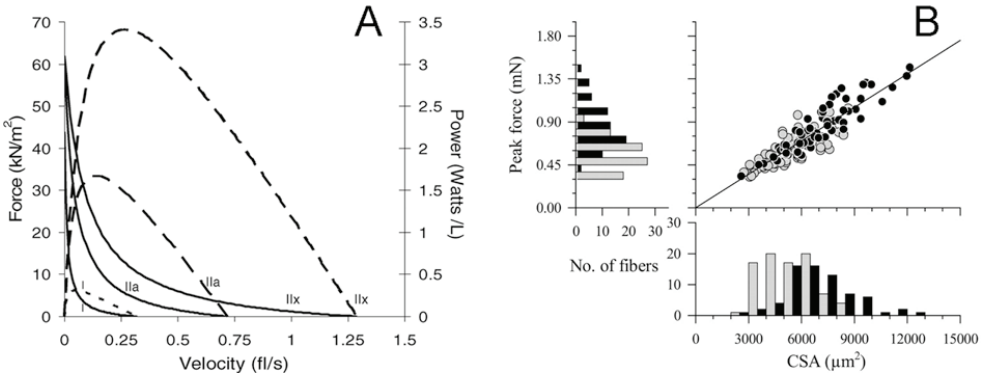

Figure 1. A. Schematic summary of force–velocity and velocity–power data from human skinned fibres containing MHC-I, MHC-IIa and MHC-IIx isoforms. The data show the slightly greater force per unit area, but markedly greater maximal shortening velocities and power outputs of the MHC-IIa and MHC-IIx fibres. Taken from Harridge et al.[52]. Reprinted with permission from John Wiley and Sons. B. Histograms and scattergrams of fiber cross-sectional area (CSA) and peak Ca^{2+}-activated force for fibers containing type 1 MyHC (Pretraining; gray bars and symbols. Posttraining; black bars and symbols). The line indicates the relationship between CSA and peak force that corresponds to a specific force of 117 kN/m^2 of the pooled pre and posttraining fibers. Taken from Widrick et al.[48]. Permission not required[c].

Muscle fiber type variability across different muscles and individuals

For whole muscles the peak force capacity is dependent upon the size and number of muscle fibers in parallel, thus the whole muscle CSA[53-55d]. It is well known that women in general has less overall muscle mass than men[56-60] and this difference persists although somewhat reduced when normalizing for differences in body size[57,61]. Thus, women has less capacity for force production and peak power than men for a given body dimension[62,63], while

[c] The publisher, The American Physiological Society did not require permissions to reprint figures in a thesis.

[d] The force a muscle can create is more stringently dependent upon the summed CSA of the muscle fibers in parallel and their angle of insertion to the line of action of the whole muscle – its physiological CSA (PCSA). When only comparing the same muscle its crude anatomical CSA (ACSA) has a similar correlation value with peak force as the PCSA[53]. Comparing the force capacity of different muscles requires assessment of the PCSA.

the specific strength (strength/CSA) is not different[55,64]. In addition to muscle size it has been known for a long time that there are intrinsically differences between separate muscles in vertebrates as for example in color. Ranvier reported in 1873 (in Needham, 1926[65]) that red and white muscles of rabbit and ray had functional differences in that the muscles displayed different twitch-contraction time. It later became clear that these muscles displayed different mean fiber type proportions which are a general trend for separate skeletal muscles. In humans, some muscles are typically composed of predominantly slow muscle fibers (for example the soleus) and others fast muscle fibers (for example the triceps brachii)[66-68], while for a large number of muscles the slow to fast proportion are about even[69].

Although the different muscles on average display a typical fiber type distribution there is a large intra-individual variation within each muscle in humans[69,70], but no systematic difference between the sexes[70-73]. For example, in the extensively examined knee extensor, the vastus lateralis muscle, Staron et al.[70] found a mean type 1 fiber proportion of 41 % in 150 young men and women, but the range in type 1 fiber proportion was 16.5 – 97.5 %. This individual fiber type proportion expressed in a given muscle in mammals seem to be partly dependent on heritable factors[74-77] and gives rise to individual differences in functional performance[78]. Thus, an increased proportion of type 1 fibers correlate with increased endurance capacity and performance[79-83] while a high proportion of type 2 fibers correlate with increased performance in fast force development and power[46,84-89].

The relationships between functional performance and the fiber type proportions have been found in investigations predominantly using a small biopsy from only one single muscle doing work in the correlated performance test. Since most tests of human performance are not only dependent on the work of a single muscle, but the combined power output of several muscles and muscle groups, one might hypothesize that there is a systematic relationship in fiber type proportion between different muscles in the same individual. In addition to correlates of performance tests, it has been reported in several studies that a low proportion of type 1 fibers in single skeletal muscles are also related to the presence of whole body metabolic and cardiovascular disease[90-93] and markers for disease[94-98]. Such correlations between markers for and presence of whole body disease with the fiber type proportion of a single skeletal muscle strengthen the hypothesis that a relationship in fiber type proportions between muscles exist. Such a relationship has been proposed a long time ago by Bengt Saltin[99] but this hypothesis does not seem to have been systematically examined.

One objective in study I was therefore to examine whether the fiber type proportion in different muscles in the same individual was interrelated, thus if some humans generally display fast muscles and others slow muscles.

Human neck muscle morphology

The human head and neck constitute some 7 % of the overall body weight for both adult men[100] and women[101] and about 20 pairs of muscles are active during dynamic movement or static holding of the head and cervical spine[102] (see table 1). Several of these muscles have been thoroughly examined for gross morphology by whole muscle dissection[102,103] and various imaging modalities[104-108]. In line with data for other muscle groups and whole body muscle mass, the neck muscles of adult women are smaller compared with men, reaching about 59-76 %[107-110]. It has be estimated that the muscles with the largest moment-generating capability in the sagittal plane are the sternocleidomastoid (SCM) in the anterior or flexion direction and semispinalis capitis and splenius capitis for posterior or extension direction[111]. With the prominent exception of the trapezius muscle[69,112-119] which predominantly exert action on the shoulder girdle[103], there are few systematic examinations of fiber type composition and cell CSA of the muscles crossing the cervical spine (see table 1 for overview). For example, the muscle fiber type composition and cell CSA of the SCM has only been examined once in a small set of six healthy individuals[69,120] and in three studies of participants with chronic neck pain[112,121] or laryngeal cancer[122]. Of the neck extensors only the multifidus muscle has been investigated in healthy subjects[123]. The semispinalis capitis has never been examined and data for splenius capitis muscle exist only for subjects with chronic neck pain[112]. Of the lateral flexors, systematic examinations of the scalenus medius and -posterior muscles seems also to be lacking and empirical data of the scalenus anterior comprise of only four subjects. Thus, there seem to be limited information regarding the normal fiber type composition in several muscles that are important for generating force and movement of the head and neck. A major factor for the small number of studies is most likely the difficult access for tissue sampling from these muscles in vivo.

It was therefore a second objective of study I to examine the fiber type composition and fiber CSA in the sternocleidomatoideus, scalenus medius and splenius capitis muscles and to compare them with two reference muscles, the trapezius and vastus lateralis.

Table 1. The range in mean proportion of type 1 fibers and number of observations reported in some of the major skeletal neck muscles acting on or across the cervical spine in a reference population and subjects with pain and disease. "-"depict that to the best of the author's knowledge, these muscles have not been analyzed for fiber type composition in humans. "n" refers to the numbers of observation in the study or range in cases of several studies. No hyoid/mandible muscles are included.

Neck muscles	Reference subjects	n	Subjects with pain/disease	n
Levator scapulae	-	-	-	-
Longissimus cervicis	-	-	-	-
Longissimus capitis	-	-	-	-
Longus capitis	-	-	-	-
Longus colli	45.8[124] – 53.0[123]	10,16	53.7[112#]	10
Mulitfidus	77.0[123]	16	-	-
Obliquus capitis inferior	-	-	56.2[112]	18
Obliquus capitis superior	-	-	-	-
Rectus capitis anterior	-	-	-	-
Rectus capitis lateralis	-	-	-	-
Rectus capitis posterior major	-	-	57.0[112]	15
Rectus capitis posterior minor	-	-	-	-
Rhomboid	44.6[69]	6	-	
Scalenus anterior	74.5[125]	4	85.1[125§]	7
Scalenus medius	-	-	-	-
Scalenus posterior	-	-	-	-
Semispinalis cervicis	-	-	-	-
Semispinalis capitis	-	-	-	-
Splenius capitis	-	-	64.0[112]	43
Splenius cervicis	-	-	-	-
Sternocleidomastoid	35.2[69]	6	36.7 – 39.0[112,121,122^]	6-33
Trapezius	53.7 – 67.0[69,114-118]	6-23	54.5 – 72.0[112-119]	7-41

[#]In the reported study of Uhlig et al.[112] the fiber type proportions in the different muscles were given in two tables (2 and 4). In table 2 up to four different sets of data were reported for each muscle (three etiology conditions and sex). In table 4 the data were spilt in two at median pain duration. Since the number of observations did not match between the two tables, the data from the table with the highest number of observations were used. The data reported above is the calculated pooled weighed mean fiber proportion, dependent of the number of observation across all conditions reported.

[§]The data of four subjects with prior tenotomy of the scalene muscle is not included from Machleder et al.[125].

^In the data from Weber et al.[121] the mean value was calculated. One subject (number 22) was removed because the summed fiber type proportions did not add up to 100 %.

Neck movement performance in health and neck pain

Models for examination of head and neck movement performance

The human head and neck complex allows for movements in all three planes and combinations of planes with reference to the trunk and movements can be accomplished and examined under various degrees of complexity. A main topic of this thesis was to elucidate performance diversity in simple head and neck movements between men and women and between subjects with and without chronic neck pain. Many everyday movements are performed relatively unconstrained in the spatial and temporal domains and introducing constraining boundaries on the movements such as precision and visuomotor dependence has large effects on how voluntary motion is executed[126]. For example, the speed of a voluntary movement decreases by increasing the requirement of spatial accuracy, known as the speed-accuracy tradeoff[127]. Thus, movements strongly dependent of accuracy and visual input and feedback on performance such as movements requiring a high degree of end-point precision[127] or movements containing pursuit[128] and trajectory[129] tracking were defined as constrained movements. In the framework of this thesis, simple unconstrained movements are defined as unidirectional head and neck movements completed in a single plane with loose boundaries for acceptance of accomplishment, such as end-point precision.

Peak voluntary head and neck performance in men and women

Neck movements at peak effort are strongly influenced by performance limiting factors such as fiber type and single cell- and whole muscle CSA. For example, the well known relationship between strength and muscle CSA[53] is confirmed empirically for the neck muscles[130]. Therefore as a function of a reduced neck muscle mass[107-110], women generate about 50 – 75 % of the peak absolute isometric neck force in all three main movement directions as compared with men[131-135]. This sex difference in force capacity also persists, although to a reduced extent after normalizing for body size or head mass[135-137] because of the relatively smaller muscle mass for a given body dimension in women[57,61]. Thus, a simple scaling of body size does not abolish sex differences in force and for a given head mass women generate less force than men. For the voluntary neck movement angular displacement in the three main planes, normative data does not suggest any systematic differences between men and women[138-141]. As there are marked sex differences for absolute and relative neck strength, while fiber type composition and displacement are similar, it is predicted by the

classic force-velocity relationship that peak velocity at a given load is different between sexes. However, as far as I know, no empirical data confirming such a suggestion has been reported.

One objective in study III was to examine the kinematics of unconstrained head and neck movements across a large range in movement speed and amplitude and to compare healthy men and women by taking movement velocity and displacement into consideration.

Peak voluntary head and neck performance in chronic whiplash-associated disorders

Despite a large number of studies displaying self-reported impairment and neck disability[142], surprisingly little attention has been given to dynamic performance such as force production during shortening and lengthening contractions and kinematic analysis of head movements in chronic WAD. Force production during shortening and lengthening contractions has for example been studied in other chronic pain conditions such as isokinetic arm abduction movements in subjects with trapezius myalgia[143] and trunk movements in lumbar disc herniation[144] but not in neck movements in people with chronic WAD. When using isometric contractions, persons with chronic WAD display reduced peak force in all movement planes, reaching 28 – 62 % of the peak force of healthy subjects[6,7,145,146]. The peak isometric endurance performance is similarly reduced compared with control participants[7,8,147,148].

Kinematic analysis of head and neck motion in participants with chronic WAD has mostly been limited to assessment of angular displacement, which has been shown to be generally reduced as compared with healthy participants[3,8,14,22,149-153]. The movements in the sagittal plane (flexion and extension) are typically the most affected directions for displacement, reaching 48-77 % of that of control participants[3,14,22,150-152]. In the limited number of studies examining head and neck movement velocity in chronic WAD, all but one[5] found that the peak angular velocity of movements were strongly reduced, reaching 39 – 66 % to that of reference subjects[3,4,150]. Some of these studies reported numerically greater reductions in angular velocity for movements in the sagittal plane as compared with the horizontal plane[3,150] hence supporting the view that movements in the sagittal plane are most affected in chronic WAD. In the one study reporting no group difference in angular velocity, Sjölander et al.[5] in contrast to the other studies adjusted for movement displacement when comparing peak velocity in participants with and without chronic WAD, thus examining

possible intrinsic differences in movement speed. Such a handling of the data seems to be of importance because of the strong relationship between voluntary movement velocity and displacement[12]. It is therefore possible that previously reported deficits in peak movement velocity in persons with chronic WAD may have been affected by concomitantly reductions in movement displacement. However people with chronic WAD are also reported to have lower angular velocity of movement when the speed is self-selected[149] a test condition which may be less exposed to differences in displacement.

In study IV, one objective was to compare the kinematics of unconstrained head movements between subjects with and without chronic neck pain after WAD and by taking movement displacement into consideration. Movements were examined across a large range of movement speeds and different head loads.

Quality of head and neck movement execution in health and neck pain

In everyday life, relatively unconstrained movements such as reaching, pointing and grasping are typically executed in a smooth manner in which the velocity profile of a given movement is reasonably symmetrical, unimodal and bell-shaped. Such smooth movement executions are observed across a variety of species and movement types[154-158]. In contrast, movements of persons with neurological injury and diseases typically display irregular velocity profiles and jerky movements compared with healthy control participants[159-162]. A measure of the quality of voluntary movement has been the assessment of the smoothness of movement[1] which is thought to represent a measure of non-irregularity, skill and coordination of voluntary movement[2]. The smoothness of voluntary movements have been quantified by the jerk cost; which is calculated as the time integral of the third derivative of position[163]. Movements that minimize the jerk cost, display bell-shaped, symmetrical velocity profiles with minimal accelerative transients[1]. Since it has been demonstrated that the jerk cost varies dramatically with both duration and displacement of the movement[164], the jerk cost is frequently normalized to allow comparison of the smoothness of movements across diverse durations and displacements[161].

If movements are subjected to increased temporal and spatial accuracy constrains such as avoidance of obstacles, pursuit tracking and end-point precision, the velocity profile becomes less symmetric, multimodal and less smooth[165-170]. However, simply slowing down

an unconstrained movement has also been observed to cause irregularities on the velocity profile[170-173], suggesting that these movements are performed less smoothly. Such observations have been done in movement of body parts across a large range in mass and inertia[170-172]. These observations imply a qualitatively difference between movements executed at various velocities and thus, a relationship between the velocity and smoothness of movement. Such a relationship have been found for spatio-temporal constrained arm movements[174], but as far as I know no systematic evaluation of such a relationship have been published for unconstrained movements.

When the smoothness of relatively unconstrained movements have been compared between participants with and without chronic neck pain after WAD, the neck movements in chronic WAD are found to be less smooth than in control subjects[3-5]. Such findings have been suggested to signify altered motor control and sensimotor disturbance in the chronic WAD subjects[3,5]. Concomitantly, in two of these studies the movements were accomplished at slower speed in the chronic WAD groups as compared with the controls[3,4]. Hence it raises the possibility that differences in the smoothness of head and neck movements may be caused by reductions in velocity and not altered motor control.

Thus, two additional objectives in study III and IV were: 1) to examine whether the smoothness and regularity of unconstrained head and neck movements is dependent upon movement displacement and velocity, and 2) to examine whether differences in movement smoothness and regularity between subjects with and without chronic WAD can be explained by group differences in movement velocity and displacement.

Neuromuscular adaptations to changes in use and chronic pain

Muscle adaptations

Skeletal muscles display an incredible ability to adapt to settings of increased or decreased demands and usage. After birth and to the age of 20, the CSA of muscle fibers increases some 25-fold[175] and at the adult age muscle mass may double as a function long term training[176]. Relatively short-term resistance training, such as three months are however sufficient for marked increases of the single fiber- and overall muscle CSA in previously untrained subjects[58,177]. For example, after three months of resistance training of the neck,

Conley et al.[178] found some 13 % increase of the neck extensor CSA. Contrary, prolonged bed-rest may after only five to six weeks reduce the CSA at the whole muscle level by some 10 – 15 %[179-181]. Alteration of muscle size is consequently a relatively fast adaptation to changes in use and is in relative terms of similar magnitude in men and women[58,182].

Muscle atrophy is also common response to musculoskeletal injury and pain[183-187]. A general reduction in CSA of the neck muscles does, however not seem to be a function of chronic WAD[188-191]. On the contrary, some cervical muscles display an increased CSA in persons with chronic WAD[190,191]. As a measure of muscle quality, the mean muscle signal to mean intermuscular fat signal ratio, thought to signify intramuscular fat content, have been reported to be increased in neck muscles of chronic WAD patients as compared with controls[191,192]. However, the functional effect of the increased signal ratio on peak effort motor performance has not been evaluated. At the single muscle fiber level, measures of the contractile function do not seem to have been examined in chronic neck pain. Generally, neither the specific force or unloaded velocity of shortening of either fiber type seem to be affected by resistance training in adults[193], while continued bed-rest and immobilization seem to lower the outcome of both variables[194,195].

Alterations in activity patterns may induce conversions in the expression of fiber types within the muscle. A typical pattern to increased use is a switch from the fast 2X phenotype to the slower 2A phenotype and conversely in the opposite direction by decreased use[196-201]. Under normal physiological conditions this alteration in the proportion of the different phenotypes does not seem to apply for the type 1 fibers, neither after long-term training or inactivity[181,196-204]. Resistance to transition between the type 1 and type 2 fibers is also seen in chronic pain settings such as in subjects with long-term trapezius myalgia[114-117], chronic low back pain[205] and lumbar disc herniation[206]. In contrast, a previous uncontrolled study has suggested that a reduction in the type 1 to type 2 fiber proportions in ventral neck muscles may change as a result of severe chronic neck pain[112]. This suggestion was made based upon a reduction in the proportion of the type 1 and 1/2A (2C) fiber type in the combined data from the ventral SCM and omohyoid muscles in subjects with long versus short duration of symptoms (divided at median). Alterations in the proportion of type 1 fibers were not reported of four examined dorsal muscles. The lack of a control group opens the question to whether people with chronic neck pain differ in fiber type proportions from that of control subjects.

It was therefore the objective of study II to examine whether chronic neck pain may change the type 1 to type 2 neck muscle fiber proportions by comparing the fiber type proportions in the SCM muscle between participants with and without chronic neck pain.

Muscle activation adaptations

In 1970 Ikai and Fukunaga[207] was the first to report a large discrepancy between increases in muscle CSA and strength after 100 days of resistance training. They suggested that the increased strength per CSA (specific strength) was a result of increased nerve discharge to the working muscles. They also found an increase in strength of 32 % in the untrained, contralateral arm with no hypertrophic response of the muscle. The discrepancy between gains in strength and muscle mass have since been confirmed across a number of studies[208,209] and anatomical regions including the neck[178]. A common finding during the first initial phase of resistance training is an increase in absolute EMG amplitude of agonistic muscles, thought to signify increased neural drive and reflecting both increases in the number of motor units activated and an increase in motor unit firing frequency[210,211]. On the other hand it is debated whether significant adaptations in antagonist activity occur and also in which direction the adaptations occurs[211]. By decreases in muscle use such as immobilization and bed-rest, strength reductions are disproportionally greater than can be accounted for by atrophy alone[212-214]. A large part of the reduction in specific muscle force seems to be explained by an accompanying large reduction in the neural drive[213-215] in addition to reduced specific force at the muscle fiber level[194].

A somewhat similar, but perhaps more pronounced pattern is seen in people with chronic WAD. On an overall basis the neck strength during peak effort is normally markedly reduced while there are seemingly no reductions in muscle CSA, suggesting reductions in specific force and neural drive. However, there are no studies that have measured both neck strength and muscle CSA in chronic WAD, which renders such a proposition somewhat uncertain. In addition, few studies measuring the peak neck strength and EMG amplitude have been presented in these subjects. In one of few studies reporting on both these variables, Juul-Kristensen et al.[216] found numerical reductions of both peak isometric neck flexion and extension force (-34 and -36 %) and accompanying reductions in the peak EMG amplitudes of the agonistic muscles (-26 and -31 %) in chronic WAD as compared with controls. However all comparisons were non-significant. Although force and neural drive were reduced, these

data suggests that the agonist activation in the participants with chronic WAD was similar to the controls for a given force during peak effort contractions.

When persons with chronic WAD were compared with controls at low to moderate absolute force levels, several studies have reported changes in the intrinsic activation patterns in persons with chronic WAD[11,146,217]. For example, the muscle activity of the SCM is increased in chronic WAD as compared with control participants[11] during isometric neck flexions at moderate force levels. Subsequent examinations[217] found decreased activity of the longus colli/capitis complex concomitantly to the increased SCM activity, thus keeping the resultant force output constant. Similar observations of increased EMG activity at standard force levels have been reported both for the SCM and the splenius muscles when functioning as agonist, but also as antagonist in subjects with chronic non-traumatic neck pain[218,219]. These data point towards a re-arrangement in muscle activation patterns between agonistic muscles and between agonist and antagonist muscles in subjects with chronic neck pain, at least when examined at standard, low to moderate isometric force levels. Muscle activation during dynamic neck movements in participants with chronic WAD does not however, seem to have been addressed.

A third objective in study IV was to compare neck muscle activation patterns between participants with and without chronic WAD during unconstrained neck movements at several different movement speeds and loads and take movement velocity and displacement into consideration.

Materials and methods

Design

Study I

In study I the fiber type proportions and single cell cross-sectional area of several human muscles were examined in the same set of individuals. In particular, several neck muscles not previously examined in presumably healthy subjects were analyzed. In the same set of data, it was also examined whether the muscle fiber type proportions in different muscles from the same individual were interrelated. The intermuscular relationship in fiber type proportion was further examined by reanalyzing three previously published, independent datasets containing other muscles.

Study II

Study II was a case-control study in which the muscle fiber type proportions in the sternocleidomastoid muscle in subjects with long term neck pain from a previously published set of data was compared with that of control subjects.

Study III

In study III several measures of head movement performance and peak isometric force was compared between healthy men and women without neck pain. In particular the movement velocity, displacement and movement smoothness during four short and two long head relatively unconstrained movements in the sagittal plane at three different speeds were examined. The kinematic outcome variables were examined for test-retest reliability. This study also investigated whether the smoothness of movement are related to movement velocity and displacement.

Study IV

Study IV was a case-control study comparing the head movement kinematics and smoothness of movement between healthy participants and with chronic WAD during similar conditions as reported in study III and also with increased head load. Factors possibly influencing differences in movement performance were also examined.

Ethics

All studies were approved by the Regional Committee for Medical and Health Research Ethics. In study I and II waiver of the informed consent requirement were given by the Regional Committee. All data in study I and II were anonymous. The participants in study III and IV signed an informed consent form for participation in the studies. The people with chronic WAD participating in study IV was recruited through a local rehabilitation clinic at their first time of visit. It was underscored that the decision for participation in the study was voluntary and of no future consequence to their following treatment at the clinic.

Participants

Study I and II

12 cases (11 men and one woman) of sudden death were included in the study and from which muscles samples were taken 24-72 hours post mortem. Subjects were 45.3 ± 15.8 years of age at the time of death and of normal build and stature. None had a history of bed rest or hospitalization the last 24 hours immediately prior to death. Cachectic or severely obese cases were excluded. For cases where the medical record or autopsy revealed neurological, rheumatological or endocrinological disorders, alcoholism, drug abuse or other severe diseases including malignancy, they were excluded. In addition, 37 (study I) and 17 (study II) subjects of three[69,121,220] and respectively one[121] previously published datasets were included in the two studies are described below and in table 2 and 3.

Table 2. The data sets included in analysis of intermuscular relationship in study I. Age is given as mean (SD) with the exception of the age data of Garrett et al.[220] which is given as mean (range).

Data sets	Subjects	Age (year)	Muscles
Own data in study I	12	45.3 (15.8)	5
Weber et al.[121]	21	52.0 (14.4)	2
Garrett et al.[220]	10	60 (37-76)	9
Johnson et al.[69]	6	21.8 (5.7)	36

Table 3. Characteristics of the chronic neck pain group from the data set of Weber et al.[121] and the controls from own set of data of study I. Age and duration of symptoms are mean (SD). Statistically significant relatively less men than in the control group; * $p < 0.05$.

	Chronic neck pain	Control
Number of subjects	17	12
Number of men	9 (53 %)*	11 (92 %)
Age (years)	44.8 (13.1)	45.3 (15.8)
Duration of symptoms (months)	31.8 (17.5)	-

Study III and IV

Participants without chronic neck pain. Twenty-six healthy men (n=12) and women (n=14) participated in the studies. In study III, all participants were included. A subset of these participants (n=12, seven men and five women) were tested for additional examination of neck strength, movement amplitude and reliability of the kinematic outcome variables (see procedures). These participants did not differ for any descriptive variables from that of the other subjects. In study IV, 15 (six men and nine women) of the 26 participants without neck pain were individually matched to the participants of the chronic WAD group for sex and age (± 5 years) to serve as a control group for the chronic WAD group. See tables 4 and 5 for details about the participants.

Table 4. Descriptive data for all participants (n=26) and subgroup (n=12) and for the men and women in study III. Results are mean (SD), except current smoking status (yes/no). Statistically significant different from the men; *** $p < 0.0005$; ** $p < 0.01$.

	All participants			Subgroup		
Variable	All (n=26)	Women (n=14)	Men (n=12)	All (n=12)	Women (n=5)	Men (n=7)
Age (yrs)	36.1 (8.4)	35.7 (8.6)	36.5 (8.5)	33.1 (6.6)	33.4 (8.6)	32.9 (5.6)
Height (cm)	173.8 (8.3)	169.0 (4.8)**	179.5 (8.1)	175.9 (10.1)	169.1 (4.6)	180.7 (10.4)
Weight (kg)	75.0 (12.9)	68.9 (9.9)**	82.2 (12.7)	76.3 (14.1)	66.2 (4.3)	83.5 (14.4)
BMI (kg/m^2)	24.7 (2.9)	24.1 (3.1)	25.4 (2.7)	24.5 (2.7)	23.2 (1.8)	25.5 (2.9)
Head mass (kg)	4.46 (0.31)	4.26 (0.23)***	4.69 (0.22)	4.42 (0.35)	4.12 (0.26)	4.63 (0.24)
Smoking (y/n)	1/25			0/12		

Abbreviations; BMI – body mass index, y/n – yes/no.

Participants with chronic neck pain after WAD. Fifteen patients (six men and nine women) suffering from long term neck pain (> 6 months) after motor vehicle accidents and classified

as whiplash associated disorders (WAD), grade 2 according to the Quebec Task Force classification[16]. All patients were recruited from a local rehabilitation clinic and examined by a specialist in physical medicine or neurology and a manual therapist before inclusion.

The following exclusion criteria were used for both the control and the chronic WAD participant groups; WAD grade 3-4, pregnancy, age ≤ 18 or ≥ 60 years, unsettled insurance claims, systemic inflammatory diseases, neurological disorders, tremor, regular usage of analgesics and strongly reduced vision/blindness or auditory defects. Descriptive data of the participant groups in the two studies are given in table 4 and 5.

Table 5. Descriptive data for the chronic WAD (n=15) and control (n=15) groups in study IV. Results are mean (SD). Absolute numbers are given for sex and smoking status. For the duration of symptoms the results are median (interquartile range). Statistically significant different from the control group; *** $p < 0.0005$; * $p < 0.05$. Statistically significant different from the pre-value within group; # $p < 0.0005$.

Variable	Chronic WAD	Control
Women/men	9/6	9/6
Smoking (y/n)	3/12	1/14
Age (yrs)	40.1 (8.7)	38.7 (8.8)
Height (cm)	170.5 (8.5)	173.2 (7.6)
Weight (kg)	78.3 (13.0)	75.8 (13.9)
BMI (kg/m^2)	26.9 (4.2)	25.1 (3.2)
Head mass (kg)	4.33 (0.34)	4.53 (0.30)
Grip strength (kg), dom. hand	45.3 (11.4)	50.1 (12.6)
non-dom. hand	41.8 (11.8)	47.3 (12.1)
SF-36, PCS (0-100)	33.4 (9.7)***	54.4 (5.0) (n=14)
MCS (0-100)	45.3 (15.0)*	55.2 (4.8) (n=14)
Duration of symptoms (mo.)	22 (98)	-
Pain intensity (1-10), pre	3.1 (1.4)	-
post	5.6 (2.0)#	-
NDI (0-50)	21.7 (5.6)	-
FABQ, W (0-42)	22.3 (10.2)	-
PA (0-24)	10.5 (4.5)	-

Abbreviations; y/n – yes/no, BMI – body mass index, dom. – dominant, SF-36 – short form-36, PCS – physical component summary, MCS – mental component summary, mo. – months, NDI – neck disability index, FABQ – fear avoidance beliefs questionnaire, W – work, PA – physical activity.

Muscle morphology (study I and II)

Muscles and muscle sampling

Muscle samples were taken from the neck muscles sternocleidomastoid (SCM), scalenus medius and splenius capitis muscle at autopsy. As reference muscles for fiber type proportion and cross-sectional area, samples were taken from the shoulder-girdle muscle trapezius and leg muscle vastus lateralis. The samples were dissected free from fat and connective tissue and superficial blood was removed. The samples were then snap-frozen in melting Isopentane cooled by liquid nitrogen and subsequently stored in a cryofreezer (-80°C) until further preparations. The muscle samples were oriented and mounted on metal discs using an embedding medium (Tissue-Tek O.C.T. Compund) and serial cross-sections of 10 μm were cut in a cryostat (HM 560M, Microm International), put on glass microscope slides and air dried at room temperature.

Fiber type proportions

Muscle fiber types were visualized by immunofluorescence using specific primary antibodies against different myosin heavy chains; BA-D5 (type 1 MyHC), SC-71 (Type 2A MyHC), BF-35 (all non-2X MyHC[35]) and 6H1 (Type 2X MyHC[221]) and anti-laminin (L-9393, SIGMA) was used to stain the basement membrane. The sections were incubated using an overnight protocol at 4°C and washed. FITC- or TRITC-conjugated secondary antibodies were applied to the sections and incubated for 60 min at 37°C in a humid chamber. After washing, the muscle cross-section samples were then placed in a microscope, illuminated by a mercury lamp through appropriate filters and photographed using a SIT camera. A mean of 880 ± 161 (SD) cells from 2 – 4 separate areas per muscle sample were analyzed for muscle fiber proportions. The fiber identities of these cells were determined on basis of the 5 MyHC staining patterns using the following criteria; cells that stained positively for BA-D5 and BF-35, but not SC-71 nor 6H1 were type 1 fibers. Cells that stained positively for SC-71 and BF-35, but neither BA-D5 nor 6H1 were type 2A fibers. Cells that stained for 6H1, but not BF-35, BA-D5 nor SC-71 were classified as type 2X-fibers. A muscle cell that stained for BA-D5, SC-71 and BF-35 either strongly or weakly and that did not stain for 6H1 was classified as hybrid 1/2A-fibers. Cells that stained SC-71, 6H1 and BF-35 strongly or weakly, but not BA-D5 was classified as hybrid 2A/X-fibers**.** See figure 2 for illustrations. In all, more than 52000 cells were classified in this study.

Muscle fiber cross-sectional area and mean cell area

The cross-sectional area (CSA) was measured by manually tracing the inner laminin border of the cells using ImageJ processing and analysis software. On average, the CSA of 100 ± 2 type 1, 95 ± 13 type 2A and 89 ± 16 type 2A/X cells were measured for each sample. Altogether, over 17000 muscle cells were analyzed for CSA. In addition to the data given for each fiber type in study I, the mean cell CSA for a given muscle was calculated. This was completed by calculating the weighted mean area based on the uneven proportions of the different fiber types. The few type 1/2A fibers were split in two and each halves were added to the type 1 and type 2A fibers. All type 2X-fibers were added to the type 2A/X fibers. The weighted mean fiber area was then calculated as follows: ((% type 1 fibers * type 1 CSA) + (% type 2A fibers* type 2A CSA) + (% type 2A/X fibers* Type 2A/X CSA))/100.

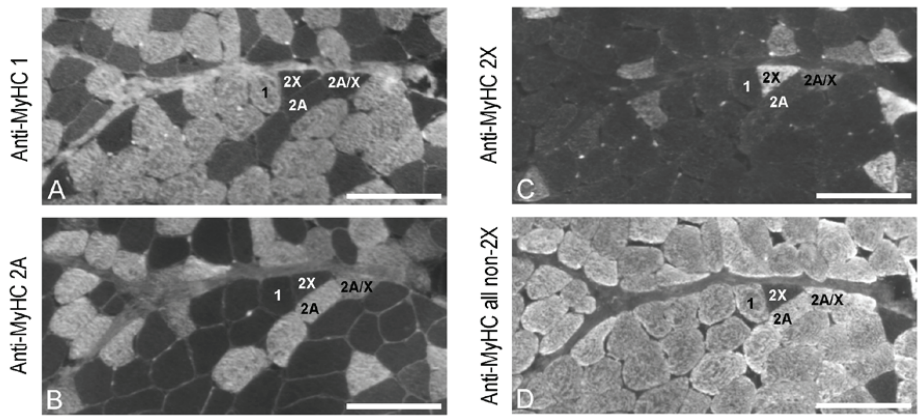

Figure 2. Serial cross-sections from the trapezius muscle from one subject (A-D). Sections were stained using immunofluorescence with antibodies (A) BA-D5 (MyHC 1), (B) SC-71 (MyHC 2A), (C) 6H1 (MyHC 2X) and (D) BF-35 (All non-2X MyHC). 1, type 1 fibers; 2A, type 2A fibers; 2A/X, type 2A/X fibers; 2X, type 2X fibers. Scale bars = 200μm. Taken from Vikne et al.[222] and reprinted with permission from John Wiley and Sons.

Reanalysis of previously published data (study I and II)

Study I. To examine the existence on an intermuscular relationship in fiber type proportion further three previously published studies were reanalyzed[69,121,220], containing the individual fiber type proportions in several skeletal muscles of the same subject. In the study of Weber et al.[121] , the fiber type proportions in two neck muscles (the SCM and omohyoid) in each of 21 (11 male) individuals were reported. The participants (52.0 ± 14.4 years of age)

all suffered from chronic neck pain (26.7 ± 16.3 months of duration) due to different etiologies (10 post-traumatic, nine degenerative and two rheumatoid). All muscle samples were taken at operation for cervical fusion. One subject (no. 22) omitted in study II (see later) was not excluded in study I since the incomplete set of data for this subject was not detected at the time. However, neither the results of this data set nor the final conclusion of study I was affected by this error. Garrett et al.[220] published the fiber type proportion in samples of nine hip and thigh muscles taken at autopsy of seven men and three women of 60 years of age (range; 37 – 76). Causes of death were myocardial infarction, lymphoma or cerebrovascular accident. The third set of data comes from an autopsy study of Johnson et al.[69] consisting of samples of 36 muscles of six presumably healthy young men (age 21.8 ± 5.7 years, weight 78.5 ± 12 kg, height 186 ± 6 cm) who had died suddenly. An overview of participants and sampled muscles of the different sets of data are given in table 2 and appendix 1.

Study II. The individual fiber type proportions of the SCM muscle in subjects with chronic neck pain were taken from the previously published dataset of Weber et al.[121] as also used in study I. As this data set should be compared with own gathered data, subjects older than 65 years of age and subjects with rheumatic disease (n = 6) were excluded to harmonize the criteria used for inclusion. One subject from the study of Weber et al.[121] was omitted (no. 22) because the summed fiber type proportion reported did not add up to 100 %. The CNP group finally consisted of 17 participants (8 women and 9 men), 44.8 ± 13.1 years of age and had suffered from neck pain of post-traumatic (n = 11) or degenerative (n = 6) etiology for a mean of 31.8 ± 17.5 months. Eight of the included subjects were reported to experience radicular pain. The six excluded subjects did not differ statistically significantly from the 17 included subjects for any fiber type proportion (all p values > 0.27). See table 3 for subject group characteristics.

Data handling

All three previously published studies stained the muscle sections using myofibrillar ATPase protocols (Guth and Samaha[223] and Brooke and Kaiser[224]) and classified between 200 – 1000 cells for estimation of fiber type proportions. Weber et al.[121] classified four fiber types (type 1, 2C (1/2A), 2A and 2B (2X), while the studies of Garrett et al.[220] and Johnson et al.[69] reported two fiber types (1 and 2). For some muscles, Garrett et al.[220] and Johnson et al.[69] reported the fiber type proportion of several samples sites within the same muscle. For those

muscles the mean values were used in the analysis. The classifications of type 1 muscle fibers are coherent between myofibrillar ATPase protocols and immuohistochemical methods, but the classifications of the type 2 subgroups are less consistent[225-227]. Therefore only the type 1 proportions of the muscles in the different studies were used for examination of an intermuscular relationship in study I. In study II the type 2 subgroups were collapsed and the proportions of type 1, type 1/2A and type 2 fibers were compared between subject groups.

Head and neck movement performance (study III and IV)

Anthropometrics

The participants' body height (cm) and weight (kg) was measured and the body mass index (BMI (kg/m^2)) calculated. Head volume was calculated based upon anthropometrics and regression equations for men and women as described by McConville et al.[100] and Young et al.[101], respectively and a density of 1.05 kg/l[228] was used for estimation of the head mass.

Grip strength and self-reported questionnaires (study IV)

Hand grip strength was tested as a measure of overall strength on a hand dynamometer (Model 78010, Lafayette Instruments) adjusted individually. A numerical rating scale (1 - 10) was used to assess subjective pain intensity before and after performance testing and the neck disability index (NDI)[229] was used as a measure of physical disability due to neck pain. Fear of movement and of movement-related pain in general was measured using the fear avoidance beliefs questionnaire (FABQ)[230]. Health-related quality of life (HRQOL) was assessed by the SF-36, version 1[231] questionnaire's mental and physical component summary measures (MCS and PCS) calculated using Norwegian normative values[232]. Hand grip strength and SF-36 was assessed for both participant groups, while only the chronic WAD group was assessed for pain, NDI and FABQ. See table 3 for group scores on grip strength and self-reported questionnaires.

Test procedures

The participants completed one separate training session to familiarize to the testing procedures 1 – 2 weeks prior to the measurements. The participant sat on an adjustable seat with a right angled back support that was individually height-adjusted. The participants were secured tightly to the chair by Velcro bands applied transversely around the arms and upper

torso, as well as across the hips. In sitting the participants were instructed to position their head in a comfortable resting position when looking straight forward at the wall approximately 120 cm in front of the participants. This was defined as the individual neutral head position (NP) At the participant`s individual focus point on the wall, a 15mm diameter dark blue dot was applied as reference for the NP. The participants were allowed to practice all movement test conditions before the test started. The participants completed 3 trials for each test condition and these were averaged for further analysis. All trials were accepted, except if the participants expressed that the movements deviated from what they had intended to do, then retrials were performed. In study III, a subset of 12 participants were retested two hours later using identical procedures as during the first test for assessment of test-retest reliability. The test-retest data are reported in detail in paper III. An overview of the performance tests and variables examined in the studies are given in table 6.

Head movement test conditions

Head movement directions and amplitudes. With the eyes open, all participants in studies III and IV completed four head and neck movements in the sagittal plane corresponding to approximately half of their full range of motion and these were defined as small amplitude movements (figure 3); extension from NP (EFN), flexion back to NP (FBN), flexion from NP (FFN) and extension back to NP (EBN). The movements started from the NP and stopped at the fully flexed or extended position (FFN and EFN) or started at the fully flexed or extended position and stopped at the NP (EBN and FBN). The order in which the direction of movements were performed was randomized for each participant. In study III, a subset of 12 participants (7 men, 5 women) completed two full ranges of movements (100 %) in the sagittal plane. These movements were defined as large amplitude movements: full extension in the posterior direction starting from a fully flexed position (EF) and full flexion in the anterior direction starting from a fully extended position (FF).

Movement speeds. The participants were tested at three different speed conditions for all movement directions and amplitudes. First, the participants were instructed to complete all the movements in a pace corresponding to what they perceived as their normal speed and was termed preferred speed (P), then with half of their preferred speed, termed slow speed (S) and finally with their maximum speed (M). To put as little constrains on the movements as possible, the participants were not given any feedback on their performance during testing.

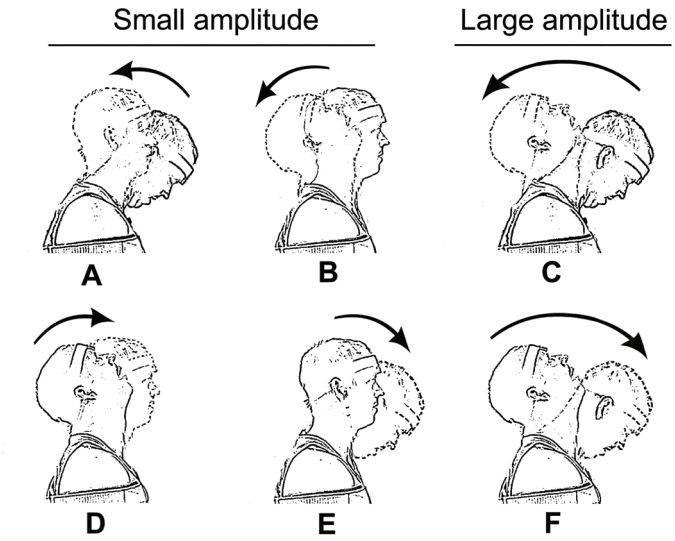

Figure 3. The movement directions of study III and IV; A) extension to neutral position (EBN), B) extension from neutral position (EFN), C) full extension in the posterior direction starting from a fully flexed position (EF), D) flexion to neutral position (FBN), E) flexion from neutral position (FFN), F) full flexion in the anterior direction starting from a fully extended position (FF). A, B, D and E; small amplitude movements. C and F; large amplitude movements. Profiles in solid lines indicate the starting positions and broken lines the end positions.

Movement loading (study IV). The subjects in study IV completed in addition the small amplitude movements with supplementary loading corresponding to 25 % of the head mass at their preferred speed only (PL). Modified pilot helmets (HGU-55/P, Gentex) were worn as base for the supplementary head loading. Load plates, manufactured from polytetrafluoroethylene (PTFE), were put on PTFE -bars attached to the helmet on an axis parallel to the frontal plane passing approximately through the combined center of gravity of head and helmet. The center of gravity were calculated separately for the helmet and for 11 subjects according to the procedures of McConville et al.[100] and Young et al.[101], and projected to calibrated 2D profile images using ImageJ. The weighed combined center of gravity of the helmet and head was calculated and marked on the 2D images of the helmet. At this point on each side of the helmet, a PTFE bar was then attached. The chronic WAD group received an extra total load of a mean of 1.08 ± 0.1 kg (24.9 ± 0.9 % of head mass). The corresponding value for the control group was 1.14 ± 0.08 kg (25.1 ± 1.2 %).

Kinematics

Sensor placements and determination of instantaneous axis of rotation C7. Position data was sampled using an electromagnetic motion tracker (Liberty, Polhemus Inc.). Three sensors were placed on the head-neck in the following configuration: A sternum sensor was placed 15mm caudally to incisura jugularis (p1), a second sensor was placed above proc. spinosus C7 (p2) and the third sensor (p3) was placed 5mm above the arcus superciliaris (figure 4A). A fourth virtual point (p4) was created at the instantaneous axis of rotation C7 (IARC7, see procedures below). The head orientation angle was calculated as the angle between the horizontal line and the vector from p4 to p3. Determination of the IARC7 (p4) was done using lateral radiograph images (DigitalDiagnost, Philips) taken from a separate population consisting of 31 (14 women) healthy participants without neck complaints in the standing position. The IARC7 (p4) was estimated according to the procedures of Amevo et al.[233] and the relative position of the p4 to that of p1 and p2 was found using two dummy metal sensors placed on p1 and p2 as described above. The distances p1 – point of interception and the distance p4 (IARC7) – point of interception were normalized to the length of p1 – p2 (57.2 ± 2.9 % and 19.8 ± 4.5 %, respectively) and these mean relative measures were subsequently applied in the establishment of the individual p4 (IARC7, figure 4B). The position of p4 was fixed relative to that of the p1, consequently; any positional changes for the p1 (sternum) would be similarly reflected in p4.

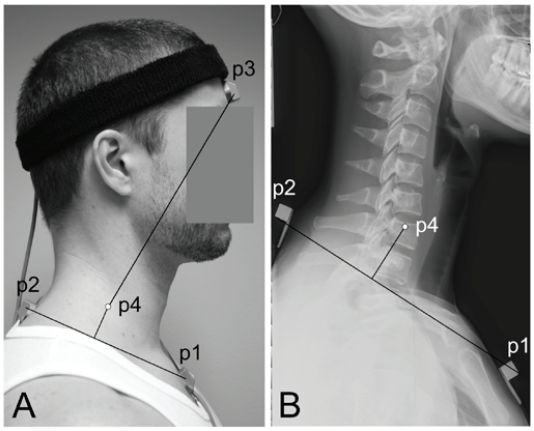

Figure 4 A. The configuration of the three position sensors (p1, p2 and p3) and the fourth virtual point (p4) at the instantaneous axis of rotation C7 and used for determination of head-neck movement from it centre of rotation. B. Lateral radiograph illustrating the method for construction of the virtual point (p4) relative to the p1 and p2 sensors. Taken from Vikne et al.[234]. Reprinted with permission from Elsevier.

Data sampling and analysis. Position data were sampled at 240Hz for each channel and analyzed off-line in MatLab. The signals were filtered using a quintic Woltring spline with a cutoff frequency of 6 Hz, chosen subsequent to a residual analysis[235]. The quintic spline additionally defines the higher order derivatives (velocity, acceleration and jerk).
Movement onset and offset were set to 4 % of the peak angular velocity. If the signal fluctuated across this 4 % threshold, the final crossing was used for the offset. Movement duration and displacement were respectively the time and angular position difference between the movement onset and offset. Movement patterns and strategies used to accomplish the movements were assessed by several outcome measures. The overall smoothness of the movement was calculated as the normalized jerk cost (NJC) according to Teulings et al.[161]. To examine the regularity of the movement, the number of submovements within trials was counted and defined as the period between two subsequent zero-crossings of the acceleration signal in direction from negative to positive values[236]. In study IV the symmetry of movement was calculated separately for movements consisting of one submovement and for movements consisting of more than one submovement. For movements consisting of one submovement, the velocity profile symmetry index[237], taken as the time to peak velocity divided by total movement time was calculated. Values less or above 0.5 indicate asymmetry in the velocity profile. For movements consisting of more than one submovement, the spatial occurrence of the submovements was calculated as the relative number of submovements started in each of the two movement amplitude halves.

Electromyography (study IV)

Muscles and sensor placement. To gain understanding of neck movements it is desirable to record the activity of most muscles generating force across the cervical column. Based on anatomical pilot studies by muscle dissection of 12 autopsy cases, MRI and ultrasound imaging it was concluded that only three muscles were relatively accessible for standard surface electromyography recordings; the SCM, splenius capitis and trapezius muscle. Possible use of intramuscular wire EMG recordings in two additional muscles, the semispinalis capitis and cervicis was also explored in pilot studies. Due to development of pain and/or stiffness during movement in the healthy participants and the observation of drifting of electrodes out of the muscles this sampling method was abandoned. Surface electromyographic signals were therefore sampled bilaterally from three pairs of muscles; the sternocleidomastoid (SCM), a cervical flexor and rotator[111] and the splenius capitis, a cervical

extensor and rotator[238] and the shoulder girdle muscle trapezius[103]. In accordance with previous studies using isometric contractions[34,239,240] very low EMG activity was found for this muscle in both subject groups and the data are therefore not reported. The signals were detected and pre-amplified 10x using single differential active surface sensors consisting of two parallel 10 x 1 mm silver electrode bars and 10mm interelectrode distance (DE-2.1, Delsys Inc.). The sensors bars were placed and oriented at a right angle of the muscle fascicles using a combination of previously published suggestions[241] and ultrasound imaging (figure 5) using a 10MHz, 5cm linear array probe (Vingmed, General Electrics). At the sensor locations the skin was shaved, rubbed and washed with 70 % isopropyl alcohol. A 50 mm diameter ground electrode was placed over the left olecranon. In the following the SCM will be referred to as agonist during flexion movements and antagonist during extension movements.

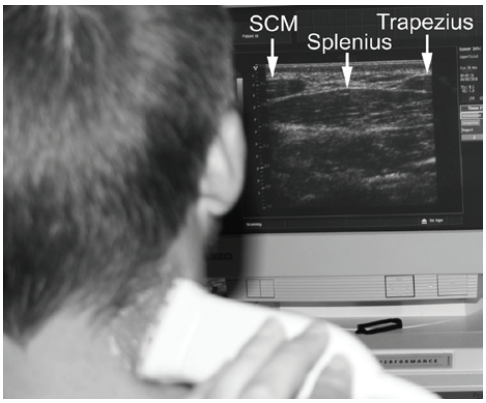

Figure 5. The picture is illustrating the ultrasound (US) localization of the splenius capitis muscle of one subject and examination of the accessibility for EMG sensor placement relative to the SCM and trapezius muscles. The picture show the 50mm linear array US probe in the foreground placed over the SCM-splenius-trapezius complex and the screen image displays the resultant US image.

Data sampling and analysis. The pre-amplified signals were passed to a main amplifier (Bagnoli-16, Delsys), amplified 1000x, band-pass filtered between 20 - 450 Hz with a built-in analog filter, AD-converted (NI-DAQ 6220, National Instruments) and sampled at 1 kHz. After sampling, the raw EMG signals then were offset-adjusted and the running root mean squares (rms) were calculated in window lengths of 50ms with 49ms window overlap using an EMG software package (EMGworks 3.7). Baseline rmsEMG recorded in sitting with the head in the neutral position were subtracted from reference and movement rmsEMG

signals. The signal obtained during movement was normalized to reference EMG and separated in two epochs; one beginning at the start of movement as defined above for the position data and ending at the time point of peak velocity, and one epoch starting at peak velocity and ending at the stop of movement. For both epochs the mean EMG amplitude was calculated. The signals of bilateral muscle pairs were then averaged for further analysis. Due to very low EMG activity during the S and P speed conditions for the gravity-assisted movements (EBN and FFN), the EMG was analyzed for the movements completed against gravity, i.e. the flexion and extension back to neutral position (FBN and EBN).

EMG normalization procedures. For the SCM muscle, the participants sat with back and head support adjusted to 45° to the vertical plane. Participants lifted and held the head slightly off the head support. For the splenius muscles, participants lay horizontally and on the side on a bench with head support that were adjusted to align the cervical- and thoracic column in all three planes. The participants then lifted and held the head slightly off the head support in the vertical direction. The participants did three isometric contractions for each test. Each contraction lasted about 10 s and the first and last 2 s epochs were removed from analysis. The median running rmsEMG signal (100ms window/99ms overlap) was calculated for each muscle and the median value of the three trials was used as reference signal.

Maximum voluntary neck contractions (study III)

In the subset of 12 subjects in study III, the maximum voluntary contractions (MVC) were measured in the flexion and extension direction of the head as measure test of neck muscle strength. These data were not reported in paper III. All force measurements were completed in the test chair with the head and neck in the neutral position. The force was measured using a custom made apparatus consisting of a telescope arm with a load cell (U4000, Maywood Instruments) attached at one end and a Styrofoam-padded plate on the other end. The load cell was calibrated in the vertical position using standard loads. The output of the load cell was linear trough the range of 0-502.1 N (R^2=0.999993). The telescope arm was positioned at a horizontal position and was gravity corrected for the change in positioning. The padded endplate was positioned so that the axis of the telescope arm was in line with the arcus supersciliaris during the tests of flexion strength and through the protuberantia occipitalis externa during extension tests. The load cell was connected to a main amplifier (Bagnoli-16, Delsys) and the signals were sampled at 1000 Hz. All participants used

a standard warm-up routine, consisting of 3-5 contractions with gradually increasing force. Two to four maximum isometric contractions in the direction of flexion and extension were completed. The peak force was taken as the highest mean force across 200 ms. See table 6 for overview of the performance tests and variables examined in the studies.

Table 6. Overview of performance tests and outcome variables in study III and IV. "§" depict that the test/variable in question was only examined in the subset of subjects (n=12) of study III. "-" depicts either not tested or examined for that study.

Performance tests	**Study III**	**Study IV**
Unloaded small amplitude movements, S, P and M speed	x	x
Unloaded large amplitude movements, S, P and M speed	x§	-
Loaded small amplitude movements, P speed	-	x
Test-retest	x§	-
Isometric neck strength	x§	-
Outcome variables		
Movement duration	x	x
Movement displacement	x	x
Peak velocity	x	x
Mean velocity	x	x
Peak acceleration	x	x
Peak deceleration	x	x
Normalized jerk cost	x	x
Number of submovements	x	x
Velocity profile symmetry	-	x
Spatial occurrence of submovements	-	x
Electromyography amplitude	-	x
Peak neck flexion and extension strength	x §	-

Abbreviations; S – slow speed test, P – preferred speed test, M – maximum speed test.

Statistics

All data are given as mean (SD). P-values less than 0.05 (all tests 2-sided) were considered statistically significant. Statistical analyses were performed using the SPSS 18 and JMP 8.0 or 9.0 statistical packages.

Study I

To examine the effects of subject and muscle on fiber type composition, subject and muscle were entered simultaneously in an analysis of variance model. This implies that the

large variation between muscles with regard to fiber type composition is taken into account when comparing subjects. The same model was used for analysis of muscle fiber CSA and in the reanalysis of the type 1 fiber proportions in the studies of Johnson et al.[69] and Garrett et al.[220], that were composed of 36 and 9 muscles, respectively. Pearson's correlation coefficient was used in the reanalysis of the type 1 fiber proportions in the two muscles reported by Weber et al.[121] and in pairs of muscles in the primary set of data.

Study II

In addition to two sample t-tests, the data were analyzed by a general linear model (GLM) using sex, age and group as factors, thus examining the independent effect of each factor when controlling for the others. The dichotomous data in study II was analyzed using Fischer`s Exact Probability Test.

Study III

To test for differences for the outcome variables between the S, P and M speed conditions within a given movement direction and movement amplitude for all participants pooled, one-way repeated measures ANOVA and Bonferroni post hoc tests were used. Partial correlations were used to explore the relationships between the peak movement velocities at the different small amplitude movement directions, and between each movement direction and the mean of the other directions when controlling for movement displacement. Partial correlations were also used to explore the relationships between peak movement velocity and displacement, when controlling for sex. To test for differences between men and women for the outcome variables, two sample t-tests were used. The effect of possible group differences (men vs. women) in velocity and displacement were taken into consideration by analyzing groups using general linear models (GLM) with covariates in the following analysis; for velocity and acceleration displacement was used as a covariate, and for NJC and submovement both velocity and displacement were used as covariates.

To examine possible relationships between NJC, mean movement angular velocity and movement direction and amplitudes a linear mixed factor model with the participants as random factor was used. Since a scatter plot of the mean angular velocity and NJC displayed a curvilinear relationship, while a log-log plot showed an approximate linear relationship, log-transforms were used in the analyses. Pearson's correlation coefficient was used to examine a

relationship between NJC and the number of submovements across the four small amplitude movements. To test for reliability of our main outcome variables, the intraclass correlation coefficient (ICC) model 1,1[242] and the relative coefficient of variation (CV) was used. CV was calculated as the within-subject standard deviation divided by the pooled mean across tests and multiplied by 100.

Study IV

To test for differences between groups for the background data, kinematic outcome variables and rmsEMG, two sample t-tests were used, if appropriate after log-transformation to obtain approximately normally distributed data. All rmsEMG data were log-transformed. Within-group differences between speed test conditions (S, P and M) within a given movement direction were examined using one-way ANOVA for repeated measures and Bonferroni post hoc tests.

Possible effects of velocity and displacement on the NJC, number of submovements and rmsEMG were taken into consideration by comparing groups using general linear models (GLM) with velocity and displacements as covariates. Since peak movement velocity is strongly related to the displacement of movement[12], the groups were additionally compared for peak velocity and acceleration at the M speed conditions using displacement as a covariate. To test for differences between groups in the spatial distribution of submovements and of the velocity profile symmetry index a mixed factor GLM with participants as random factor was used. Bivariate correlations were performed using Pearson's correlation coefficient.

Main results

The detailed results are reported in study I – IV, while an overview of the main results related to the six aims will be presented here. Additional, non-published data are given in detail for substantiation of aim 1 and 4.

Study I

The fiber type proportions for each muscle are given in figure 6. There was a strong overall effect of muscle on the proportion of type 1 fibers ($p < 0.0001$). In general, the vastus lateralis and SCM muscles were composed of less type 1 fibers than the splenius, trapezius and the scalenus anterior. A similar strong overall effect of muscle on the weighted mean cell area was also found ($p < 0.01$, table 7). The leg muscle vastus lateralis displayed larger weighted mean muscle cell CSA than the shoulder girdle muscle trapezius and all neck muscles. An effect of individuals on the weighed mean area; $p < 0.01$) was also found, thus subjects that displayed large muscle cells in one muscle did also display large muscle cells in other muscles.

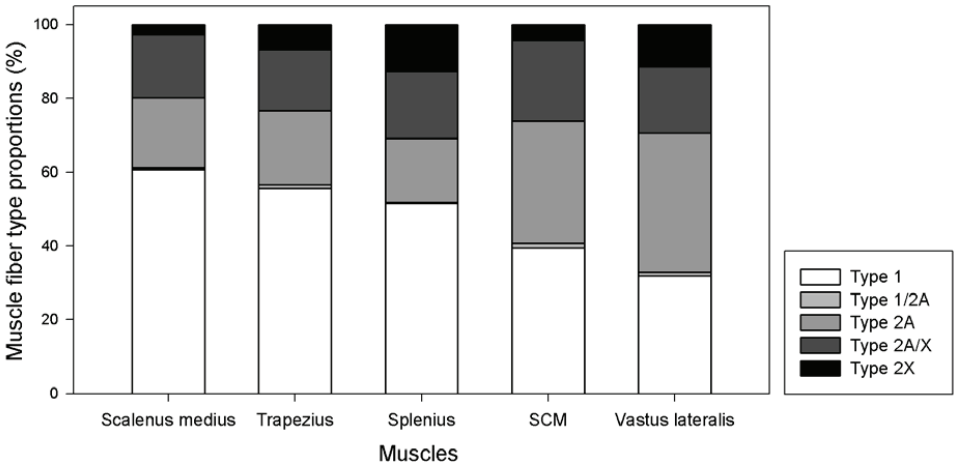

Figure 6. Mean fiber type proportions (%) in the 5 different muscles. The fiber type identity are represented by increasing intensities of gray according to ordering of fiber shortening velocity (type 1 fiber are white, type 2X fiber are black). Muscles are ordered from the highest to the lowest mean proportion of type 1 muscle cells starting from the left. Taken from Vikne et al.[222] and reprinted with permission from John Wiley and Sons.

Table 7. Single fiber and weighed mean fiber CSA (μm^2) of the five different muscles. Results are mean (SD). The significant differences between muscles in mean fiber CSA are given in the text.

	Muscles				
Fiber type	Scalenus medius	Trapezius	Splenius	SCM	Vastus lateralis
Type 1	2275 (694)	3173 (1115)	1971 (546)	2503 (880)	3926 (1188)
Type 2A	1918 (682)	2369 (993)	1845 (706)	2788 (894)	3583 (1065)
Type 2A/X	1821 (661)	2206 (874)	1645 (660)	2397 (821)	2654 (1255)
Weighted mean area	2144 (625)	2799 (976)	1820 (554)	2560 (845)	3515 (1069)

We found an overall significant difference between subjects with respect to the type 1 fiber proportions across muscles for our own data ($p < 0.001$) and in the data of Johnson et al.[69] ($p < 0.0001$; figure 7) and Garrett et al.[220] ($p < 0.001$). Also, the type 1 fiber proportions for the two muscles reported by Weber et al.[121] correlated significantly ($r=0.52$, $p < 0.02$). Thus subjects that express a high proportion of type 1 fibers in one muscle are likely to express a high proportion of type 1 fibers in other muscles as well.

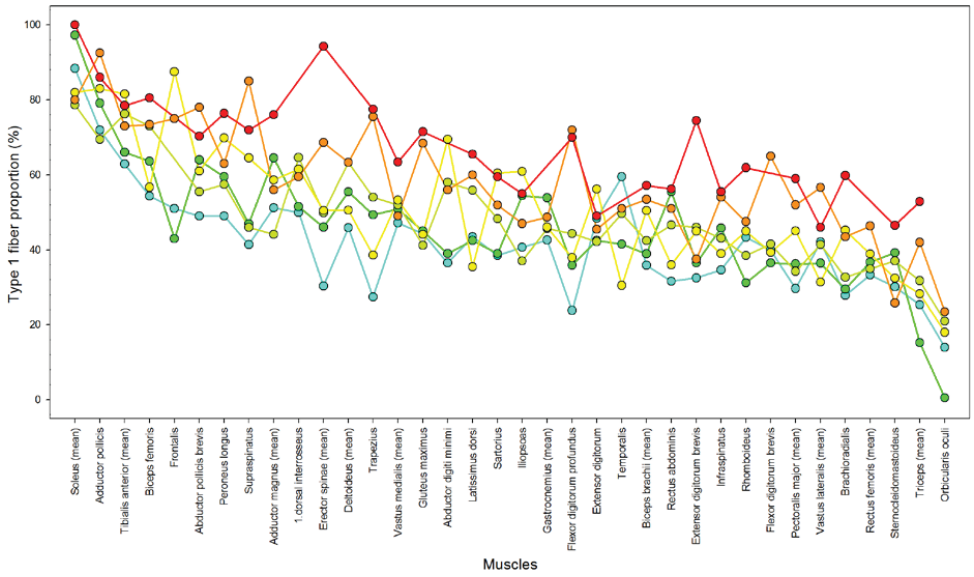

Figure 7. The individual type 1 fiber proportion (%) of 6 subjects in 36 muscles from Johnson et al.[69]. Each subject has a unique color and muscles are ordered according to its mean type 1 fiber proportion starting with the highest proportion from the left. From Vikne et al.[222]. Reprinted with permission from John Wiley and Sons.

Study II

The chronic neck pain and control groups displayed very similar proportions of all fiber types of the SCM muscle with no statistical significant difference between the two groups (all p values > 0.46, figure 8). There was no effect of sex in either fiber type (all p > 0.13).

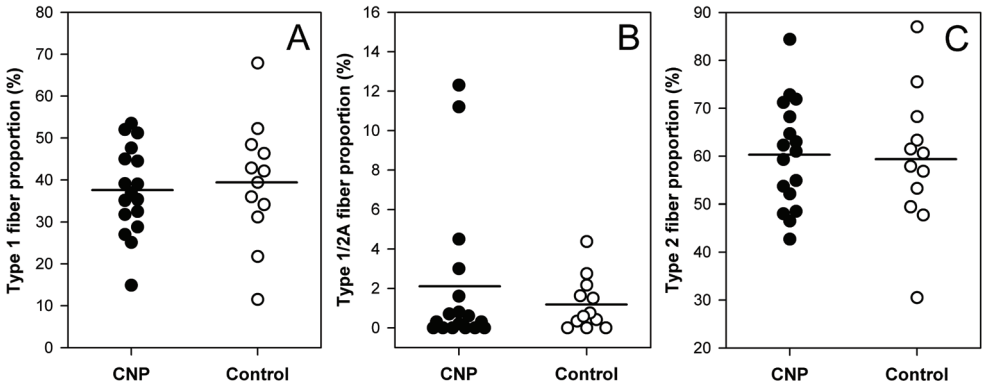

Figure 8. Individual type 1 (A), type 1/2A (B) and type 2 (C) fiber proportions in the CNP group (filled circles, n=17) taken from the study of Weber et al.[121] and control (open circles, n=12) group. Horizontal lines indicate the mean values. Note the differences in scaling of Y-axis.

Study III

The differences in kinematics between the separate speed conditions were relatively similar between the four different small amplitude movement directions. In the following a general description of the variables across all movements will be given and only one direction (FBN) is reported in detail in the tables as an example. The detailed results for all kinematic analysis for all movement directions and amplitudes are given in appendices 2-4. The test-retest reliability of the kinematic parameters is reported in detail in study III.

For men and women pooled, there were large differences between the three speed conditions (S, P and M) for movement time, peak and mean velocity, peak acceleration and deceleration, NJC and number of submovements across all directions and amplitudes (see tables 8 and 9 and appendices 2 – 3 for complete results). Only minor differences in

movement displacement between speed conditions were found. There were strong correlations between peak velocity and displacement for all short movement directions at the M speed condition when controlling for sex (r range 0.68 – 0.83; all p values < 0.0005). There were similarly strong correlations between the peak movement velocities at the M speed test at the different movement directions after controlling for movement displacement (table 10). Thus, individuals displaying a high peak velocity in one movement direction are likely to display a high peak velocity in the other directions as well.

Table 8. Kinematic data for the three speed conditions in the FBN movement for the participants (14 women and 12 men). Results are mean (SD). Statistically significant differences for all subjects from the P speed condition; *** $p < 0.001$; ** $p < 0.01$. Statistically significant difference from the men; §§ $p < 0.01$; § $p < 0.05$.

Group	Test	Duration (s)	Displ. (°)	Peak vel. (°/s)	Mean vel. (°/s)	Peak acc. (°/s/s)	Peak dec. (°/s/s)
All	S	3.62 (1.27)***	62.4 (16.3)	39.1 (18.5)***	20.1 (9.5)***	125.4 (60.4)***	99.9 (50.0)***
Women		3.94 (1.35)	71.6 (14.9)§§	42.7 (20.3)	21.2 (10.0)	137.5 (65.6)	101.5 (45.6)
Men		3.23 (1.11)	51.7 (10.4)	34.8 (15.9)	18.8 (9.1)	111.3 (53.0)	98.1 (56.6)
All	P	1.37(0.48)	60.8 (17.2)	91.6 (26.0)	47.0 (13.4)	392.9 (171.3)	235.5 (92.8)
Women		1.61 (0.46)§§	69.1 (17.6)§§	86.1 (23.3)	44.9 (13.6)	326.8 (110.8)§	198.6 (79.2)§
Men		1.09 (0.32)	51.1 (11.0)	98.1 (28.5)	49.3 (13.4)	470.1 (200.3)	278.5 (91.5)
All	M	0.50 (0.17)***	63.4 (14.3)	265.5 (69.0)***	135.6 (41.0)***	1889.6 (715.1)***	2027.5 (1111.8)***
Women		0.59 (0.18)§§	68.3 (15.6)	245.8 (67.6)	124.0 (42.2)	1640.1 (735.4)	1446.7 (639.4)§§
Men		0.40 (0.09)	57.7 (10.6)	288.8 (65.8)	149.2 (36.5)	2180.7 (592.8)	2705.0 (1181.6)

Abbreviations; Displ. – displacement, Peak vel. – peak velocity, Peak acc. – peak acceleration, Peak dec. – peak deceleration, S – slow movement speed, P – preferred movement speed, M – maximum movement speed.

The women displayed larger displacement across the speed conditions for both the EFN and FBN movement, while the sexes were either similar or the men showed marginally larger displacement for the FFN and EBN movements. The velocities of the P speed test were between 30 – 36 % of that of the M speed test across all movement directions, with no significant group differences. While there were relatively few significant differences between men and women for the EFN and FBN movement, almost all variables differed significantly between the sexes at the M speed condition for the FFN and EBN movement directions (table 8). There were no statistical significant kinematic differences between men and women for the two large movements. The smoothness of movement also differed marginally between the sexes (table 9).

Table 9. Normalized jerk cost (a.u.) and number of submovements for the three speed conditions in the FBN movement for the participants (14 women and 12 men). Results are mean (SD). Statistically significant difference from the P speed test; *** $p < 0.001$; ** $p < 0.01$.

Group	Test	NJC (a.u.)	Submovements (no.)
All	S	413.7 (339.2)***	10.5 (6.0)***
Women		479.7 (401.7)	11.1 (6.1)
Men		336.6 (242.4)	9.9 (6.0)
All	P	45.2 (28.2)	1.6 (0.9)
Women		54.9 (32.9)	1.8 (1.1)
Men		33.8 (16.3)	1.4 (0.6)
All	M	21.4 (8.5)***	1.0 (0.1)**
Women		23.4 (9.0)	1.0 (0.1)
Men		19.1 (7.5)	1.0 (0.1)

Abbreviations; NJC, normalized jerk cost, a.u. – arbitrary units, no. – number, S – slow movement speed, P – preferred movement speed, M – maximum movement speed.

Table 10. Partial correlations between the peak movement velocities at the M speed test at the different movement directions, and between each direction and the mean of the other directions, after controlling for movement displacement (n=26). * $p < 0.0005$.

	EFN	FBN	FFN	EBN
FBN	0.862*	-		
FFN	0.713*	0.707*	-	
EBN	0.761*	0.797*	0.834*	-
Mean other directions	0.839*	0.868*	0.804*	0.867*

Abbreviations; EFN – extension from NP, FBN – flexion back to NP, FFN – flexion from NP, EBN – extension back to NP.

When the displacement was controlled for, the sex difference in peak movement velocity and acceleration between became more prominent for the small amplitude movements. The women displayed between 64 – 89 % of the performance of the men and the differences were either statistically significant or the p-values were between 0.1 and 0.05. There was no systematic difference between the sexes for NJC or number of submovements across the test conditions after controlling for differences in velocity and displacement (table 11).

Table 11. Mean (SD) adjusted kinematic data and measures of smoothness for the three speed conditions in the FBN movement for the men (n=12) and women (n=14). Velocity and acceleration are adjusted for movement displacement. NJC and submovements are adjusted for velocity and displacement. Statistically significant difference from the men; §§§ $p < 0.001$; §§ $p < 0.01$. P values between 0.1 and 0.05 are given; ^.

Group	Test	Peak vel. (°/s)	Mean vel. (°/s)	Peak acc. (°/s/s)	NJC (a.u.)	Submovements (no.)
Women	S	33.7 (15.3)^	16.8 (8.4)^	114.2 (58.4)	459.5 (238.6)	10.1 (3.2)
Men		45.4 (15.6)	23.9 (8.6)	138.5 (59.5)	360.1 (244.3)	10.9 (3.3)
Women	P	78.4 (24.1)§§	40.3 (11.7)§§	299.1 (166.6)§§	41.4 (21.4)	1.4 (0.8)
Men		107.1 (24.4)	54.7 (11.9)	502.3 (168.7)	49.6 (21.9)	1.8 (0.8)
Women	M	229.4 (51.8)§§§	115.1 (32.8)§§	1512.1 (607.0)§§	20.0 (7.4)	1.0 (0.1)
Men		307.9 (52.1)	159.7 (33.0)	2330.0 (210.5)	23.1 (7.6)	1.0 (0.1)

Abbreviations; Peak vel. – peak velocity, Peak acc. – peak acceleration, NJC – normalized jerk cost, a.u. – arbitrary units, no. – number, S – slow movement speed, P – preferred movement speed, M – maximum movement speed.

There was a large difference between men and women in peak isometric neck strength for both the extension and flexion direction both in an absolute sense and when normalized for stature and by head mass (table 12). Women generated between 50-74 % of the force of the men depending on direction and method of normalization.

Table 12. Maximum isometric neck strength (N) in the neutral position in the direction of extension and flexion (n=12). Results are mean (SD). Statistically significant difference from flexion;*** $p < 0.0005$. Statistically significant difference from the men; §§ $p < 0.01$.

	Absolute strength (N)		Strength/head mass (N/kg)		Strength/stature (N/m)	
	Extension	Flexion	Extension	Flexion	Extension	Flexion
All (n=12)	270.9 (72.1)***	145.1 (57.6)	60.6 (12.3)***	32.1 (10.6)	152.9 (34.3)***	81.4 (29.0)
Women (n=5)	207.8 (35.1)§§	92.4 (28.8)§§	50.3 (6.2)§§	22.2 (5.5)§§	123.0 (21.9)§§	54.7 (17.7)§§
Men (n=7)	316.0 (54.9)	182.7 (39.5)	68.0 (9.9)	39.2 (6.7)	174.2 (23.8)	100.5 (17.6)

While most of the M speed movements and many of the P speed movements were unimodal and relatively bell-shaped in the velocity profile, the S speed movements typically displayed multiple speed peaks (figure 9). In line with this, there was a significant increase in NJC and the number of submovements by reduced speed test across all movements (table 9 and appendix 3).

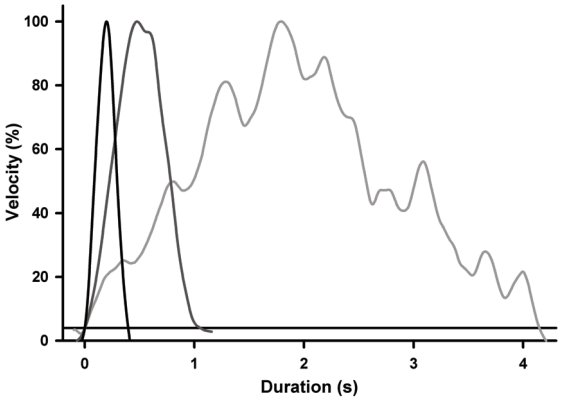

Figure 9. Example of normalized velocity versus absolute time for the three speed conditions (M; black line, P; dark grey line, S; light grey line) from one subject for the flexion from neutral position movement. The subject scored approximately median values for all speed conditions. Solid horizontal line depicts the relative value of peak velocity defining movement onset and offset (4 %).

A strong effect of head and neck angular velocity was found on movement smoothness as assessed by the NJC, independent of movement directions and amplitudes (all $p<0.0001$). Thus the smoothness of movement decreases by reductions in movement velocity. The large amplitude movements display higher NJC values for a given mean angular velocity than the small amplitude movements ($p<0.001$, figure 10A). There was also a small, but statistically significant difference between the four small amplitude movements; the EFN displayed higher NJC for a given angular velocity than the other movements ($p<0.05$).

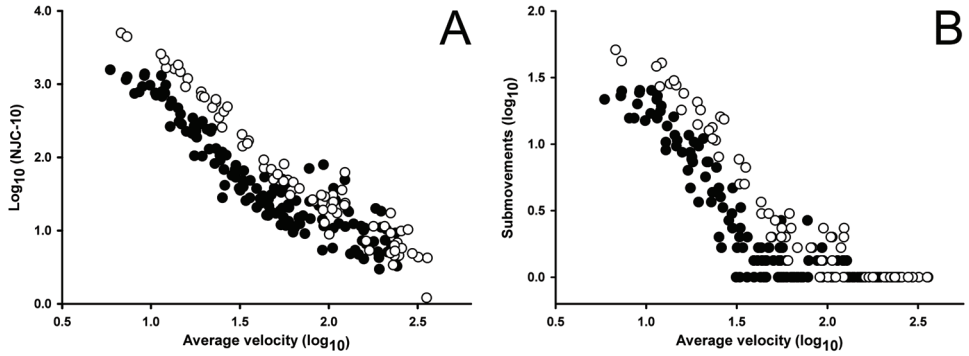

Figure 10. Log-log plots for mean velocity versus A; NJC(-10) and B; number of submovements, for all speed conditions in four small amplitude movements pooled (filled circles, 144 trials) and two large amplitude movements pooled (open circles, 72 trials) in 12 subjects. Taken from Vikne et al.[234]. Reprinted with permission from Elsevier.

Study IV

In general the chronic WAD group displayed numerically reduced movement displacement, peak and mean velocity and peak acceleration and deceleration across all different test conditions. For movement displacement 8 of 12 comparisons were statistically significant (all p-values < 0.05). For the M speed test condition peak and mean velocity and peak acceleration and deceleration were significantly lower in the chronic WAD group as compared with the control group at all movement directions (all p-values < 0.01). The velocities of the P speed condition relative to that of the M speed condition were higher for the chronic WAD group across movement directions (range; 40 – 45 % of the M speed test) than for the control group (range; 30 – 35 %, all p – values < 0.05). The chronic WAD group displayed numerically higher NJC scores and number of submovements than the control group. However, the groups differed significantly only for three test conditions and in another four comparisons the p-values were between 0.05 and 0.1. The relative rmsEMG amplitude of both the agonistic and antagonistic muscles during the acceleratory phase of all movement directions at the M speed condition were significantly decreased for the chronic WAD group as compared with the controls (all p values < 0.01). The results and discussion of the extra loading test conditions is given in paper IV.

As described above, the group differed significantly for displacement and movement velocity and these variables were then included as a covariates in relevant analysis. The statistical significant group differences for velocity and acceleration still persisted for the M speed condition when displacement was used as a covariate. This was seen across all movement directions (all p values < 0.05; table 13). However, for the measures of movement smoothness (NJC and number of submovements), there were no statistical significant differences between groups at any test velocity for any movement direction after controlling for movement velocity and displacement. Figure 11 displays the log-log plot for NJC versus movement velocity, not controlled for displacement. In line with these data no statistical significant difference was found between groups in the spatial distribution of submovements in either of the two movement halves, nor any difference in the velocity profile symmetry for the movements consisting of one submovement only.

Table 13. Adjusted mean data (SD) of the four short movement directions for the chronic WAD group (n=15) and controls (n=15). Statistically significant difference from the controls; * p<0.05; ** p<0.01; *** p<0.001. Only data for the M speed conditions are shown. Peak velocity and acceleration are adjusted for movement displacement while NJC and submovements are adjusted for velocity and displacement.

Movement	Group	Peak vel. (°/s)	Peak acc. (°/s/s)	NJC (a.u)	Submovements (no.)
EFN	Chronic WAD	145.5 (52.0)***	1201.3 (983.0)***	24.8 (17.9)	1.29 (0.53)
	Control	219.5 (52.0)	2563.3 (983.0)	34.4 (17.9)	1.26 (0.53)
FBN	Chronic WAD	174.4 (68.3)*	1071.6 (670.4)*	31.5 (27.3)	1.22 (0.66)
	Control	236.0 (68.3)	1673.2 (670.4)	30.1 (27.3)	1.18 (0.66)
FFN	Chronic WAD	187.3 (55.9)**	1242.1 (670.8)**	19.4 (10.0)	1.03 (0.16)
	Control	248.1 (55.9)	2104.0 (670.8)	23.9 (10.0)	1.09 (0.16)
EBN	Chronic WAD	183.1 (60.0)**	1272.4 (845.0)**	25.0 (9.8)	1.15 (0.34)
	Control	252.4 (60.0)	2429.9 (845.0)	29.7 (9.8)	1.16 (0.34)

Abbreviations; Peak vel. – peak velocity, Peak acc. – peak acceleration, NJC – normalized jerk cost, a.u. – arbitrary units, no. – number, EFN – extension from NP, FBN – flexion back to NP, FFN – flexion from NP, EBN – extension back to NP.

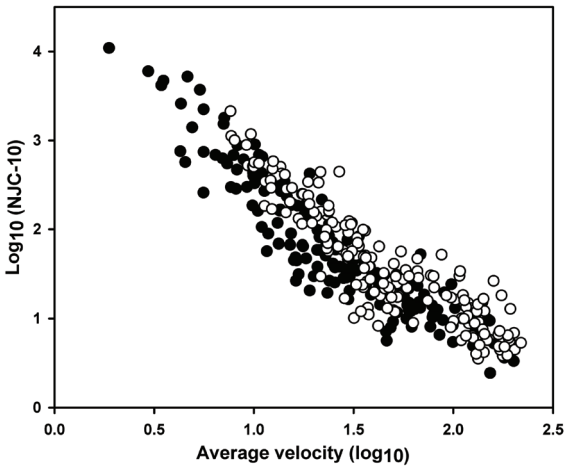

Figure 11. Relationship between average velocity (log_{10}) and NJC(-10) (log_{10}) across all speed conditions for all movement directions pooled for the chronic WAD (filled circles, n = 15, 180 trials) and the control (open circles, n = 15, 180 trials) groups.

When the rmsEMG amplitude was analyzed using both displacement and velocity as covariates, all statistical significant differences between groups in rmsEMG for the agonist and the antagonist muscles disappeared at all speed and loading conditions with one exception (table 14).

Table 14. Adjusted mean (SD) rmsEMG amplitude (%) for the agonist and antagonist muscles of the accelerative and decelerative phases at the FBN and EBN movement directions for the chronic WAD group (n=15) and controls (n=15). Only data for the M speed conditions are shown. Statistically significant difference from the controls; * $p<0.05$. The data are adjusted for movement angular velocity and displacement.

		Accelerative phase		**Decelerative phase**	
Movement	Group	Agonist (%)	Antagonist (%)	Agonist (%)	Antagonist (%)
FBN	Chronic WAD	332.0 (230.4)	94.1 (85.4)	43.1 (100.3)	52.5 (71.0)
	Control	332.4 (230.4)	89.5 (85.4)	43.9 (100.3)	63.1 (71.0)
EBN	Chronic WAD	336.3 (186.7)	21.7 (56.1)*	37.7 (44.3)	34.4 (25.8)
	Control	327.9 (186.7)	56.0 (56.1)	35.4 (44.3)	37.3 (25.8)

Abbreviations; FBN – flexion back to neutral position, EBN – extension back to neural position.

Discussion

The discussion will emphasize two topics, the main findings of the thesis and methodological aspects thereof. In the discussion of the main findings, the movement performance variables for healthy men and women and subjects with chronic neck pain will be discussed based on the M speed condition in particular, and the role of muscle physiology, muscle activation and additional factors influencing performance will be considered. In part two, methodological considerations of the study design, participants, sample size and some specific aspects concerning the EMG measurements will be covered in particular. The detailed discussion of the specific outcome variables and the methodological considerations concerning them has otherwise been presented in the separate papers.

Main findings

Peak head and neck movement performance in healthy subjects

In study III, there was a large interindividual variation in the kinematic variables at the maximum (M) speed condition across all movement directions and amplitudes in all healthy subjects. For example, the movement displacement ranged 2.2 – 3.1 folds across the small amplitude movements, while peak velocity and acceleration ranged between 2.8 – 3.5 and 4.3 – 5.0, respectively. Parts of this relatively large variation in peak velocity are probably explained by the displacement of movement, as indicated by the strong relationship found between these variables and known from previous studies[12]. To further examine factors affecting movement velocity the displacement was taken into consideration by adding this factor as a covariate in the statistical analyses. There was a strong correlation in peak velocity between the different movement directions after controlling for movement displacement, suggesting that some participants were generally faster and some participants generally slower, independent of movement direction and muscles responsible for force production. This result is in line with the finding in study I of a relationship in the fiber type proportion between different muscles in the same individual. This was confirmed in four sets of independent data and across 42 different human muscles. Thus, in practical terms this means that the expression of fiber types in one muscle can be regarded as a marker for a “global”

muscle fiber type proportion and in paper I the "across-muscle phenotype" was suggested as a term of this relationship.

An important question is whether such a relationship is a function of heritage or environment. Data from previous studies indicate that the proportion of the type 1 (to type 2) fibers is very stable in humans with intact upper motoneuron-muscle connections and does not change as a function of long-term changes in environmental stimuli such as increased or decreased physical activity[181,196-204]. Thus under normal, physiological conditions, the type 1 to type 2 stability indicate an influence of heritable factors on this intermuscular relationship. It is known from studies in rodents, that selective breeding for a fast fiber type proportions in a leg muscles, increases the fast fiber proportions in other muscles as well in the following broods[76,243], strongly supporting an heritable effect. This relationship in fiber type proportions between muscles also suggest that on an overall basis some individuals hold a greater capacity for fast velocity contractions and other individuals slower velocity contractions, including neck movements. It therefore seems reasonable that a portion of the variation in peak head movement velocity is explained by individual differences in the across-muscle phenotype. In addition to muscle fiber type, an important contributor to the variation in peak velocity is most likely total neck muscle CSA and thus muscle force. It is predicted by the force-velocity relationship and shown empirically[244,245] that larger and stronger muscle creates higher peak velocity at standard light loads as compared with smaller and weaker muscles. In study I an intermuscular relationship in the fiber CSA was also found, suggesting that individuals displaying large fiber CSA in one neck muscle displayed large fiber CSA also for other neck muscles. This finding can therefore, together with the across-muscle phenotype probably explain to a large degree the strong correlations in peak velocity between different movement directions in study III. However, it cannot be excluded that variation in peak muscle activation during the M speed condition may also have contributed to the diversity in peak movement velocity.

When the kinematics of men and women were compared, the displacement of the small amplitude movements EFN and FBN was significantly greater for women than men, a finding that to some extent is in conflict with normative studies that have reported no difference between groups[138-141]. Two factors suggest that this result is probably a function of different initial head positioning (NP) relative to the thorax. The displacement in the movement directions FFN and EBN was numerically greater for the men, and the large

amplitude movements (between full flexion and full extension) were very similar between men and women. After controlling for differences in movement displacement, women in general displayed less peak acceleration and velocity than the men did (64 – 89 % of that of the men). As a number of normative studies have found no systematic difference in fiber type proportions between men and women in either extremity[70,71] or spinal muscles[72,73] it seems improbable that muscle fiber type proportions could explain the differences in peak acceleration and velocity. Neither seem there to be any differences in the specific force capacity of the muscle fibers between men and women[50], nor whole muscle specific strength[55,64], thus collectively these finding indicates both similar intrinsic muscle quality and degree of muscle activation capacity between men and women. However, the peak isometric neck force in the extension and flexion direction of the women was 50 – 66 % of that of the men. This is in agreement with previous studies measuring peak neck force[131-137] and in neck muscle CSA[107-110] in men and women. It is therefore likely that it is the difference between men and women in absolute muscle CSA and thus force generation capacity that explains the differences in peak velocity and acceleration. However for the variation in peak acceleration and velocity within the sexes, both individual variations in the across-muscle phenotype and muscle CSA are both likely have strong modulating effects. It can neither be excluded that differences in voluntary muscle activation may also affect the within-group diversity in acceleration and velocity. The women also displayed lower preferred movement speed than the men did after adjusting for displacement. However, the velocity at the preferred speed test was about 30-36 % of that of the maximum speed test across all movement directions and with no significant differences between men and women. The preferred velocity therefore seems to be scaled to that of the maximum speed.

Peak head and neck movement performance in subjects with chronic WAD

To control for the confounding effects of sex on neck movement kinematics, the participants with and without chronic WAD in study IV were subsequently matched for sex but also age before comparing the neck movement performance. Overall, the chronic WAD group displayed reduced movement performance as compared with the healthy controls. When compared in an absolute sense, that is not considering other factors, the movements were shorter, slower and more irregular. The displacement for all four different movement directions ranged 69 – 84 % of the displacement compared to that of the control participants and are in close agreement with previous studies in persons with chronic WAD[3,14,22,149-152].

The peak velocity and acceleration for the majority of test conditions were also reduced in the chronic WAD group. For the M speed condition the peak velocity and acceleration were respectively 49 – 64 % (range) and 36 – 53 % of the control group which are very similar to what have been reported previously[3,4,150]. The preferred movement velocity (P speed test) was also lowered, ranging 59 – 92 % of that the controls, which are in conformation of the results of Baydal-Bertomeu et al.[149]. It also seems that the chronic WAD subjects in general use a relatively larger proportion of their peak movement velocity for their preferred movement speed than the controls. For the movement conditions that differed significantly in peak acceleration and velocity between the groups, accompanying statistically significant lower mean EMG amplitudes were found for the acceleratory and deceleratory phases of movement in the chronic WAD group, signifying reduced neural drive.

Many of the kinematic variables and EMG amplitude are highly interdependent as shown previously[12,13] and in study III. Since the chronic WAD group and controls differed significantly for movement displacement, the performance at the M speed condition was compared by taking this factor into consideration by adding this factor as a covariate in the statistical analyses. The group differences persisted after these analyses although to a reduced extent; the chronic WAD group displayed 66 – 75 % of the peak velocity and 47 – 64 % of the peak acceleration as compared to that of the control participants. This finding is in contrast to the study of Sjölander et al.[5] that found no group differences in peak head rotation velocity between chronic WAD and control participants after adjusting for displacement. Such discrepancy between studies may be related both to the movement directions used and to the reduced number of observations and statistical test power in the study of Sjölander et al.[5] as compared to the present study. Another explanatory factor may be that the ratio of females to males was elevated in the control group (4.3) as compared with the chronic WAD group (2.5) in the study of Sjölander et al.[5]. As shown in study III, women produce lower peak velocity than men, and this factor may have thus have made the two groups in the Sjölander et al.[5] study more similar for movement speed.

The reductions in intrinsic peak velocity and acceleration in the chronic WAD group may be caused by several factors including muscle morphological and activation patterns. The overall neck muscle CSA does however not seem to be an potential candidate, since the muscle sizes does not appear to be notably altered as a function of chronic WAD CSA[188-191]. Based upon measures of increased mean muscle signal to mean intermuscular fat signal

ratio[191,192], it has been suggested that intramuscular fat content increases due to chronic WAD. Since presently there are no empirical data on whether the fat-free contractile area is affected or on the functional significance of the increased signal ratio, these findings are difficult to interpret in terms of kinematic performance. At the muscle fiber level, the type 1 and 2 fiber proportions of the SCM muscle was not found to be different between controls and subjects with severe, chronic neck pain operated for cervical fusion in study II which suggests that chronic neck pain does not lead to changes in the type 1 to type 2 fiber proportion ratio. Although the SCM is predominant force generator in the flexion direction[111] and therefore of vital importance for movement performance in the FBN and FFN movement directions, it cannot be established whether the result of this study is representative for the other cervical muscles. The conclusion is however, in concert with a number of studies examining the effect of pain on the fiber type proportion in other muscles, such as the trapezius muscle in subjects with chronic trapezius myalgia[114-117] and the lumbar multifidus of subjects with spinal disc herniation[206] or idiopathic chronic low back pain[205]. These data are therefore also consistent with data for healthy subjects finding no fiber type transition between the type 1 to type 2 fibers as a result of changes in physical activity. Together, the data seems to indicate that minimal transitions occur between these two fiber populations in people with intact upper motoneuron-muscle connection. These findings do not exclude a possible fiber type transitions between the type 2 subgroups (2A and 2X) which is known to occur rapid after changes in physical activity patterns[196-201] and which may influence the peak velocity[246]. A previous study in subjects with severe chronic neck pain[112] have however suggested increase in the proportion of the type IIB (X), which are not in concert with the reductions in peak acceleration and velocity in the chronic WAD group. A morphological factor that in theory could affect velocity and acceleration is a reduction in specific force of the individual muscle fibers, leading to an overall reduction in strength per unit muscle mass similar to that seen with immobilization[195] and prolonged bed-rest[194]. However, reductions in specific force of single muscle fibers are usually accompanied by large decreases in fiber and whole muscle CSA[194], which has not been found in subjects with chronic WAD. It therefore seems that persons with chronic WAD have intact muscle morphology and latent muscular capacity of normal force development.

The large group differences in peak movement acceleration and velocity seem to be explained upstream of the muscle level. When the chronic WAD participants were compared

with the controls at the M speed conditions without taking differences in displacement into consideration, significantly lower agonist and antagonist EMG amplitudes were found for the chronic WAD group. This finding seems to be a reasonable explanation for the group difference in both acceleration and velocity. Parallel reductions in EMG amplitude and peak effort performance as compared with controls have also been seen in other groups with chronic pain conditions such as chronic trapezius myalgia[143] and chronic low back pain[247]. It has been suggested that decrease in peak isometric force induced by experimental pain is caused by motoneuron inhibition through group III and IV pain afferents[248,249]. It is possible that the reduced EMG amplitude, peak acceleration and velocity in the chronic WAD group may partly be explained by similar mechanisms. Part of the decrease in EMG amplitude and kinematics may also be mediated by reduced voluntarily exertion due to pain and/or fear of pain. The associations found between the Fear Avoidance Beliefs Questionnaires (FABQ) physical activity component with displacement, velocity, acceleration and EMG amplitude found in study IV are in support of such a hypothesis. Due to the strong relationship of movement displacement with velocity, acceleration and EMG amplitude it seems likely that parts of the associations between the FABQ scores and velocity, acceleration and EMG are mediated through the reductions in displacement. A moderate relationship between fear-avoidance beliefs and displacement has been reported in subjects with acute WAD[250], which suggest that such associations may develop at an initial stage of WAD.

To examine whether the EMG amplitude differed between the groups for a given movement velocity and displacement, the chronic WAD and controls were compared when taking these factors into consideration by adding them as covariates in the statistical analyses. No statistical significant differences in EMG amplitude were subsequently found between the chronic WAD group and the control participants at the different speed and loading conditions. It therefore appears that the chronic WAD group completed the movements with apparently normal activation patterns, adjusted to the desired movement velocity and displacement. As far as I know, the first study to compare the EMG amplitude of neck muscles during dynamic neck movements in chronic WAD, thus more studies are warranted. The findings are however, in contrast to what have been reported for chronic WAD subjects at isometric contractions at standard low to moderate force tasks[11,146]. Jull et al.[11] reported an increased EMG amplitude of the SCM muscles in subjects with chronic WAD during isometric cervical flexions at standard force levels as compared with control subjects. It was later shown in a

combined group of chronic WAD and insidious neck pain that the increased EMG activity in the SCM are paralleled by reductions in activity of the agonistic longus colli and capitis muscles[217], and thereby keeping net isometric flexion force output about constant. Similarly for chronic WAD participants, Schomacher et al.[146] found reduced mean activity of the semispinalis cervicis at isometric 15N and 30N force levels as compared with control participants. To be able to explain the net production of force in that study, a parallel increased activity of other extensor muscles or decreased activity of flexor muscles are necessary. If a similar pattern for neck muscle activation were present for dynamic contractions in the chronic WAD group it should be noticeable as a group difference in EMG amplitude after controlling for velocity and displacement, which however was not found in study IV. Although isometric contractions were not systematically examined as an outcome variable, the EMG sampled during the isometric normalization contractions during head-holding was neither significantly different for any muscle between groups. This result is also in contrast to the studies of Jull et al.[11] and Schomacher et al.[146]. A hypothetical explanation for these differences may be rooted in differences in the experimental set-ups. In study IV the isometric head-holding and the dynamic head movements were subjected to only a minimum of feedback and thus the tasks were relatively easy to accomplish. In the studies of Jull et al.[11] and Schomacher et al.[146] the participants were instructed to match specific force levels visualized to the subjects by displays. It could be that such force matching constrains of the contractions are simply more challenging for participants with chronic WAD to accomplish and induces altered muscle activation patterns.

Movement quality in healthy subjects and in subjects with chronic neck pain

In study III, a strong relationship between the smoothness and the velocity of unconstrained head movement was found across all movement directions and amplitudes examined. Additionally, a modulating effect of movement displacement was found on this relationship. Thus, for voluntary head movement in participants without neck pain, movements become gradually less smooth by reductions in movement velocity and by increases in movement displacement. As illustrated in figure 9 most movements at the M speed test across all test conditions were typically completed smoothly, displaying unimodal and relatively bell-shaped velocity shape profiles. At the S speed condition the velocity profiles were multipeaked and irregular, consisting of multiple submovements. This is in accordance with other studies that have observed irregular velocity profiles in deliberately

prolonged and slow movements of arms and fingers[170-173,251]. After movement velocity and displacement were taken into consideration, there were no systematic difference in smoothness of movement, as assessed by the NJC or number of submovements between men and women for any movement direction or speed condition. The relationship between velocity and displacement with smoothness of movement may be connected to the time used for movement exertion. Milner and Ijaz[170] suggested that movements of long duration are difficult to accomplish using single motor commands and that prolonged movement durations may be approximated by overlapping sequences of submovements of shorter intervals. In support of this hypothesis is the findings of Vallbo and Wessberg[251] who demonstrated that during slow motion of the finger, the submovements correlated with pulsatile gross muscle activation alternating between agonistic and antagonistic activity. Furthermore, in slow finger movements Gross et al.[252] found the velocity changes and pulsatile gross EMG of the hand muscles correlated with pulsatile activity of the motor cortex. These connections between movement kinematics, EMG patterns and motor cortex activity strongly suggest that submovements are of central origin and that slow movements are driven by pulsatile, intermittent motor commands.

For dynamic and relatively unconstrained movements it has been reported that subjects with chronic WAD display jerkier and less smooth head and neck movements as compared with control participants [3-5]. Such altered movement pattern have been ascribed to altered motor control and sensimotor disturbance in the chronic WAD subjects[3,5]. To examine whether differences in movement velocity and displacement could explain reported differences in movement smoothness between healthy participants and chronic WAD[3,4,149,150], head movement smoothness were compared between groups across a large range in movement speeds. When groups were compared without taking movement velocity or displacement into consideration, the chronic WAD group displayed overall reduced smoothness as compared with the control participants which are in concert with previous studies[3-5]. However, when the groups were compared using both movement velocity and displacement as covariates, there were no significant differences between groups. Thus, this study strongly indicates that reduced movement smoothness is not a sequel of chronic WAD or sign of altered motor control in these subjects. The groups were also compared using other measures of movement patterns such as movement symmetry and temporal distribution of submovements and likewise no group differences were found using these variables. Using

four different measures for the quality of movement execution no significant differences between subjects with and without chronic WAD were found when studying relatively unconstrained head movements.

Methodological considerations

Study design

All studies in this thesis were observational in the sense that no treatment or intervention was performed. Study I and III were cross-sectional studies and study II and IV had a case-control design. The main difference between these designs is that the cross-sectional design intends to generate information about a general population, while in case-control study one wants to compare a population with a specific set of characteristics with a control group. To elucidate causal relationships between chronic neck pain after WAD and changes in the various outcome variables, longitudinal studies are needed. However, there are also a series of possible biases related to the comparison between the cases and controls[253] including the selection of study samples. The inclusion criteria of the study participants are of overall importance for the external validity of the study. In other words, is the participants representative for the population intended to generalize the data to? In this thesis, the cross-sectional design seems to be appropriate to elucidate the aims in study I and III, because of the descriptive nature of the aims. In study II and IV the case-control design are suitable to establish whether differences between the groups do exist, but not the causes for the differences.

Study participants

Study I and II. In the primary set of data in these two studies, that is the data sampled by the author and co-workers, the study population was 11 adult men and one woman and the data was sampled at autopsy. To control for possible confounding factors on either the expression of a normal muscle fiber type distribution or the analyzing methods used, a number of exclusion criteria were employed (see paper I and in the methods). To examine for possible sampling biases, muscle biopsies were taken in two well studied muscles, the vastus lateralis and trapezius muscle for comparison with prior published data. The mean type 1 fiber proportion in both the vastus lateralis and the trapezius was within the normal range of what

has previously been reported for these muscles, although somewhat on the faster end range for both muscles[69,70,113,114,254,255]. Additionally there was a large individual variation in the type 1 fiber proportion for each muscle, which is also consistent with previous studies. Thus, it is believed that the people examined in study I are reasonable representative for a normal population. In the three previously published sets of data used to test the hypothesis of an intermuscular relationship in fiber type proportion (aim 2), the populations differed somewhat from that of the primary set of data[69,121,149]. However, since the main hypothesis was to examine muscles within an individual and between individuals within the same set of data and not between separate datasets this was not considered to be a critical factor. On the contrary, despite the differences in sample population in the four different sets of data used, the same conclusion was reached from each dataset; a strong relationship between separate muscle and muscle fiber type proportions in and individual. Thus, the difference in the populations in the different studies may rather strengthen than weaken the conclusion of an intermuscular relationship in fiber type proportion.

In study II, the fiber type proportion of the SCM muscle was compared between subjects with and without chronic neck pain. The data for the controls and subjects with chronic neck pain were taken from study I and the study of Weber et al.[121], respectively. Since the two sets of data differed for a number of factors, the exclusion criteria used for the controls were applied for the subjects with chronic neck pain reported by Weber et al.[121]. Thus, subjects with age above 65 and with rheumatic disease were excluded. The main uncertainty concerning the control group was to establish whether they suffered from chronic neck pain. Although there was no information of neck dysfunction or chronic neck pain in the medical records, this does not exclude the possibility that some of the subjects may had suffered from chronic neck pain. The participants from the original study of Weber et al.[121] consisted of subjects with two etiologies of the chronic neck pain; degenerative (35 %) and post-traumatic (65 %) after excluding subjects suffering from rheumatism. Thus the result of the study was applied for chronic neck pain in general and not chronic WAD. There were no statistical significant differences in fiber type proportions between the two etiologies within the neck pain group. The cases and the control group had similar age, but there was a higher ratio of males to females in the control group. Since a number of normative studies have not found any systematic difference in muscle fiber type proportion between men and women the[70-73], it is likely that the ratio of males to females did not affect the results. The participants

were reported to have severe chronic neck pain that were persistent to conservative treatment and muscle samples were taken at surgical operation for cervical fusion. Thus, the neck pain group was severely affected by the pain and is probably not representative for subjects with chronic neck pain in general. However, it could be argued that if chronic neck pain in general would influence the type 1 to type 2 fiber type proportion, a larger effect would be expected in people more severely affected by pain.

In study III and IV the healthy participants were recruited among colleagues, friends and personal networks by oral invitation. These participants can be considered to be a sample of convenience and may therefore have deviated from that of the normal population. None of the healthy participants had been involved in whiplash accidents or experienced recurrent episodes of neck or head pain exceeding one week during the previous two years. Identical exclusion criteria were used for the healthy participants and the chronic WAD group (see the methods for details). Only one of the 26 healthy participants (4 %) reported to smoke, which is lower than the 17 % in the general Norwegian population as of 2013, reported by Statistics Norway[256] and which might indicate better general health. The healthy participants also reported slightly higher values than the normative data for the health related quality of life SF-36 summary scores. It is therefore possible that the controls had better health than the normal population. However, despite the controls possibly being healthier and perhaps performing better than the normal population, they did not differ from the chronic WAD group for several measures of movement smoothness nor rmsEMG after adjusting for displacement and velocity. One could therefore argue that potential differences between the controls and the normal population render these findings even more robust.

In study IV 15 of the healthy participants from study III was matched for sex and age to 15 participants with chronic neck pain after whiplash injury. All participants in the chronic WAD group were recruited through a specialist rehabilitation clinic located in the larger Oslo regional area at the first time of visit and examined by a specialist in physical medicine or neurology and a manual therapist before inclusion. The participants were classified according to the Quebec Task Force, classification system[16] for severity and duration. The participants were graded as WAD I – II and reported a median pain duration of 22 months (range 7 - 294). The score of 21.7 (of a maximum of 50) for the self-reported Neck Disability Index in the chronic WAD group indicate “moderate” (15-24) disability due to neck pain according to the scale of Vernon et al.[229] and is very similar with a number of studies previously reported for

this group (20 – 25.6)[5,6,8,146,190,216,257]. Additionally, reductions in physical measures such as range of motion as compared with controls is also in agreement with a number of reports in chronic WAD[3,8,14,22,149-153]. It is suggested that the participants with chronic WAD examined in this thesis also seem to be reasonable representative for people with chronic WAD displaying moderately scores for the NDI. Besides from being matched for sex and age, the chronic WAD and control group were also similar for anthropometrics and grip strength, but scored differently for self reported health as assessed by the SF-36. Reduced scores for the SF-36 as compared with controls is also reported in other studies in chronic WAD[216]. There were marginally differences for smoking habits between the groups. It seems therefore that the two subject groups were well contrasted concerning neck pain and disability due to neck pain, while being similar for other background variables.

Sample sizes

Group differences were primarily assessed in the case-control studies (II and IV), although some additional comparisons between genders were completed in study III. In general, a low number of participants will reduce the statistical power of the study, which is the probability of detecting a true difference between groups. For example, using 15 experimental participants and controls, and the true, mean difference between the groups is 1 SD, then the probability of detecting this difference is 0.75, using a type 1 error probability of 0.05. Thus, for the case-control studies, true mean differences between groups were probably detected if they differed of 1 SD, while differences of smaller values may have been masked by random variation. In study II, three comparisons were made between 17 cases and 12 control participants to elucidate the research question. The result of this study was that the 0-hypothesis was kept. As the sample sizes were relatively limited, the main question is therefore; what is the probability of keeping a faulty 0-hypotehsis because of insufficient power? If one studies figure 8 in the results section, both the mean values and the variation within groups are almost identical for all three fiber types. Thus, there seem to be little reason to believe the 0-hypothesis was kept due to lack of statistical power alone.

In study IV, a large number of outcome variables were compared for 15 chronic WAD cases and 15 controls. A number of statistical significant group differences were found for the majority of comparisons of both the kinematics and the rmsEMG at the M speed condition when covariates were not taken into consideration. The group differences were internally

coherent, that is they pointed in the same direction for all test conditions and were in the order of 1 SD of the variability within groups. Bonferroni post hoc tests were also used reduce the probability of Type I errors due to multiple comparisons. Thus, it is reasonable to assume that the observed group differences were not caused by chance. When the data were analyzed using velocity and displacement as covariates, the differences between groups in measures of smoothness and rmsEMG vanished. Both the rmsEMG and NJC displayed relatively large and overlapping variation within groups and the mean differences were small compared with this variation. These data suggest that if there were true group differences undetected because of low test power, these are probably small and not important.

Electromyography

Accessibility to neck muscles for EMG recording. Both the SCM and trapezius muscles are superficially positioned and are readily accessible for surface EMG (sEMG) recordings. Several other potential cervical muscles were considered for accessibility for the surface electrodes. After anatomical examinations using MRI and US imaging, and dissection of 12 autopsy cases only the splenius capitis of other relevant neck muscles was concluded to be accessible for sEMG. In the upper part of the posterior triangle of the neck, the superior and lateral parts of this muscle were superficial in most examined cases. This is in accordance to what found by Joines et al.[258]. The activity of the scalenus anterior has been reported in several previous studies using sEMG[216,217,241,259], but the anatomical examination completed in this thesis found this muscle inaccessible for sEMG recordings. The scalenus anterior muscle was in its full length almost completely covered by the SCM in addition to being sheltered by fat tissue. Similar findings regarding the accessibility of the scalenus anterior to sEMG sampling have been made previously[260].

To validate appropriate sEMG sensor placements, real-time US imaging was used for positioning of all electrodes. In addition, all electrodes could be positioned in line with the muscle fascicles which are visualized by the US image, thus theoretically covering the same muscle fibers and improving the quality of the signal. However, concerns has also been raised regarding selective sEMG recordings from the splenius muscle and the possible cross-talk from the SCM[240]. In some subjects the gap between the SCM and trapezius muscles was indeed small, and in those cases the electrode was positioned closer to the trapezius muscle. The reason for this handling was that both previous studies[34,239,240] and pilot studies prior to

this investigation showed that the trapezius display very low EMG amplitude during neck movements in the sagittal plane. Although not quantified systematically, the splenius signal was examined during peak velocity neck flexions and there were no clear signs of cross-talk from neither the SCM nor trapezius appearing on the splenius channels. Although the data of study IV suggest that both the SCM and splenius muscles are important for movement of the head, these are only two of at least a dozen muscles that can contribute to force generation across the cervical spine in the sagittal plane. It is therefore somewhat prematurely to generalize the findings from the SCM and splenius to that of cervical muscles in general.

Normalization. A general problem with surface EMG measurement is the large individual variation of the signal amplitude for a standard contraction. To control the factors responsible for the variability, the signal is usually normalized to maximal or sub-maximal standard contractions and given as a percentage of the standard value[261]. The use of normalization to both sub-maximal and maximal contractions usually display very good reliability[262,263]. Although there is no clear consensus for which type of contraction used as standard for normalization are the superior, the maximum isometric voluntary contraction is often used in healthy participants[261,264]. In participants with pain, peak voluntary contractions may not be the maximum and therefore reference contractions at some sub-maximum levels are most often employed[11,217,257,261]. In study IV reference contractions were accomplished using the head as loading, which normalizes for individual anthropometric differences. While such a normalization procedure allows for comparisons between different individual and groups for a given muscle it does not allow for meaningful comparisons between the different muscles examined as each muscle is tested at its own relative, unknown contraction force. It should also been noted that if the EMG is intrinsically altered between the subject groups, then this difference could also be present during the reference contractions and thus possibly affect the normalized EMG signals for the movement tests. Such a possibility was examined by comparing the non-normalized rmsEMG amplitude during the reference contractions between the groups, but no differences were found between groups (paper IV). It seems therefore reasonable to assume that group differences in the normalized EMG amplitude were not introduced by the reference signal.

Conclusions

- An intermuscular relationship in the type 1 fiber proportions was found. Individuals that express relatively large amount of fast fibers in one muscle express a large amount of fast fiber in other muscles as well.

- There were no differences in type 1, type 2 or the hybrid type 1/2A muscle fiber proportions in the SCM muscle between healthy subjects and subjects with severe chronic neck pain. Chronic neck pain does not seem to induce fiber type transformations between the type 1 and type 2 pools of muscle fibers.

- The smoothness of head movements were found to be strongly related to movement velocity and displacement. Fast movements are smooth and slow movements are jerky.

- Men generally exert faster head and neck movements than women, but the movements are equally smooth. The increased velocity seen in men is likely related to increased neck muscle mass and force generation capacity.

- Subjects with chronic WAD show reduced head movement displacement, velocity, acceleration and EMG amplitude during unconstrained movements as compared with control subjects.

- After differences in movement displacement and velocity between subjects with and without chronic WAD were taken into account, there were no group differences in the EMG amplitude or smoothness of movement. Simple, unconstrained head movements in participants with chronic WAD are accomplished with reduced velocity and displacement, but with normal muscle activation levels and movement patterns for that velocity and displacement.

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Paper I

Harald Vikne, Kristian Gundersen, Knut Liestøl, Jan Mæhlen and Nina Vøllestad. *Intermuscular relationship of human muscle fiber type proportions: Slow leg muscles predict slow neck muscles.* Muscle & Nerve. 2012; 45(4):527-535.

INTERMUSCULAR RELATIONSHIP OF HUMAN MUSCLE FIBER TYPE PROPORTIONS: SLOW LEG MUSCLES PREDICT SLOW NECK MUSCLES

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ABSTRACT: *Introduction:* Our aim in this study was to examine whether the muscle fiber type proportions in different muscles from the same individual are interrelated. *Methods:* Samples were excised from five skeletal muscles in each of 12 human autopsy cases, and the fiber type proportions were determined by immunohistochemistry. We further examined the intermuscular relationship in fiber type proportion by reanalyzing three previously published data sets involving other muscles. *Results:* Subjects demonstrated a predominantly high or low proportion of type 1 fibers in all examined muscles, and the overall difference between individuals was statistically significant ($P < 0.001$). Accordingly, the type 1 fiber proportions in most muscles were positively correlated (median $r = 0.42$, range −0.03–0.80). Similar results were also obtained from the three reanalyzed data sets. *Conclusions:* We suggest the existence of an across-muscle phenotype with respect to fiber type proportions; some individuals display generally faster muscles and some individuals slower muscles when compared with others.

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In humans, about 40% of the total body weight is skeletal muscle. Individual variation in the use of skeletal muscles is the dominant cause of variation in total energy consumption. Variation in energy consumption is also directly or indirectly influenced by individual variation in the metabolic properties of the skeletal muscle tissue, such as fiber type composition. In humans, the limb and trunk skeletal muscles consist of different proportions of three main muscle fiber types, type 1, 2A, and 2X, classified on basis of the myosin heavy chain (MyHC) they express. Most human muscles also contain a variable number of hybrid fibers that express either both type 1 and 2A MyHC (type 1/2A) or both type 2A and 2X MyHC (type 2A/X). Studies of mono- and dizygotic twins in humans[1,2] and breeding studies of rodents,[3,4] horses,[5] and pigs[6] have shown that the proportions of fiber types in single muscles are dependent on heritable factors. Under normal physiological conditions in humans the type 1 fibers seem to be resistant to change and do not switch into type 2, even when exposed to long-term training[7–13] or a long-term reduction in physical activity.[8,11–13–17] In contrast, a switch between the type 2 fiber subsets (2A and 2X in humans) is induced by changes in physical activity.[8,11,13,14,17]

The fiber type proportions of a single muscle have been associated with outcomes of various physical performance tests[18,19] and are also linked to several cardiovascular risk factors in humans.[20,21] It has been demonstrated that a high proportion of type 1 fibers in the vastus lateralis muscle is associated with low blood pressure,[22] increased insulin sensitivity,[23] and other indicators of a low risk of cardiovascular disease.[21,24] Conversely, a low proportion of type 1 fibers in single muscles is associated with the presence of diabetes mellitus type 2,[25] peripheral artery disease,[26] coronary artery disease,[27] and chronic heart failure.[28] These relationships between the fiber type proportions of one single skeletal muscle alone and cardiovascular risk factors and human performance raise the question of whether there is a systematic relationship between the fiber type proportions of different muscles in the same individual. This hypothesis was proposed by Saltin et al. in a review from 1977,[29] but we have not found any studies that address this in a systematic fashion in humans. The main purpose of this study was to determine whether some individuals consistently display predominantly type 1 fibers or predominantly type 2 fibers in different muscles. In addition to presenting new empirical data, we have reanalyzed three previously published, independent data sets with respect to this hypothesis.[30–32]

METHODS

Approach to the Problem. To test the hypothesis that the distribution of fiber types in different skeletal muscles is interrelated at the individual level we completed an autopsy study of 12 subjects. Five muscles with presumably diverse patterns of activity were excised: the sternocleidomastoideus (SCM); splenius; scalenus medius; trapezius; and vastus lateralis. Fiber type composition was assessed by immunohistochemistry and muscle fiber cross-sectional area (CSA) was completed by tracing the cell borders. In addition to our data, we tested the

Abbreviations: CSA, cross-sectional area; CVD, cardiovascular disease; MyHC, myosin heavy chain; SCM, sternocleidomastoideus

Key words: human striated muscle, immunohistochemistry, intermuscular correlations, MyHC, skeletal muscle phenotype

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hypothesis by reanalyzing three different published data sets on human fiber type proportions in different muscles from the same individual.[30–32]

Our study was approved by the Regional Committee for Medical and Health Research Ethics.

Muscle Sampling. Muscle specimens were excised between 24 and 72 hours postmortem from 12 cases of sudden death [1 car accident, 1 accidental poisoning, 3 suicides (1 carbon monoxide poisoning and 2 drug overdoses), 6 coronary-related deaths, and 1 hemorrhage]. The cases (11 men and 1 woman) ranged from 18 to 65 years of age (mean ± SD: 45.3 ± 15.8 years). Inclusion of cases was based on pathologist evaluation and medical records. None had a history of bed rest or hospitalization in the final 24 hours prior to death. Cachectic or severely obese cases were excluded. We also excluded cases in which the medical record or autopsy revealed neurological, rheumatological, or endocrinological disorders; alcoholism or drug abuse; or other severe diseases, including malignancy. The general lifestyle or physical activity levels of the cases were not known. Samples were taken from one muscle in the thigh (vastus lateralis), one in the shoulder girdle (trapezius), and three in the neck (SCM, scalenus medius, and splenius muscle). To our knowledge, the scalenus medius and splenius muscle have not been studied previously for fiber type proportions in presumably normal subjects. From the knee extensor vastus lateralis muscle, samples were taken in the superficial portion, midway between trochanter major and the lateral epicondyle of the knee. Samples from the trapezius were collected from the lower descending portions of the muscle, and for the scalenus medius and SCM at their midpoints. The samples from the lateral portion of the splenius were excised at approximately the C4–C5 level. From the muscle tissue excised, smaller samples with lengths of approximately 2 cm and 0.5 cm in diameter were dissected free from fat and connective tissue, and superficial blood was removed. The samples were snap frozen in melting isopentane cooled with liquid nitrogen and stored at −80°C until further preparation.

Immunofluorescence and Microscopy. The muscle samples were oriented and mounted on metal disks using an embedding medium (Tissue-Tek OCT compound), and serial cross-sections of 10 μm were cut in a cryostat (HM 560M; Microm International), put on glass microscope slides, and air dried at room temperature. Muscle fiber types were visualized by immunofluorescence using a series of antibodies against different myosin heavy chains, including BA-D5 (type 1 MyHC), SC-71 (type 2A MyHC), BF-35 (all non-2X MyHC), which were donated by Stefano Schiaffino (University of Padova, Italy[33]), and 6H1 (type 2X MyHC), which was donated by Joseph Hoh (University of Sydney, Australia).[34] Anti-laminin (L-9393; Sigma) was used to stain the basement membrane. The specificity of the myosin antibodies in human muscles has been tested in previous studies using Western blots (BA-D5, SC-71, and BF-35 by Wu et al.[35] and 6H1 by Li et al.[36]). Primary antibodies were diluted with 1% bovine serum albumin in 1 × phosphate buffer saline to final concentrations of 1:2000 (BA-D5, SC-71, and BF-35), 1:700 (anti-laminin), and 1:3 (6H1). The cryosections were incubated with the primary antibodies using an overnight protocol at 4°C. The secondary antibodies used included goat anti-mouse IgM, fluorescein isothiocyanate (FITC)-conjugated (F9259; Sigma) against the 6H1 antibody and rabbit anti-mouse IgG, and FITC-conjugated (F9137; Sigma) against the other MyHC primary antibodies. Goat anti-rabbit IgG and tetramethyl-rhodamine isothiocyanate (TRITC)-conjugated (T6778; Sigma) antibodies were used against the anti-laminin antibody. All incubations of secondary antibodies were completed in a humid chamber at 37°C for 1 hour. The muscle cross-section samples were then placed in a microscope (BX50WI; Olympus) connected to an SIT camera (C2400-08; Hamamatsu), magnified using a 10× water immersion objective (UMPLFL10XW; Olympus), and photographed. The images were digitized by an image processer (Argus-20; Hamamatsu) and transferred to a MacIntosh G3 computer. Composite photomontages of the images were then assembled in Adobe Photoshop CS3.

Fiber Type Proportions. For determination of fiber type composition, two to four separate areas containing approximately 200–400 fibers, each with good cell integrity, were first chosen randomly in the laminin staining images. Each area contained fibers with intact cell borders and that appeared cross-sectionally cut. The fiber identities of these cells were then determined on the basis of the four MyHC staining patterns using the following criteria: cells that stained positively for BA-D5 and BF-35, but not SC-71 nor 6H1, were type 1 fibers; cells that stained positively for SC-71 and BF-35, but neither BA-D5 nor 6H1, were type 2A fibers; and cells that stained for 6H1, but not BF-35, BA-D5 nor SC-71, were classified as type 2X fibers. Any muscle cell that stained for BA-D5, SC-71, and BF-35 either strongly or weakly and did not stain for 6H1 was classified as a hybrid 1/2A fiber. Cells that stained SC-71, 6H1, and BF-35 strongly or weakly, but not BA-D5, were classified as hybrid 2A/X (Fig. 1). A total of of 880 ± 161 (mean ± SD) cells per muscle were analyzed.

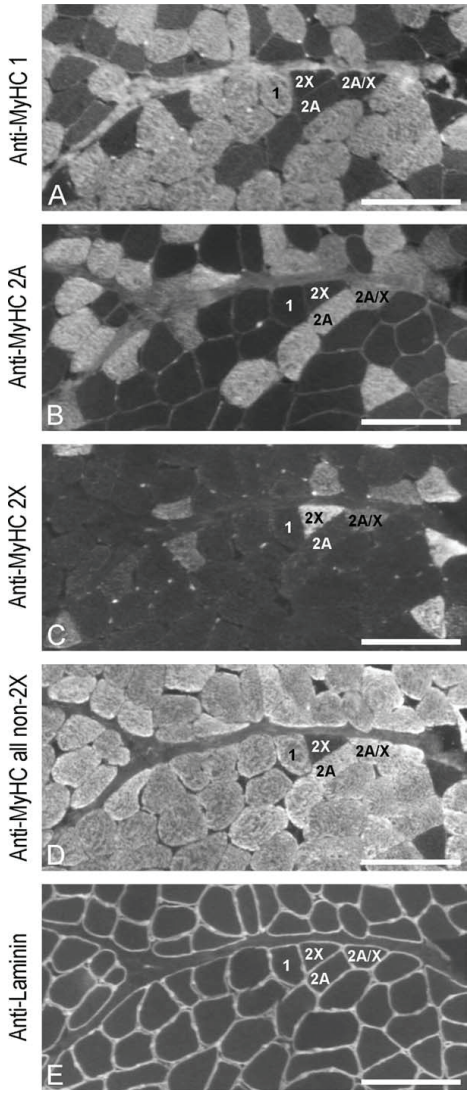

FIGURE 1. Serial cross-sections from the trapezius muscle from 1 subject **(A–E)**. Sections were stained using immunofluorescence with antibodies **(A)** BA-D5 (MyHC 1), **(B)** SC-71 (MyHC 2A), **(C)** 6H1 (MyHC 2X), **(D)** BF-35 (all non-2X MyHC), and **(E)** anti-laminin. 1, type 1 fibers; 2A, type 2A fibers; 2A/X, type 2A/X fibers; 2X, type 2X fibers. Scale bars = 200 μm.

Muscle Fiber Type Cross-Sectional Area. After inspection of cell integrity the cross-sectional area (CSA) was measured by manually tracing the inner laminin border of the cells. The CSA of at least 50 and up to a maximum of 100 cells of each fiber type, evenly distributed in the muscle samples, were measured.[37] All measurements were completed using ImageJ software, version 1.31 (W.S. Rasband, National Institutes of Health, Bethesda, Maryland). On average, we measured a CSA of 100 ± 2 type 1, 95 ± 13 type 2A, and 89 ± 16 type 2A/X cells. Because of the low proportion of 2X and 1/2A fibers, they were not analyzed in detail.

Reanalysis of Previously Published Data. Three earlier studies,[30–32] containing information on the individual fiber type proportions in several skeletal muscles of the same subject, were reanalyzed with respect to the hypothesis. If samples had been taken from more than one site within the same muscle, we used the average values in the analysis. Weber et al.[32] reported fiber type proportions in biopsies from neck muscles SCM and omohyoideus of 11 male and 10 female patients [age 52 years ± 14 (mean ± SD)] with cervical dysfunction. The second study was an autopsy investigation by Garrett et al.,[31] which included samples taken from 9 hip and thigh muscles from 7 men and 3 women (mean age 60 years, range 37–76 years). Their causes of death included myocardial infarction, lymphoma, or cerebrovascular accident, and thus the inclusion criteria deviated from those of the primary data set. Finally, we reanalyzed data from the autopsy study by Johnson et al.[30] (also reanalyzed by Medbø[38]) in 6 young men (age 21.8 ± 5.7 years, weight 78.5 ± 12 kg, height 186 ± 6 cm), all of whom had died suddenly. Samples were taken from 54 different sites of 36 different muscles across the body, which included a wide variation in location, size, and presumably activity patterns (see Fig. 4). No information was given regarding the subjects' general lifestyle or level of physical activity in these three studies. The myofibrillar ATPase protocols employed in these three studies provides results of the proportions of type 1 and 2 fibers that are indistinguishable from those of immunohistochemical methods.[33]

Statistics. All data are given as mean ± SD. To examine the effects of subject and muscle on fiber type composition, both subject and muscle were entered simultaneously in an analysis of variance model. This implies that the large variation between muscles with regard to fiber type composition is taken into account when comparing subjects. The same model was used for analysis of muscle fiber CSA and in the reanalysis of type 1 fiber proportions in the studies by Johnson et al.[30] and Garrett et al.,[31] which included 36 and 9 muscles, respectively. The Pearson correlation coefficient was used to explore the relationship between pairs of muscles and in one muscle and the mean of the others in our primary data set. This test was also used in the reanalysis of the type 1 fiber proportions in the two muscles reported by

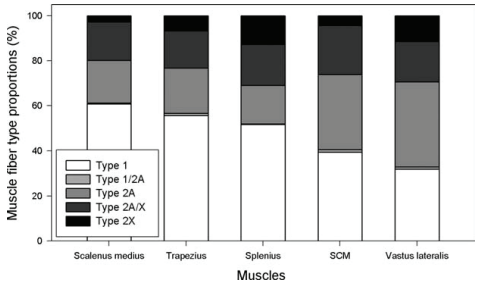

FIGURE 2. Mean fiber type proportion (%) in the five different muscles. Muscles are ordered from the highest to the lowest mean proportion of type 1 muscle cells, starting from the left.

Weber et al.[32] The *t*-tests were used for evaluating pairwise differences. $P < 0.05$ (all tests two-sided) was considered statistically significant. All analyses were performed using JMP (version 8.0) statistical software.

RESULTS

Muscle Fiber Type and Size. The muscles in the primary set of data displayed a marked difference in the proportion of the fiber types ($P < 0.0001$; Fig. 2). Type 1 fiber proportion was relatively low in our samples from vastus lateralis (mean ± SD: 31.9 ± 11.0%) and SCM (39.5 ± 14.5%). Both muscles were composed of fewer type 1 fibers than the splenius (51.6 ± 11.5%, $P < 0.01$), the trapezius (55.6 ± 10.2%, $P < 0.001$), and the scalenus medius (60.8 ± 13.4%, $P < 0.001$). Only a small fraction of the cells in the muscles were hybrid 1/2A fibers (0.3–1.2%). The mean proportion of type 2A fibers also differed between muscles ($P < 0.01$). The vastus lateralis and the SCM muscles had the highest proportions of type 2A fibers (37.6 ± 8.2% and 33.2 ± 14.1%, respectively) and were significantly different ($P < 0.01$) from trapezius (20.1 ± 6.5% type 2A), scalenus medius (18.9 ± 6.4%), and splenius muscles (17.2 ± 7.6%). All muscles were comprised of a relatively high proportion of hybrid 2A/X fibers, with no significant difference between muscles. The vastus lateralis was comprised of 18.1 ± 7.6%, the SCM 21.6 ± 10.4%, and trapezius 16.5 ± 6.8% of type 2A/X fibers. The scalenus medius and splenius muscle had 17.2 ± 9.0% and 18.3 ± 7.6% type 2A/X fibers, respectively. The proportions of 2X fibers also differed somewhat in the muscles. The vastus lateralis and splenius displayed 11.4 ± 7.4% and 12.7 ± 12.3% type 2X fibers, respectively and were significantly different ($P < 0.01$) from the trapezius, SCM, and scalenus medius (6.7 ± 7.0%, 4.3 ± 6.7%, and 2.7 ± 5.2% 2X fibers, respectively). The results from the single female and from the 2 oldest cases (age 65 years) did not deviate from those of the other cases in our material and, more generally, no association was found between the overall mean type 1 fiber proportions and age or cause of death.

Table 1. Mean fiber type CSA (μm^2) of the different muscles.

Muscles	Fiber type		
	Type 1	Type 2A	Type 2A/X
Scalenus medius	2275 ± 694	1918 ± 682	1821 ± 661
Trapezius	3173 ± 1115	2369 ± 993	2206 ± 874
Splenius	1971 ± 546	1845 ± 706	1645 ± 660
SCM	2503 ± 880	2788 ± 894	2397 ± 821
Vastus lateralis	3926 ± 1188	3583 ± 1065	2654 ± 1255

Results are presented as mean ± SD. Significant differences between muscles in the mean fiber type CSA are given in the text (n = 12).

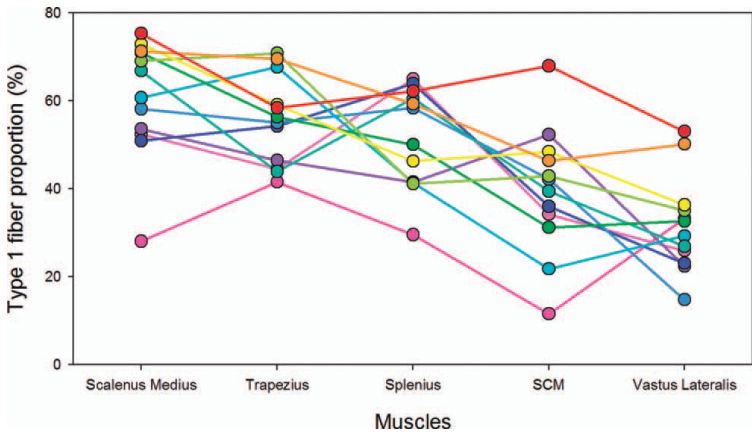

FIGURE 3. Type 1 fiber proportion (%) in 5 different muscles and 12 individuals. Each individual is represented by a unique color in all muscles. Muscles are ordered according to mean type 1 fiber proportion (see Fig. 2).

Table 2. Relationship between type 1 fiber proportions (%) of the different muscles, and between each muscle and the mean of the other muscles.

	Muscles				
Muscles	Scalenus medius	Trapezius	Splenius	SCM	Vastus lateralis
Trapezius	0.62*	–			
Splenius	0.39	−0.03	–		
SCM	0.67*	0.23	0.46	–	
Vastus lateralis	0.47	0.45	0.03	0.38	–
Mean other muscles	0.80*	0.43	0.32	0.64*	0.45

Pearson correlation coefficient was used (n = 12).
**P < 0.05.*

The leg muscle vastus lateralis was comprised of cells with larger CSA than the other muscles for all fiber types (Table 1), whereas the neck muscles scalenus medius and splenius generally had small CSAs. The difference between vastus lateralis and the two neck muscles is clearly significant ($P < 0.01$).

Intermuscular Relationship. As displayed in Figure 3, subjects demonstrated an overall high or low proportion of type 1 fibers for the muscles examined in our primary set of data. Some deviation from this general pattern is seen in Figure 3, but the overall difference between individuals was statistically significant ($P < 0.001$). Accordingly, the proportions of type 1 fibers were positively correlated between pairs of muscles and between one muscle and the mean of the other muscles (Table 2). Although only four correlations were significantly different from zero, all except one displayed a positive relationship for the type 1 fiber proportion. Taken together, the data point to a clear correlation between the proportion of type 1 fibers in the muscles, although there may be differences in the strength of this correlation.

To test the hypothesis further, we also reanalyzed three independent sets of published data on human fiber type proportions in multiple muscles.[30–32] As for our primary set of data, we found an overall significant difference between subjects with respect to the type 1 fiber proportions across muscles in the studies by Johnson et al.[30] ($P < 0.0001$; Fig. 4) and Garrett et al.[31] ($P < 0.001$), who assessed 36 and 9 muscles, respectively. Finally, the type 1 fiber proportions for the two muscles (SCM and omohyoideus) reported by Weber et al.[32] correlated significantly ($r = 0.52$, $P < 0.02$; Fig. 5).

DISCUSSION

The most important finding from our study is that there seems to be an intermuscular relationship in human muscle fiber type composition. Subjects who express a high proportion of type 1 fibers in one muscle are likely to express a comparably high proportion of type 1 fibers in other muscles as well. This result was observed for muscles covering a wide range of functional demands and fiber type proportions.

Muscle Fiber Type and Size. In general, the mean type 1 fiber distribution and variation of the five examined muscles in our primary data set were similar to those of previously published studies. Only for vastus lateralis were our results for type 1 fiber proportion (32%) somewhat in the lower range of typical findings.[39] This may reflect the fact that our samples were taken in the superficial part of the muscle.[40] The proportion of type 1 fibers of the shoulder girdle muscle trapezius in this study was found to be about 10–15% lower than in some studies,[41,42] yet similar to others.[30,43] There are fewer comparable studies of human neck muscles. We found 39.5% type 1 fibers in the SCM, which is similar to findings by Johnson et al.[30] and among patients with cervical disorders.[32,43] The splenius was comprised of 52% type 1 fibers in our data set, which is comparable to the 55% found in subjects with neck complaints.[43] In our data set, the scalenus medius had a mean of 61% type 1 fibers (Fig. 2). We are not aware of other studies of fiber type proportions of this muscle.

As expected, there were some differences in the mean fiber type proportions between the muscles. The vastus lateralis and SCM were composed of significantly fewer type 1 fibers and, reciprocally, more type 2A fibers than the other muscles studied (Fig. 2). Conversely, proportions of hybrid (1/2A and 2A/2X) fibers were very similar between muscles. Because we were among the first investigators to study humans using a specific antibody against type 2X MyHC (6H1), we were able to positively detect large fractions (17–22%) of hybrid 2A/X fibers in all muscles examined. In accordance with prior studies, only small portions (0.3–1.2%) of hybrid 1/2A fibers were found.[11,12,39,44]

Compared with the other muscles, the leg muscle vastus lateralis had the greatest cell areas and the neck muscle splenius had the smallest cell areas for all fiber types (Table 1). As muscle fibers readily increase or decrease in cell CSA in response to training or inactivity,[13–15,17,44] such use-dependent change may explain a significant fraction of the intermuscular and interindividual variation in the muscle fiber CSA.

Intermuscular Relationship. We tested and found a significant overall difference between individuals in the proportion of the type 1 fibers across muscles both in our primary set of data and for

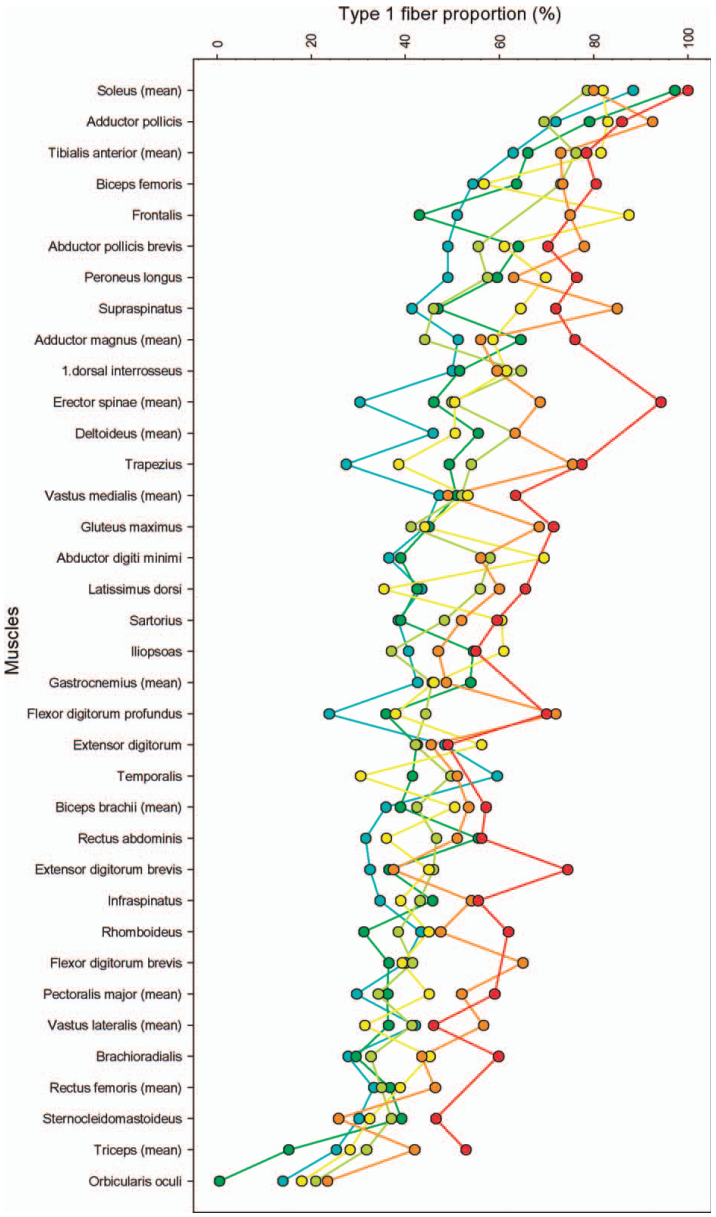

FIGURE 4. Individual type 1 fiber proportion (%) of 6 subjects in 36 different muscles. The 'mean' given in parentheses in 12 of the muscles depicts the average fiber type proportion taken from two or three separate samples in these muscles. Each subject is given a unique color and muscles are ordered according to mean type 1 fiber proportion (%). All reanalyzed data are from Johnson et al.[30]

the data sets of Johnson et al.[30] and Garrett et al.[31] Also, the bivariate analyses of the type 1 fiber proportions showed positive correlations for the two muscles in the study by Weber et al.[32] and in pairs of muscles from our primary set of data. Thus, the results of four independent sets of data consisting of a wide range of muscles, with presumably a large variation in activity patterns and fiber type proportions, suggest that the individual type 1 fiber proportions in different muscles are not

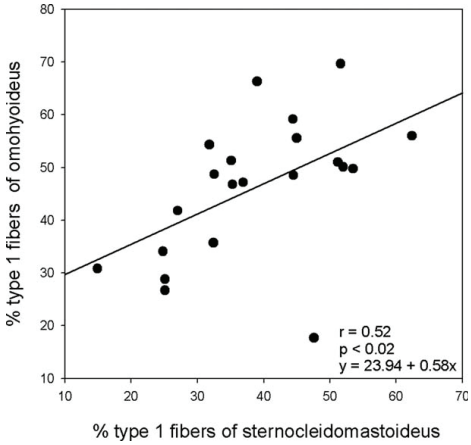

FIGURE 5. Relationship between type 1 fiber proportions (%) of SCM and omohyoideus in 21 subjects. The data were reanalyzed from Weber et al.[32] $r = 0.52$, $P < 0.02$.

random, but instead subject to an overall across-muscle regulation. Accordingly, subjects who express a relatively high proportion of type 1 fibers in one muscle will also express a relatively high proportion of type 1 fibers in other muscles, which supports the proposal made in 1977 by Saltin and colleagues.[29] Hence, these results point to the existence of an individual, across-muscle phenotype with respect to fiber type proportions.

As illustrated in Figures 3 and 4 there are discrepancies in the general pattern of an intermuscular relationship because subjects do not display a fully consistent interindividual difference for all muscles. These deviations from the overall pattern may be due to some individual biological variation and to the uncertainty of the method for estimating the true, unknown fiber type proportion for a whole muscle.[45] In this study, all four sets of data were, in general, based on one muscle sample from each muscle and, for two of the data series,[30,31] only 200 cells per sample. It is thus unreasonable to regard each single, small muscle sample to be truly representative of the whole muscle. Blomstrand and Ekblom[46] found a mean variation of 6.2% in the type 1 fiber proportions between two muscle samples at the same site in the vastus lateralis muscle. In the data analyzed from Johnson et al.,[30] the absolute difference in type 1 fiber proportion between a deep and a superficial sampling site in 11 muscles was, on average, 9.6%-point (range 0–36%-points). Thus, the uncertainty of the method for estimating the true, mean fiber type proportion of the muscles is likely to explain a significant fraction of the deviation among subjects from the general pattern of an intermuscular relationship. Despite such measurement errors and the likelihood of some biological deviations from the overall pattern, the hypothesis was supported in all four sets of data.

If the fiber type proportions of various muscles of an individual are interrelated, the proportion of one muscle may also be indicative of the general fiber type proportions of the total muscle mass. Our findings therefore offer a possible explanation for the observation that the type 1 fiber proportion of one single skeletal muscle alone seems to correlate with more global phenomena such as the presence or absence of risk factors for cardiovascular disease (CVD)[20–25,47] and CVD itself[26–28] or athletic performance.[19] Breeding studies in rats offer strong support for the existence of an across-muscle phenotype. Suwa et al.[4] first demonstrated that selective breeding over several generations for a large proportion of fast fibers in the medial gastrocnemius increased the fast fiber proportions in the gastrocnemius in each brood of rats. Concurrently, they observed that the proportion of fast fibers in the synergistic slow soleus muscle increased as well, indicating that selective breeding for a large proportion of fast fibers in one muscle may have a response among the fiber type proportions of skeletal muscles in general. In a later study they confirmed this proposition after analyzing a series of skeletal muscles in each individual rat.[48]

There are several possible genetic and non-genetic factors that may cause the intermuscular relationship. At the adult age, it is well known that physical activity can affect the metabolic and contractile properties of a muscle[49] and cross-sectional studies of elite athletes and sedentary subjects imply that physical activity may also influence the fiber type proportions.[50] For the three data sets based on samples taken at autopsy there is no information about lifestyle, including habitual physical activity. An evaluation of the possible impact of such factors is therefore not possible. However, causal relations are more suitably examined by an experimental study design. Thus, under normal physiological conditions, data from long-term, controlled experimental studies demonstrate that increased physical activity, such as long-term endurance training[7,11] or strength training,[8,9] sprint training,[12] or extreme endurance activity,[10] has a limited effect on the fraction of type 1 fibers in human muscles. Comparable observations were made for reduced muscle activity, such as continued bed rest[15] or detraining.[8,13,14,16,17] Furthermore, similar conclusions could also be drawn from long-term exercise experiments in rodent muscles under otherwise normal physiological conditions.[51] In contrast, the proportions of 2A and 2X fibers are readily changed due to modulation in physical activity in humans.[8,11,13,14,17]

The hybrid fibers (1/2A and 2A/X) have been suggested to be intermediate or transitional between muscle cells expressing only one MyHC and may indicate the state of fiber type alteration at a given time-point. In this study we found a large number of hybrid 2A/X fibers in all muscles but only minute fractions of 1/2A fibers. Thus, the existing experimental evidence does not suggest that any substantial activity-dependent transition occurs between type 1 and type 2 fibers under normal physiological conditions in adulthood. Therefore, it appears unlikely that the findings in the four sets of data presented herein simply reflect individual differences in physical activity at an adult age. We cannot, however, rule out that the fiber type proportions may be more changeable during prenatal or early postnatal periods. It has been suggested that the intrauterine milieu may affect the postnatal skeletal muscle fiber type proportions, and thus it may influence the intermuscular relationship. Both low birth weight,[52] a marker for suboptimal intrauterine milieu, and a protein-restricted diet during pregnancy[53] are associated with changes in postnatal fiber type proportions. It seems, however, that both in humans[52] and rodents[53] such alterations mainly occur within the type 2 fiber subsets, whereas the fraction of type 1 fibers is more stable. The results from the rat breeding studies of Suwa et al.[4,48] suggests a clear role for heritable factors in the intermuscular relationship of fiber type proportions. Such genetic influence is also supported by studies of single muscles in mono- and dizygotic human twins.[1,2] Our study had a cross-sectional design, and the results are compatible both with an influence of genetic factors and possibly early milieu on the development of the intermuscular relationship in fiber type proportions. Similar investigations should be done with younger subjects to strengthen and extend our findings.

In conclusion, we suggest the existence of an across-muscle phenotype with respect to fiber type proportions; some individuals display generally faster muscles and some individuals slower muscles compared with others.

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Paper II

Harald Vikne, Jan Mæhlen, Eva Sigrid Bakke and Nina Vøllestad. *Type 1 to type 2 neck muscle fibre proportion in persons with chronic neck pain and controls.* Submitted.

Type 1 to type 2 neck muscle fibre proportion in persons with chronic neck pain and controls

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Short title: *Muscle fibre types and neck pain*

Type 1 to type 2 neck muscle fibre proportion in persons with chronic neck pain and controls

Abstract

OBJECTIVE: To examine whether people with chronic neck pain (CNP) differ from controls in the proportion of type 1 and type 2 fibre in cervical muscles.

METHODS: The proportions of type 1, 1/2A and pooled type 2 fibres in the sternocleidomastoid (SCM) muscle of 17 subjects with CNP were compared with a control group of 12 subjects. Muscle fibre types were identified by means of myofibrillarATPase and immunohistochemistry.

RESULTS: The mean (SD) proportions of fibre types 1, 1/2A and 2 in the SCM muscle were 37.6 (10.6), 2.1 (3.8) and 60.3 (11.2) %, respectively, in the CNP group and 39.5 (14.5), 1.2 (1.3) and 59.3 (14.4) % in the control subjects. There were no statistically significant group differences in the proportions of either muscle fibre type (all p values >0.46).

CONCLUSIONS: We suggest that chronic neck pain does not induce transitions between the type 1 and type 2 muscle fibre population pools in human neck muscles.

MeSH terms

Neck pain, cervical pain, skeletal muscle fibre, immunohistochemistry, humans

Key words

Chronic neck pain, sternocleidomastoid, muscle fibre type transitions, MATPase, cervical muscles

Introduction

The adult human skeletal muscle fibres display a large range of contractile and functional properties. Type 1 fibres are characterized by low intrinsic shortening velocity and are fatigue-resistant, while types 2A and 2X have a higher shortening velocity but are more susceptible to fatigue (1). Muscle fibres are highly adaptable to changes in activity patterns and the 2A and 2X muscle fibre subtypes also readily interconvert as a function of increased or decreased regular muscle use (2-7). However, this plasticity does not seem to extend to conversion between type 1 and type 2 fibres, even after prolonged alteration in physical activity in subjects with an intact upper motoneuron-muscle connection (2-9).

People with chronic neck pain (CNP) may experience functional disability in daily life (10) and their neck muscle activation patterns have been shown to be changed as compared with control participants (11). A previous uncontrolled, cross-sectional study of persons with CNP suggested that conversion between type 1 and type 2 fibres occurs in cervical muscles, including the sternocleidomastoid (SCM) (12). Because of the difference in the intrinsic properties of the muscle fibres such transitions may have functional consequences for neck movements and may contribute to the altered movement kinematics seen in subjects with chronic neck pain (13, 14). However, as far as we know, no controlled studies have examined the effects of CNP on type 1 and type 2 muscle fibre transitions in cervical muscles. We therefore reanalyzed the previously reported individual fibre type proportions of the SCM muscle of subjects with severe CNP from the study of Weber et al. (15) and compared them with control subjects of similar age.

Methods

Study sample

Control subjects. Samples of the SCM muscle were excised from 12 cases (11 men and one woman) of sudden death 24-72 hours post mortem. The subjects averaged 45.3 (SD 15.8) years of age and were not subject to neurological, rheumatologic or endocrinological disorders, alcoholism, drug abuse or other severe diseases. Subjects aged < 18 and > 65 years were excluded. The fibre type proportions of several of the subjects' muscles were examined originally, and parts of the data have been reported previously (16). The study was approved by the Regional Committee for Medical and Health Research Ethics.

Subjects with chronic neck pain. The individual fibre type proportions of the SCM muscle reported for 24 subjects with chronic neck pain were taken from the data of Weber et al. (15). The muscle samples were taken during cervical fusion surgery that had been indicated by severe neck pain resistant to conservative treatment. Inclusion and exclusion criteria were harmonized between studies by excluding subjects over 65 years of age and/or with rheumatic disease (n=6). One subject (number 22) was omitted because the aggregated fibre type proportions reported was less than 100%. The CNP group finally consisted of 8 women and 9 men, with a mean age of 44.8 (13.1) with chronic neck pain of post-traumatic (n=11) or degenerative (n=6) aetiology for a mean period of 31.8 (17.5) months (range 6 – 60 months).

Fibre type classification

Control subjects. A detailed description of the method of fibre type analysis has been reported elsewhere (16). Muscle fibre types were visualized in serial, 10 μm cryosections by means of immunofluorescence using specific primary antibodies against different myosin heavy chains

(MyHC); BA-D5 (type 1), SC-71 (Type 2A), BF-35 (all non-2X;(17)) and 6H1 (Type 2X;(18)). A mean of 967 (206) cells from 2 – 4 separate areas per muscle sample were analyzed and the fibre identities (types 1, 1/2A, 2A, 2AX and 2X) of these cells were determined on the basis of the following MyHC staining patterns: muscle cells that stained positively for BA-D5 and BF-35, but not SC-71 or 6H1 were type 1 fibres; cells staining positively for SC-71 and BF-35, but neither BA-D5 nor 6H1 were type 2A fibres; cells that stained for 6H1, but not BF-35, BA-D5 or SC-71 were classified as type 2X-fibres; a muscle cell that stained for BA-D5, SC-71 and BF-35 either strongly or weakly but that did not stain for 6H1 was classified as a hybrid 1/2A-fibre; cells that stained SC-71, 6H1 and BF-35 strongly or weakly, but not BA-D5 were classified as hybrid 2A/X-fibres.

Subjects with chronic neck pain. Weber et al. (15) employed a modified version of the myofibrillar ATPase method of Guth and Samaha (19) for identification of muscle fibre types. Four fibre types were classified (types 1, 2C (1/2A), 2A and 2B (2X)) on the basis of the staining patterns of consecutive, 12 μm cryosections after alkaline and acid preincubations. The relative fibre type proportions were reported on the basis of classifications of at least 1000 fibres per subject. The six excluded subjects did not differ statistically significantly from the 17 included subjects for any fibre type proportion (all p values > 0.27).

Data processing and statistics

The classification of the main fibre types (1 and 2) is consistent between myofibrillar ATPase and immunohistochemical methods, but classifications of the type 2 subgroups are less consistent (20-22). The type 2 subgroups were therefore merged into a single type 2 group for both sets of data separately (2A, 2AX and 2X were merged for the controls and 2A and 2B for the CNP group). The proportions of type 1, type 1/2A and type 2 fibres were then compared.

Data are presented as means (SD) and compared using independent samples t-tests and a general linear model (GLM) using sex, age and group as factors, thus examining the independent effect of each factor when controlling for the others. Dichotomous data (sex) were analyzed using Fischer`s Exact Probability Test.

Results

The CNP and control groups differed significantly in the proportion of men and women ($p<0.05$), but not with respect to age ($p=0.92$). The mean fibre type proportions of the SCM muscle in the CNP group were 37.6 (10.6) % type 1, 2.1 (3.8) % type 1/2A and 60.3 (11.2) % type 2 fibres. The control group displayed 39.5 (14.5) % type 1 fibres, 1.2 (1.3) % type 1/2A fibres and 59.3 (14.4) % type 2 fibres (figure 1). There were no statistical significant differences between the groups in any fibre type proportions as examined by the t-test (type 1; $p=0.69$, type 1/2A; $p=0.46$, type 2; $p=0.84$). The GLM model confirmed the t-tests, displaying no independent effect on any fibre type proportions either by group (all p values >0.88) or by sex (all p values >0.13).

Discussion

Our data show strikingly similar proportions of types 1, 1/2A and 2 fibres of the SCM muscle in both participants with CNP and controls, and with no significant group differences for any fibre type. As seen in figure 1, both the mean values and the variation are very similar in the two groups for the different fibre types. These results are therefore in contrast to the uncontrolled study of Uhlig et al. (12), which reported a reduction in the proportions of type 1 and type 1/2A fibres from combined datasets of the ventral SCM and omohyoid muscles in persons with long versus short duration of neck pain. Our results are consistent with a series of studies that found no statistically significant difference in type 1 fibre proportions between controls and other cases with chronic musculoskeletal pain such as chronic trapezius myalgia (23-25), chronic low back pain (26) and lumbar spinal disc herniation (27). Furthermore, the type 1 fibre proportion of skeletal muscles also seems to be very resistant to change after a long-term increase or decrease in physical activity in healthy subjects (2-9). Thus, it does not appear as though CNP due to degenerative changes or trauma *per se* initiates any major fibre type transitions between the type 1 and type 2 fibres in the SCM muscle even in subjects scheduled for cervical fusion because of severe pain. It is however, possible that transitions between the type 2 subgroups (2A, 2AX and 2X) might occur as a result of chronic neck pain, as these transitions characteristically follow changes in patterns of physical activity (2-7).

Methodological considerations

The separate datasets for the controls and the CNP participants differed with respect to tissue condition, muscle fibre typing method and sex distribution. Previous research has shown that reliable myosin-based fibre typing can be performed for up to ten days post mortem (28) and that the methods used for fibre type identification in the two sets of data yield identical values

for the fibre types analyzed in this study (20-22). With regard to muscle fibre type proportions and the sexes, normative studies have not revealed any systematical difference between men and women in muscle fibre type proportions in either muscles in the lower extremities (29, 30) or muscles of the spine (31, 32). We likewise found no independent effect of sex on the fibre type proportions in this study. Thus, differences in the groups with respect to muscle condition, methods of visualizing fibre types and sex distribution most likely did not constitute a threat to the external validity of the study.

Abbreviations

CNP, chronic neck pain

MyHC, myosin heavy chain

SCM, sternocleidomastoideus

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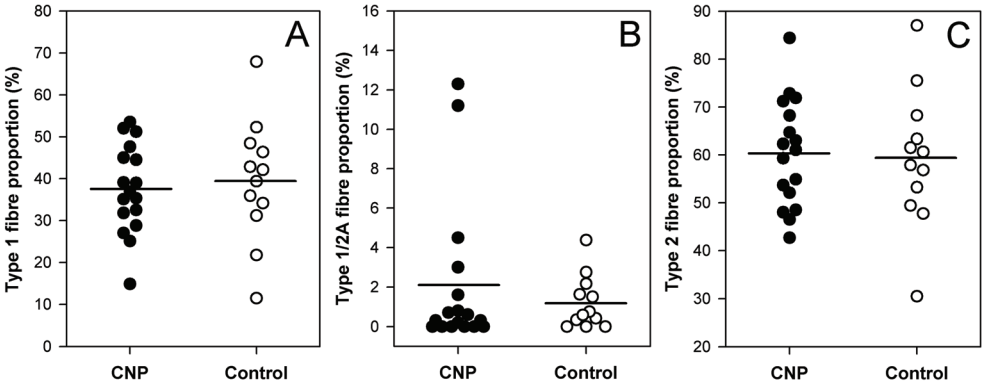

Figure legend

Figure 1. Individual type 1 (A), type 1/2A (B) and type 2 (C) muscle fibre proportions in the CNP group (filled circles) and control group (open circles). Horizontal lines indicate mean values. Note the differences in Y-axis scaling between subfigures.

Paper III

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The smoothness of unconstrained head movements is velocity-dependent

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ABSTRACT

Non-smooth, irregular movements reported in persons with neck pain have been suggested to signify motor impairment. However, irregular movements are additionally observed during slow movements in healthy participants. We therefore examined whether the smoothness of head movements is related to the movement speed in 26 healthy participants. Six unconstrained small and large amplitude head movements were completed in the sagittal plane at three different self-chosen speeds. Kinematic variables were calculated from position data and overall smoothness of the movement was assessed by the normalized jerk cost (NJC). Relationship between NJC and average movement angular velocity was analyzed using a mixed factor model. Movement duration, angular velocity, NJC and number of submovements differed significantly between speed conditions for all movement directions and amplitudes (all $p < .05$). We found a strong relationship between the average angular velocity and NJC across all movement directions and amplitudes (all $p < .0001$). Large amplitude movements showed higher NJC for a given movement velocity than small amplitude movements ($p < .001$). We have shown that the smoothness of head movements is strongly related to the movement velocity, thus fast movements are smooth while slow movements are jerky. In addition, movements of larger amplitude are less smooth than movements of smaller amplitude.

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1. Introduction

Natural, unconstrained voluntary movements in humans are normally smooth and exhibit a near symmetrical, bell-shaped velocity profile containing a single velocity peak with approximately equally long acceleration and deceleration phases. Such profiles have been reported in studies addressing movements such as reaching, pointing and grasping and across several species (Aflalo & Graziano, 2007; Alstermark, Lundberg, Pettersson, Tantisira, & Walkowska, 1993; Atkeson & Hollerbach, 1985; Ostry, Cooke, & Munhall, 1987; Paulignan, MacKenzie, Marteniuk, & Jeannerod, 1990). When temporal or spatial accuracy constrains are introduced, the movements become less smooth, and irregularities in the velocity profiles have been reported across various species (Milner & Ijaz, 1990; Roitman, Massaquoi, Takahashi, & Ebner, 2004; Thompson, McConnell, Slocum, & Bohan, 2007). The irregularities within the movements have been suggested to be submovements, appearing as down scaled, bell-shaped velocity peaks (Crossman & Goodeve, 1983; Krebs, Aisen, Volpe, & Hogan, 1999; Milner, 1992).

Movements of patients with neurological injury and diseases are less smooth compared with healthy controls and are characterized by submovements within the velocity profile (Rohrer et al., 2002; Smith, Brandt, & Shadmehr, 2000; Teulings, Contreras-Vidal, Stelmach, & Adler, 1997; Tsao & Mirbagheri, 2007). Also in musculoskeletal neck pain, movements are shown to be less smooth and more irregular compared with controls without pain (Feipel, Rondelet, LePallec, DeWitte, & Rooze, 1999; Grip, Sundelin, Gerdle, & Karlsson, 2008; Sarig Bahat, Weiss, & Laufer, 2010; Sjölander, Michaelson, Jaric, & Djupsjöbacka, 2008). Consequently, increased irregularity and reduced smoothness of movement as compared to control situations have been considered a sign of altered motor behavior and impaired motor performance (Sjölander et al., 2008; Smith et al., 2000; Teulings et al., 1997).

However, it has been observed in healthy participants that when relatively unconstrained movements are completed with reduced velocity, irregularities appear on the velocity tracings (Darling, Cole, & Abbs, 1988; Milner, 1992; Milner & Ijaz, 1990; Morasso, Ivaldi, & Ruggiero, 1983). For example, Morasso et al. (1983) noted that while planar pointing movements performed at natural speed displayed a single peaked velocity profile, more velocity peaks appeared at slower movements. Similarly, in a time-constrained pinching task, Darling et al. (1988) reported that while 100 ms movements of the thumb and index finger were completed with a single submovement, 200–400 ms pinches contained a series of submovements. Although no statistical analysis of smoothness or irregularity between movements velocities were completed in either of these studies, the descriptions of increased irregular velocity profiles at relatively slow movements imply a relationship between movement velocity and smoothness. Using spatio-temporal constrained arm movements, van der Wel, Sternad, and Rosenbaum (2009), found an overall statistically significant effect of standardized movement times on the number of velocity peaks within a movement. Although the accuracy constraints in their study were relatively limited, the arm movements were completed in a continuous, rhythmic mode and paced by a metronome, which previously has been reported to reduce movement smoothness as compared to unpaced movements (Balasubramaniam, Wing, & Daffertshofer, 2004). Thus, these results accomplished for constrained movements may not directly apply to unconstrained movement. Although the above studies strongly suggest that a relationship between movement smoothness and velocity exist, to our knowledge, no statistically based evaluation of such a relationship in simple, unconstrained movements have been published. Of particular interest was to examine a relationship between smoothness and velocity in head and neck movements. As noted above, these movements are previously reported to be less smooth in humans with musculoskeletal neck pain as compared to unimpaired controls and this finding has been interpreted as a sign of altered motor control. However, since these movements were reported to be less fast and have less amplitude than for unimpaired control participants (Grip et al., 2008; Sarig Bahat et al., 2010), we wanted to examine whether the movement velocity and amplitude could be main sources of irregularity in head movements.

The goal of this study was thus to examine the relationship between movement smoothness and velocity of unconstrained movements in healthy human participants, and particularly to consider the case of head movements. We tested the hypothesis that overall movement smoothness is related

to movement velocity by systematically altering the velocity of movements in separate trials and for several different movement directions and amplitudes.

2. Methods

2.1. Participants

Twenty-six healthy men ($n = 12$) and women ($n = 14$) of 36.1 ± 8.4 ($M \pm SD$) years of age participated in the study. The participants were 173.8 ± 8.3 cm tall, weighed 75.0 ± 12.9 kg and the BMI was 24.7 ± 2.9 kg/m^2, all values close to the Norwegian average values. None of the participants in the study suffered from neurological or rheumatic disorders, had current head or neck complaints or had experienced recurrent periods of neck or head pain exceeding one week during the previous 2 years. The study was approved by the Regional Committee for Medical and Health Research Ethics, and all participants signed an informed consent form for participation in the study.

2.2. Test chair

A custom-made chair was constructed in order to be able to isolate the head and neck movements. The participant sat on an adjustable seat with a right-angled back support that was individually height-adjusted. The feet support was adjusted to keep the knee angle at approximately 90°. The participants were secured tightly to the chair by Velcro bands applied transversely around the arms and upper torso, as well as across the hips.

2.3. Procedures

All participants completed one separate training session to familiarize to the testing procedures 1–2 weeks prior to the measurements. All tests were supervised by two examiners. In sitting the participants were instructed to position themselves in their individual neutral position (NP) of the head when looking straight forward at the wall approximately 120 cm in front of the participants. At the participant's individual focus point on the wall, a 15 mm diameter dark blue dot was applied as reference for the NP. As the present study was the first using the presented experimental setup from our lab, we quantified the uncertainty of the outcome variables by testing the reliability of the measurement. Twelve participants who did not differ in age or anthropometrics from that of the other participants were retested two hours later using identical procedures as during the first test.

2.3.1. Movement directions and amplitudes

With the eyes open, the participants completed four movements corresponding to approximately half of their full range of motion and these were defined as small amplitude movements: forward flexion from NP (FFN), extension back to NP (EBN), extension from NP (EFN) and flexion back to NP (FBN). The movements started from the NP and stopped at the fully flexed or extended position (FFN and EFN) or started at the fully flexed or extended position and stopped at the NP (EBN and FBN). Additionally, 12 of the participants (7 men, 5 women) who did not deviate in age or anthropometrics from that of the other participants completed two full ranges of movements (100%) in the sagittal plane. These movements were defined as large amplitude movements: full extension in the posterior direction starting from a fully flexed position (EF) and full flexion in the anterior direction starting from a fully extended position (FF).

2.3.2. Movement speed conditions

To obtain a large range in movement angular velocity for each participant, they were tested at three different speed conditions. First, the participants were instructed to complete all the movements in a pace corresponding to what they perceived as their normal speed and was termed preferred speed (P), then with half of their preferred speed, termed slow speed (S) and finally with their maximum speed (M). To put as little constraints on the movements as possible, the participants were not given any

feedback on their performance during testing. For the S speed condition, the participant tended to move more slowly than half of the P speed. The order in which the direction of movements were performed was randomized for each participant. The participants were allowed to practice the movement directions and speed conditions before the test started. The participants completed 3 trials per speed condition for each direction and these were averaged for further analysis. All trials were accepted, except if the participants expressed that the movements deviated from what they had intended to do, then retrials were performed. In sum, participants performing the small amplitude movements completed a total of 36 trials, while the participants that in addition performed large amplitude movements completed 54 trials.

2.4. Kinematics

2.4.1. Sensor placements

Position data were sampled using an electromagnetic motion tracker (Liberty, Polhemus Inc. Colchester, Vermont, and USA). The system's reference frame, defined by the transmitter, was positioned such that the axis of *Z* was vertical and the axis of *x* and *y*, respectively, were parallel to the sagittal and frontal planes of the participant. Three sensors were placed on the head–neck in the following configuration: A sternum sensor was placed 15 mm caudally to incisura jugularis (p1), a second sensor was placed above proc. spinosus C7 (p2) and the third sensor (p3) was placed 5 mm above the arcus superciliaris (Fig. 1A). A fourth virtual point (p4) was created at the instantaneous axis of rotation C7 (IARC7, see procedures below), to measure the angular position of the head–neck from its center of rotation. The head orientation angle was calculated as the angle between the horizontal line and the vector from p4 to p3. Hence, the rotation of the vector around the *y*-axis defined the movement for the head and neck complex.

2.4.2. Radiography and determination of the instantaneous axis of rotation

To be able to determine the position of IARC7 we used radiograph images and calculated the placement relative to that of p1 and p2. Lateral radiographs (DigitalDiagnost, Philips) were taken from a separate population consisting of 31 (14 women) healthy participants without neck complaints (age 38.3 ± 11.0 years; height 177.7 ± 9.9 cm; weight 76.1 ± 13.3 kg) in the standing position using a film focus distance of 150 cm. Two dummy metal sensors with identical dimensions as the original sensors

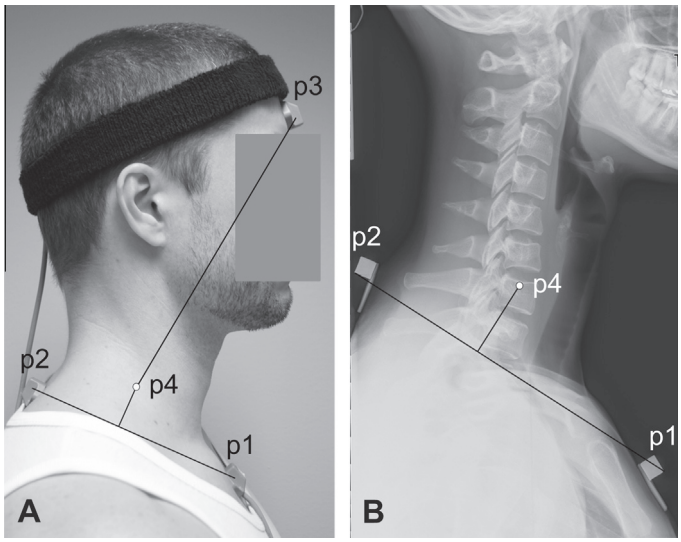

Fig. 1. A. The configuration of the three position sensors (p1, p2 and p3) and the fourth virtual point (p4) at the instantaneous axis of rotation C7 used for determination of head-neck movement from its centre of rotation. B. Lateral radiograph illustrating the method for construction of the virtual point (p4) relative to the p1 and p2 sensors.

were placed on p1 and p2 as described above, and used as reference. Radiographs were imported to the ImageJ software, version 1.31 (Rasband, W.S., National Institute of Health, USA) and the IARC7 was estimated and marked on the image according to the procedures of Amevo, Worth, and Bogduk (1991). The position of the IARC7 was measured relative to that of the dummy sensors. First, a line between the two dummy sensors (p1 and p2) was drawn and measured (180.4 ± 15 mm, *M* ± *SD*). A normal from the point of IARC7 to the interception with this line were subsequently drawn. The distances p1 – point of interception and the distance p4 (IARC7) – point of interception were normalized to the length of p1–p2 (57.2 ± 2.9% and 19.8 ± 4.5%, respectively) (Fig. 1B). There were no gender differences for these relative values. Hence, these mean relative measures were subsequently applied in the establishment of the individual p4 (IARC7) in the present study. The position of p4 was fixed relative to that of the p1, consequently; any positional changes for the p1 (sternum) would be similarly reflected in p4.

2.4.3. Signal reduction and data analysis

Position data were sampled at 240 Hz for each channel and analyzed off-line in MatLab. The signals were filtered using a quintic Woltring spline with a cutoff frequency of 6 Hz, chosen subsequent to a residual analysis (Winter, 2005). The quintic spline additionally defines the higher order derivatives (velocity, acceleration and jerk). Since the choice of threshold defining the movement onset and offset based upon relatives of the peak velocity will affect the kinematic variables in the study, comparative analyses using 4% and 10% of peak angular velocity as thresholds were conducted for the EFN movement direction. We also examined whether both thresholds could detect a relationship between movement velocity and smoothness. As the 4% threshold incorporates a larger part of the movement than the 10% limit, we chose to use 4% of peak angular velocity as the threshold for start and stop in this study. If the signal fluctuated across this 4% threshold, the final crossing was used for the offset. Movement duration and displacement were respectively the time and angular position difference between the movement onset and offset. To examine the angular velocity profile for regularity, the number of submovements within trials were counted and defined as the periods between two subsequent zero-crossings of the acceleration signal in direction from negative to positive values (Ketcham, Seidler, van Gemmert, & Stelmach, 2002). To measure the overall smoothness of the movement, we calculated the normalized jerk cost (NJC) according to Teulings et al. (1997), i.e., $\sqrt{(½ \int dt\, j^2(t) \times \text{duration}^5/\text{displacement}^2)}$, where "j" is the third derivate of position. The NJC is a unit-free measure and normalized for both duration and displacement, two factors that are known to strongly affect the jerk cost function of a movement (Schneider & Zernicke, 1989). Consequently, the NJC allows for comparison of the smoothness of movements across diverse durations and displacements. Large values signify reduced smoothness and low values signify increased smoothness. Hogan and Sternad (2009) showed, using a mathematical model, that the NJC scores increase both with increasing number of speed peaks in the movement and the magnitude of speed fluctuations between speed peaks, in consequence displaying the efficacy of the NJC to measure both smoothness and non-smoothness.

2.5. Statistics

Data are given as mean ± *SD*. To test for differences for the outcome variables between the S, P and M speed conditions within a given movement direction and movement amplitude, we used one-way repeated measures ANOVA and Bonferroni post hoc tests. The independent, within-subject factor was speed conditions and the dependent factor was the kinematic outcome variables. To examine possible relationships between NJC, average movement angular velocity and movement direction and amplitudes we used a linear mixed factor model with the participants as random factor. Since a scatter plot of the average angular velocity and NJC displayed a curvilinear relationship, while a log–log plot showed an approximate linear relationship (see Appendix, Fig. A.1), log-transforms were used in the analyses. Pearson's correlation coefficient was used to explore a possible relationship between age and the main outcome variables for all small amplitude movements at the P speed condition. This test was also used to examine a relationship between NJC and the number of submovements across the four small amplitude movements. Paired *t*-tests were used to test for differences in the outcome variables when comparing 4% and 10% of the peak velocity as threshold value for movement onset and offset. To test for reliability of our main outcome variables, we calculated the intraclass correlation

coefficient (ICC) model 1,1 (Shrout & Fleiss, 1979) and the coefficient of variation (CV). CV was calculated as the within-subject standard deviation divided by the pooled mean across tests and multiplied by 100. Tests are two-sided and *p*-values less than .05 were considered statistically significant. Statistical analyses were performed using the SPSS 18 and JMP 9.0 statistical packages.

3. Results

3.1. Reliability

The reliability of our main outcome variables is shown in Table A.1 (Appendix). In general, the ICC values for duration, displacement and peak and mean angular velocity were acceptable for all movement directions and amplitudes (median value .83; range .66–.95), while the ICC for NJC was more variable, ranging from .33 to .96 (median .69). While the CV was low for duration, displacement and peak and average angular velocity (median value 11.7%; range 5.6–21.5%), the variation was somewhat greater for NJC (median value 31.9; range 13.8–39.8%).

3.2. Duration, displacement and angular velocity

We found no significant systematic effect of age (range 23–51 years) upon movement duration, displacement, peak and average angular velocity, number of submovements or NJC for the P speed condition in any of the four small amplitude movements. Table 1 shows the data for movement duration, displacement and peak and average angular velocity for the three different speed conditions at each of the six different movements. Movement displacement did not differ significantly between the three speed conditions during EFN, FBN, EF and FF, while the displacement during M speed condition differed statistically significantly from that during P and S speed conditions in the FFN and EBN movements (all $p < .01$). Relative to that of the P speed condition, the average angular velocity of the M speed condition was some 3.4 times higher (range 3.0–3.6) while the S speed condition was .4 times lower (range .36–.44) for the four small amplitude movements. The corresponding pooled relative angular velocity values for the M and S speed conditions for the large amplitude movements were

Table 1
Average kinematic data (±SD) for the three speed conditions at each of the six different movements. Significant differences from the P speed condition; ***, $p < .001$; **, $p < .01$.

Movement		Test	Duration (s)	Displacement (°)	Peak velocity (°/s)	Average velocity (°/s)
EFN	($n = 26$)	S	3.72 ± 1.27***	56.8 ± 14.5	31.9 ± 14.6***	17.3 ± 7.3***
		P	1.47 ± .57	55.9 ± 15.3	78.7 ± 26.6	41.4 ± 12.9
		M	.47 ± .14***	57.3 ± 14.5	249.1 ± 66.9***	133.4 ± 48.7***
FBN	($n = 26$)	S	3.62 ± 1.27***	62.4 ± 16.3	39.1 ± 18.5***	20.1 ± 9.5***
		P	1.37 ± .48	60.8 ± 17.2	91.6 ± 26.0	47.0 ± 13.4
		M	.50 ± .17***	63.4 ± 14.3	265.5 ± 69.0***	135.6 ± 41.0***
FFN	($n = 26$)	S	3.74 ± 1.50***	49.6 ± 7.4	30.5 ± 13.2***	15.6 ± 7.1***
		P	1.17 ± .41	48.9 ± 9.4	88.6 ± 30.6	46.0 ± 15.7
		M	.39 ± .09***	55.5 ± 10.9**	278.8 ± 76.5***	148.7 ± 43.9***
EBN	($n = 26$)	S	3.35 ± 1.28***	53.4 ± 8.0	32.0 ± 13.6***	18.5 ± 7.7***
		P	1.28 ± .29	51.4 ± 11.2	88.0 ± 33.7	42.9 ± 15.5
		M	.43 ± .10***	60.0 ± 12.8***	292.7 ± 81.8***	144.1 ± 41.3***
EF	($n = 12$)	S	6.42 ± 2.97***	106.0 ± 12.0	36.6 ± 15.6***	20.1 ± 8.4***
		P	1.62 ± .50	108.5 ± 12.6	141.8 ± 49.3	74.1 ± 26.1
		M	.54 ± .16***	115.2 ± 15.9	429.6 ± 93.5***	228.4 ± 70.4***
FF	($n = 12$)	S	6.16 ± 2.63***	106.7 ± 12.7	38.4 ± 16.9***	20.5 ± 8.6***
		P	1.48 ± .44	107.5 ± 12.1	144.2 ± 43.8	78.7 ± 23.1
		M	.56 ± .19***	114.5 ± 17.1	410.8 ± 115.4***	221.3 ± 71.4***

Abbreviations: NP – neutral head position, EFN – extension from NP, FBN – flexion back to NP, FFN – flexion from NP, EBN – extension back to NP, EF – full extension, FF – full flexion, S – slow movement speed, P – preferred movement speed, M – maximum movement speed.

3.1 and .3, respectively. While the average angular velocity at the M and P speed conditions were 1.6 and 1.7 times greater for the large (n = 12) versus the small (n = 26) amplitude movements pooled, respectively, the S speed condition was performed at equal average angular velocity for the two different movement amplitudes.

3.3. Movement smoothness

The NJC differed between velocities for all movements (Table 2). The P and M speed conditions displayed relatively low NJC values and were of similar magnitude irrespective of movement direction or amplitude, thus representing smooth movements. In contrast, the S test expressed large NJC values across all six movements. As shown in Fig. 2, the angular velocity profiles, taken from a representative participant, was also clearly different between test speeds. While the M- and many of the P speed conditions were relatively unimodal in the angular velocity profile shape, the S speed condition typically displayed multiple velocity peaks, indicating the increase in the number of submovements by reduced speed condition across all movements (Table 2). We also found a strong positive correlation between NJC and number of submovements for the four small amplitude movements pooled (r = .93). About 90% of the trials were completed using only 1 submovement at the M speed condition. For the P speed, about 37% of the trials was completed by 1 submovement for the small amplitude case and 17% for the large amplitude movements. None of the trials at the S speed condition for any movement condition were completed by one submovement only. Consequently, some of the trials at the M and the P speed conditions were more irregular (Fig. 3). There was a general tendency for the large amplitude movements to be more irregular than the short amplitude movements, both measured as NJC and number of submovements.

3.4. Relationship between movement angular velocity and smoothness

As illustrated in Figs. 4 and 5A, we found a strong effect of movement angular velocity on overall movement smoothness as assessed by the NJC. This was true for all movement directions and amplitudes (all $p < .0001$). When comparing the four small – with the two large amplitude movements, the

Table 2
Normalized jerk cost (a.u.) and number of submovements for the three speed conditions at each of the six movements. Results are mean ± SD. Significant differences from the P speed test; ***, $p < .001$; **, $p < .01$; *, $p < .05$.

Movement		Test	NJC (a.u.)	Submovements (no.)
EFN	(n = 26)	S	407.4 ± 329.6***	10.5 ± 5.6***
		P	53.8 ± 36.5	2.2 ± 1.4
		M	32.0 ± 20.6*	1.2 ± .4**
FBN	(n = 26)	S	413.7 ± 339.2***	10.5 ± 6.0***
		P	45.2 ± 28.2	1.6 ± .9
		M	21.4 ± 8.5***	1.0 ± .1**
FFN	(n = 26)	S	534.5 ± 528.1***	12.1 ± 7.3***
		P	39.3 ± 24.8	1.7 ± .8
		M	17.7 ± 8.6***	1.0 ± .1**
EBN	(n = 26)	S	327.7 ± 325.8***	10.4 ± 7.6***
		P	43.8 ± 18.0	1.4 ± .5
		M	22.9 ± 6.2***	1.0 ± .1**
EF	(n = 12)	S	1225.1 ± 1316.8*	21.3 ± 14.2**
		P	52.4 ± 22.1	2.0 ± .6
		M	23.7 ± 16.2**	1.1 ± .3**
FF	(n = 12)	S	1193.2 ± 1240.4*	19.6 ± 11.8**
		P	45.8 ± 22.2	1.9 ± .9
		M	19.4 ± 9.6**	1.1 ± .3*

Abbreviations: NP – neutral head position, EFN – extension from NP, FBN – flexion back to NP, FFN – flexion from NP, EBN – extension back to NP, EF – full extension, FF – full flexion. S – slow movement speed, P – preferred movement speed, M – maximum movement speed.

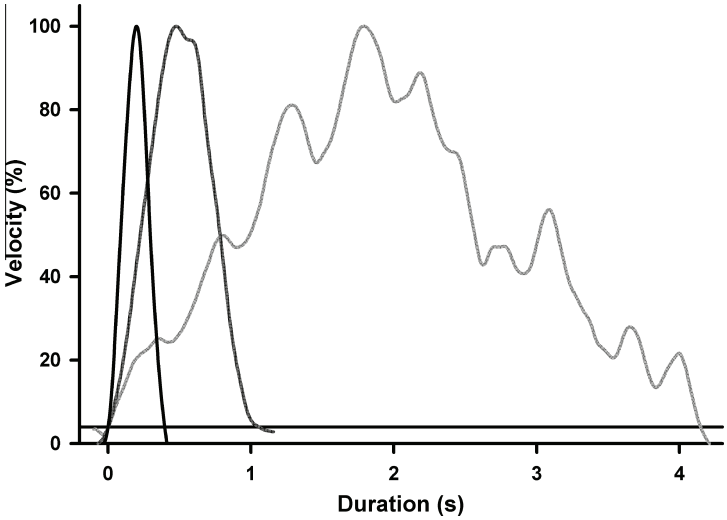

Fig. 2. Example of normalized velocity versus absolute time for the three speed conditions (M; black line, P; dark grey line, S; light grey line) from one subject for the flexion from neutral position movement. The subject scored approximately median values for all speed conditions. Solid horizontal line depicts the relative value of peak velocity defining movement onset and offset (4%).

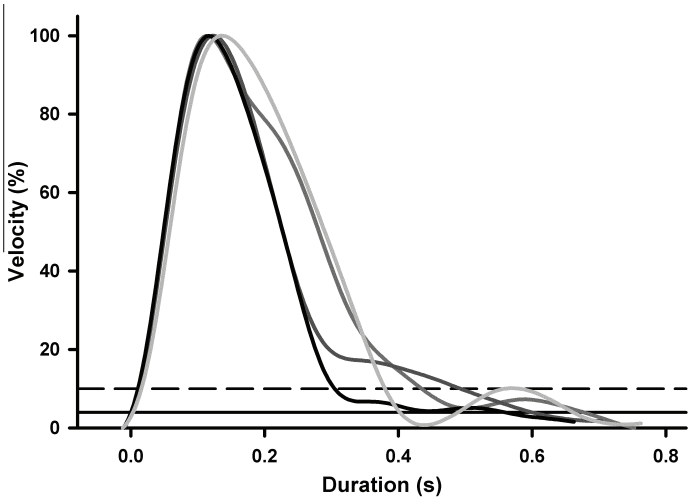

Fig. 3. Examples of non-smooth movements at the M speed condition for the extension from neutral position of 4 subjects. The velocity profiles (different shades of grey) represent separate trials and subjects. Horizontal line corresponds to the relative value of peak velocity defining movement onset and offset (4%). Dashed line represents 10% of peak velocity. Velocity is normalized (%) and time absolute (s).

large amplitude movements display higher NJC values for a given average angular velocity ($p < .001$, Fig. 5A). We also found a small, but statistically significant difference between the four small amplitude movements; the EFN displayed higher NJC for a given angular velocity than the other small amplitude movements ($p < .05$).

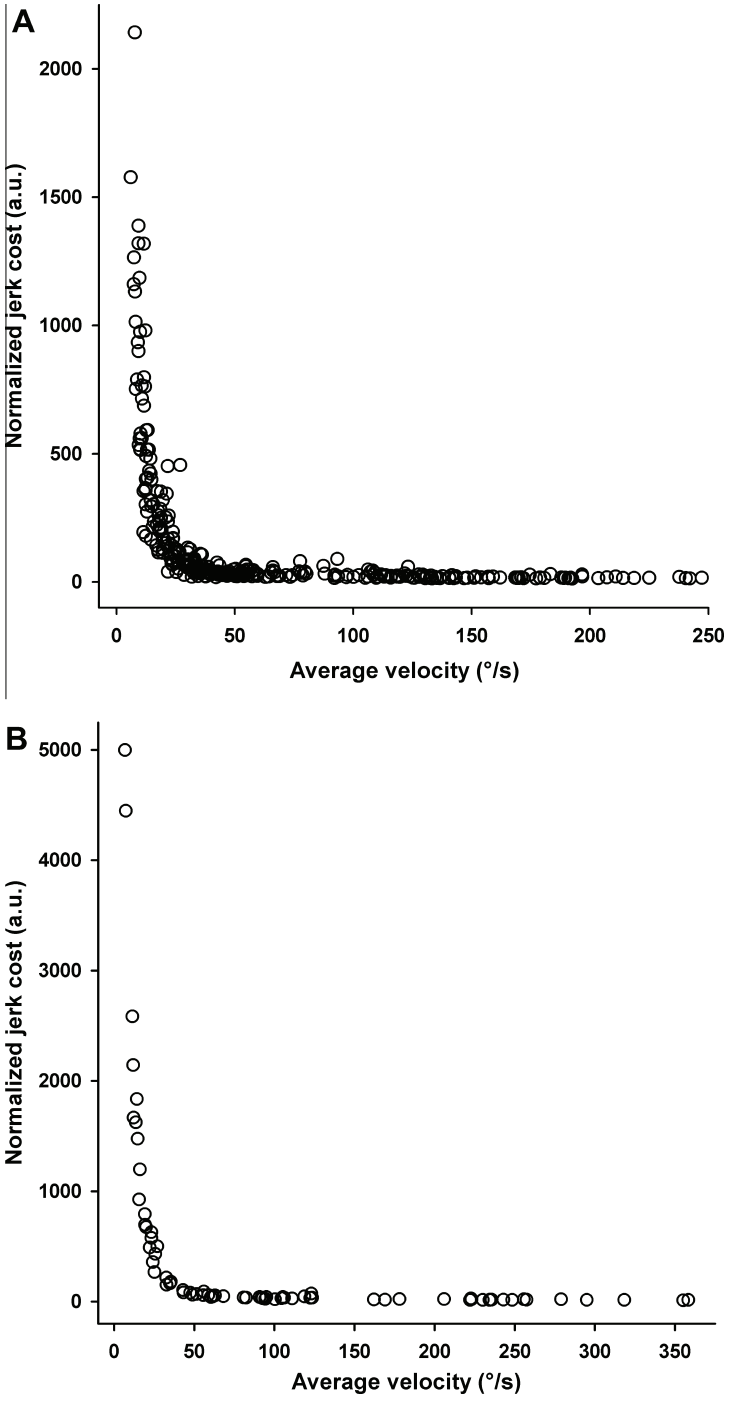

Fig. 4. Relationship between normalized jerk cost (a.u.) and average velocity (°/s) across all speed conditions for the four small (n = 26) and two large amplitude movements (n = 12). Small amplitude movement consists of 312 separate trials and large amplitude movements 72 trials.

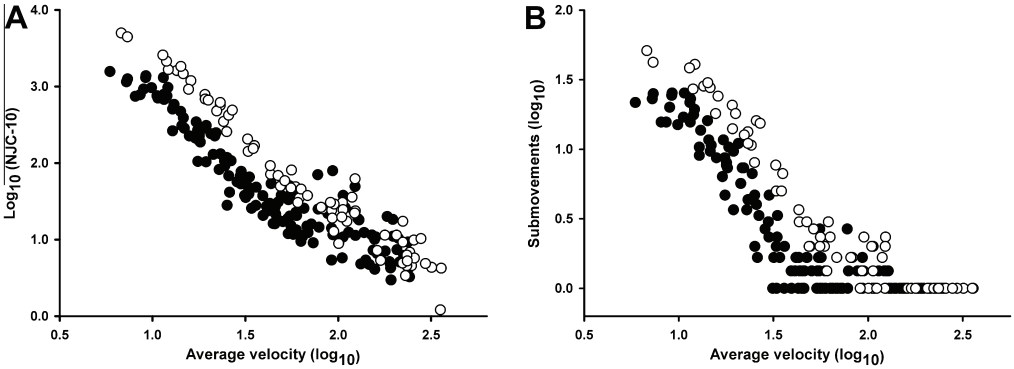

Fig. 5. Log-log plots for average velocity versus A; NJC(-10) and B; number of submovements, for all speed conditions in four small amplitude movements pooled (filled circles, 144 trials) and two large amplitude movements pooled (open circles, 72 trials) in 12 subjects.

3.5. Movement threshold

With the exception of peak velocity, there were significant differences between the 4% and 10% of peak velocity thresholds for the movement onset and offset on all kinematic outcome variables, although the numerical differences were moderate (see Appendix Table B.1 for detailed results). The relationship between movement smoothness and movement velocity was found using both thresholds (Appendix Fig. B.1).

4. Discussion

The main finding in this study was that the smoothness of unconstrained voluntary head movements in healthy humans is strongly dependent on the movement angular velocity. This relationship was found for all movement directions and amplitudes. However, the two large amplitude movements displayed higher NJC values for a given angular velocity than small amplitude movements.

4.1. Are slower movements less smooth than faster ones?

Everyday movements, such as walking, reaching and pointing appear to be executed smoothly when the precision demands of the movements are limited. When such movements are time- and velocity normalized, the velocity profiles typically display approximately symmetrical bell-shaped forms and are reported to be invariant over a threefold increase in movement velocity (Atkeson & Hollerbach, 1985). In line with this, we observed unimodal velocity profiles containing a single submovement over a relatively large range in angular velocity. However, the frequency of unimodal velocity profiles was gradually reduced as the velocity of movement decreased and the main finding was that the overall smoothness of head movements was strongly dependent upon the movement angular velocity and this relationship was observed for all head movement directions and amplitudes examined (Fig. 4). Examples of representative individual velocity profiles for the three different speed conditions are illustrated in Fig. 2. As seen from this figure, there is a clear difference in the velocity profiles between the three speed conditions, which is a visual representation of the statistical difference in both NJC values and the number of submovements between speed conditions (Table 2). The velocity profile of the S speed trials (Fig. 2) are very similar to the profiles described previously in slow, moderately constrained arm and finger movements in healthy participants (Darling et al., 1988; Milner, 1992; Milner & Ijaz, 1990; Morasso et al., 1983). Our findings are therefore in line with their observations. Similar findings have also been reported for spatio-temporal constrained movements. van der Wel et al. (2009) found that repetitive, back and forth slower arm movements displayed sta-

tistically significant more submovements than faster movements. Our findings extend these results to unconstrained head movements, indicating that slower movements are less smooth than faster movements over a wide range of movement situations and anatomical regions.

Even though there is a strong association between speed and smoothness, both NJC and submovements show some variation at a given speed. The moderate reliability for NJC at preferred speed underscores this finding, although there was also some variation in velocity in the test–retest. It seems likely that difference in movement displacement may generate some of this variation in smoothness since we found an effect of movement displacement upon movement smoothness at a given velocity. However, it is also possible that an underlying, true individual difference in movement smoothness explains parts of this variation in NJC and submovements at a given velocity.

4.2. Why are slower movements less smooth than faster ones?

For a chosen set of data consisting of movements of about 55° displacement, we observed unimodal velocity profiles for velocities ranging from 203°/s (261 ms) to 31°/s (1763 ms), which suggests that a single submovement could be scaled in terms of a velocity and time factor above 6 to cover a given movement. Lower velocities movements were all completed with additional submovements. This is in line with the results of Milner and Ijaz (1990), who reported that for deliberately prolonged pointing movements from about 380 ms to about 1000, irregularities appeared in the velocity profile, thus which they suggested to be a series of overlapping submovements. Therefore it seems to be a lower limit for which a single submovement can be scaled to cover a given movement. Milner and Ijaz (1990) proposed the hypothesis that the appearance of submovements were related to the regulation of movement duration. They speculated whether single motor commands of long duration was difficult to generate and that movements of long duration was approximated by an overlapping sequence of submovements at shorter intervals. Our results may strengthen the hypothesis proposed by Milner and Ijaz (1990) since in addition to movement speed we also examined different amplitudes. We found the trials with the longest duration that were composed of a single submovement had similar movement duration for both movement amplitudes (1763 ms for the small amplitude- and 1860 ms for the large amplitude movements). Thus, an approximate doubling of the movement amplitude did not increase the total movement time for a movement consisting of a single submovement. Our findings suggest that unconstrained movements at the middle and faster end of the speed continuum are mostly accomplished by temporal scaling of a single submovement to cover the movement, which is in accordance with previous studies. At the slower end of the speed continuum, a single submovement cannot longer scale to cover the movement but is completed by additional submovements. Such repetitive submovements have been suggested to be of central origin. Vallbo and Wessberg (1993) demonstrated that for slow tracking movements of the finger, velocity peaks was reoccurring at about 8–10 Hz. Furthermore, they found these submovements to be driven by pulsative gross muscle activation patterns of both the agonist and antagonist muscles. The single motor unit activity and acceleration signal of both finger and wrist movements display coherence (Kakuda, Nagaoka, & Wessberg, 1999; Wessberg & Kakuda, 1999) and pairs of motor units correlate (Kakuda et al., 1999) around these frequencies, which are pointing towards a common modulation of motor unit activity. A common modulator of motor unit firing during slow finger movement has been identified in the sensimotor cortex both in humans and monkeys (Gross et al., 2002; Williams, Soteropoulos, & Baker, 2009) and is regulated by synchronized, oscillatory activity in the cerebello–thalamo–cortical loop (Gross et al., 2002). This firm connection between cerebral neural activity, muscle activity and movement imply that passive mechanical factors do not play a central role in the origin of submovements. However, as we have no data quantifying either central or peripheral activation patterns, we cannot confirm such a hypothesis although it fits well with the pulsatile behavior of the velocity tracings during slow movements in the present study.

4.3. Effect of movement amplitude

The large amplitude movements displayed higher NJC values for a given average angular velocity than the small amplitude movements (Fig. 5A). This was somewhat unexpected, since NJC is normal-

ized for duration and displacements and thus movements completed by a single submovement should display similar NJC values, irrespective of movement velocity. However, when comparing the trials composed of one single submovement for the M speed condition, the small and large amplitude movements did display almost identical NJC-values despite a large difference in both displacement and angular velocity, thus they were equally smooth. Since the M and P speed conditions were completed at substantially greater average movement angular velocity at the large amplitude movements than the small amplitude movements, this implies that the large amplitude movements are jerkier than small amplitude movements when comparing equal angular velocities. The clear difference in NJC between the two movement amplitudes appears when they are exerted equally fast at the low angular velocity continuum (S speed condition; Fig. 5A). For the S speed condition, both movement amplitudes were completed at comparable angular velocities, but the large amplitude movements displayed far higher NJC-values and approximately twice the number of submovements compared to the small amplitude movements. Thus, if the movement amplitude is increased while movement velocity is unchanged, the number of submovements necessary to complete the movement is increased.

4.4. The effect of threshold for movement onset and offset

We conducted a comparative analysis of threshold values of 4% and 10% of peak velocity for the EFN movement and found moderate numerical effects on the kinematic variables in general. However, some trials of the M speed condition were composed of several submovements when analyzed using the 4% threshold and for some of these trials the additional submovements were removed when using the 10% threshold, since they appeared at low velocity towards the end range of the movement (Fig. 3). Consequently, the choice of threshold had a relatively large impact upon the kinematic variables for these given trials. We therefore chose to use the 4% threshold in the present study since it included a larger part of these movements and not only the smoother part. However, for the main topic of this study, the choice of threshold did not appear to be critical, since the relationship between movement angular velocity and movement smoothness was identified using either threshold (Fig. B.1).

4.5. Implications

Previous studies have reported differences in the smoothness of movement between various groups of participants. Arm movements in children and senior adults are shown to be less smooth than compared to young adults (Ketcham et al., 2002; Poston, van Gemmert, Barduson, & Stelmach, 2009; Yan, Thomas, Stelmach, & Thomas, 2000) and head movements in musculoskeletal neck pain are less smooth than compared with healthy controls (Grip et al., 2008; Sarig Bahat et al., 2010; Sjölander et al., 2008), implying altered motor control patterns. In several of these studies, the speed of movement also differed between the compared groups (Grip et al., 2008; Ketcham et al., 2002; Poston et al., 2009; Sarig Bahat et al., 2010; Yan et al., 2000). However, these studies did not examine whether the exerted speed and the smoothness of the movement were related. It is therefore possible that movement smoothness is not only affected by age or pain per se, but may in addition be an accompanying result of differences in movement speed and amplitude. Hence, the present findings might have implications for how to assess and compare movement smoothness both in unimpaired humans and in clinical studies. Both the velocity and displacement of the movement should be taken into consideration when designing and interpreting studies comparing movement smoothness of different age groups or populations.

5. Conclusions

We have shown that the smoothness of head movements is strongly related to the movement velocity, thus fast movements are smooth while slow movements are jerky. In addition, movements of larger amplitude are less smooth than movements of smaller amplitude.

Acknowledgments

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Appendix A

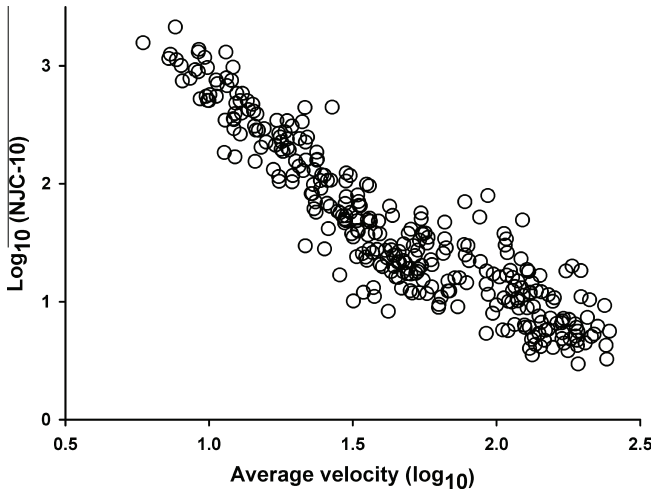

Fig. A.1. Relationship between average velocity (log_{10}) and NJC(-10) (log_{10}) across all speed conditions for all small amplitude movements pooled (26 subjects, 312 trials).

Table A.1
Test–retest reliability of the main outcome variables for all movement directions for the P speed condition ($n = 12$). Reliability is measured by the intraclass correlation coefficient (ICC1,1) with 95% CI and coefficient of variation (CV).

Direction		Duration	Displacement	Peak velocity	Mean velocity	Norm. Jerk Cost
EFN	ICC	.87 (.63–.96)	.81 (.47–.94)	.66 (.18–.89)	.63 (.14–.88)	.72 (.30–.91)
	CV	16.0	7.7	20.8	21.5	39.8
FBN	ICC	.95 (.83–.98)	.69 (.25–.90)	.66 (.20–.89)	.71 (.28–.91)	.96 (.88–.99)
	CV	9.5	9.1	15.8	15.8	13.8
FFN	ICC	.78 (.41–.93)	.88 (.64–.96)	.88 (.64–.96)	.90 (.70–.97)	.33 (−.25–.75)
	CV	14.1	6.4	11.6	11.3	38.4
EBN	ICC	.68 (.22–.89)	.90 (.71–.97)	.89 (.67–.97)	.82 (.51–.94)	.42 (−.15–.79)
	CV	15.0	6.0	11.8	15.0	34.6
EF	ICC	.80 (.46–.94)	.75 (.35–.92)	.84 (.55–.95)	.83 (.54–.95)	.66 (.18–.89)
	CV	15.0	6.3	14.2	13.9	29.1
FF	ICC	.90 (.70–.97)	.78 (.42–.93)	.87 (.64–.96)	.91 (.73–.97)	.78 (.42–.93)
	CV	10.8	5.6	11.1	9.3	28.9

Abbreviations: NP – neutral head position, EFN – extension from NP, FBN – flexion back to NP, FFN – flexion from NP, EBN – extension back to NP, EF – full extension, FF – full flexion.

Appendix B

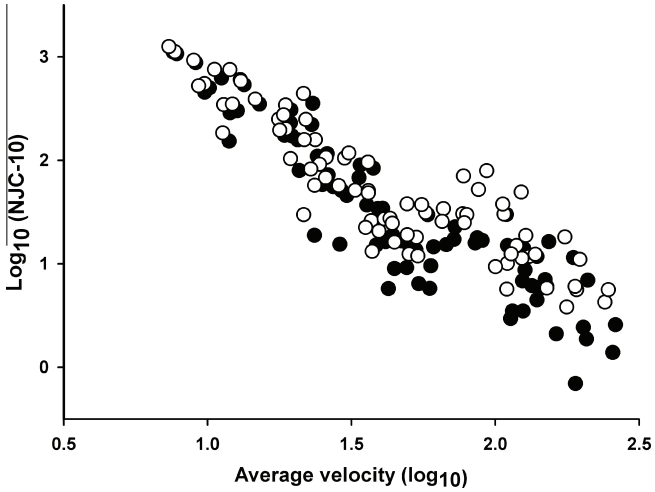

Fig. B.1. Relationship between average velocity (log_{10}) and NJC(-10) (log_{10}) across all speed conditions for the EFN movement at movement threshold values of 4% (open circles) and 10% (filled circles) of the peak velocity (26 subjects, 78 trials at each threshold).

Table B.1
Differences in the main outcome variables for the three different speed conditions at the extension from the neutral position movement using 4% or 10% of peak velocity as threshold for movement onset and offset. Significantly different from the 4% threshold; **, $p < .001$; *, $p < .05$.

Speed	Cutoff (%)	Duration (s)	Displacement (°)	Mean velocity (°/s)	NJC (a.u.)	Submovement (no.)
S	4	3.72 ± 1.27	56.8 ± 14.5	17.3 ± 7.3	407.4 ± 329.6	10.5 ± 5.6
	10	3.49 ± 1.26**	56.3 ± 14.3**	18.5 ± 8.2**	354.1 ± 306**	10.0 ± 5.5**
P	4	1.47 ± .57	55.9 ± 15.3	41.4 ± 12.9	53.8 ± 36.5	2.2 ± 1.4
	10	1.31 ± .53**	55.2 ± 15.2**	45.9 ± 14.4**	39.1 ± 28.7**	2.0 ± 1.4*
M	4	.47 ± .14	57.3 ± 14.5	133.4 ± 48.7	32.0 ± 20.6	1.2 ± .4
	10	.39 ± .11**	56.4 ± 14.5**	149.9 ± 47.8**	18.5 ± 7.0**	1.1 ± .1*

Abbreviations: S – slow movement speed, P – preferred movement speed, M – maximum movement speed.

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Paper IV

Harald Vikne, Eva Sigrid Bakke, Knut Liestøl, Stian R. Engen and Nina Vøllestad. *Muscle activity and head kinematics in unconstrained movements in subjects with chronic neck pain; cervical motor dysfunction or low exertion motor output?* Re-submitted.

Muscle activity and head kinematics in unconstrained movements in subjects with chronic neck pain; cervical motor dysfunction or low exertion motor output?

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Abstract

Background. Chronic neck pain after whiplash associated disorders (WAD) may lead to reduced displacement and peak velocity of neck movements. Dynamic neck movements in people with chronic WAD are also reported to display altered movement patterns such as increased irregularity, which is suggested to signify impaired motor control. As movement irregularity is strongly related to the velocity and displacement of movement, we wanted to examine whether the increased irregularity in chronic WAD could be accounted for by these factors.

Methods. Head movements were completed in four directions in the sagittal plane at three speeds; slow (S), preferred (P) and maximum (M) in 15 men and women with chronic WAD and 15 healthy, sex and age-matched control participants. Head kinematics and measures of movement smoothness and symmetry were calculated from position data. Surface electromyography (EMG) was recorded bilaterally from the sternocleidomastoid and splenius muscles and the root mean square (rms) EMG amplitude for the accelerative and decelerative phases of movement were analyzed.

Results. The groups differed significantly with regard to movement velocity, acceleration, displacement, smoothness and rmsEMG amplitude in agonist and antagonist muscles for a series of comparisons across the test conditions. The group differences in peak movement velocity and acceleration persisted after controlling for movement displacement. Controlling for differences between the groups in displacement and velocity abolished the difference in measures of movement smoothness and rmsEMG amplitude.

Conclusions. Simple, unconstrained head movements in participants with chronic WAD are accomplished with reduced velocity and displacement, but with normal muscle activation levels and movement patterns for that velocity and displacement. We suggest that while reductions in movement velocity and displacement are robust changes and may be of clinical

importance in chronic WAD, movement smoothness of unconstrained head dynamic movements are not.

Keywords

Whiplash associated disorder, persistent neck pain, movement kinematics, electromyography, neck muscles, movement smoothness.

Background

People having long-term musculoskeletal neck pain after motor vehicle accidents (Whiplash associated disorders - WAD) may have pronounced disability that affects daily living [1]. One of the most prominent clinical manifestations in persons with long-term WAD is cervical motor dysfunction [2], signified by altered neck muscle activation and reduced peak motor output. For example, measures of peak performance such as low load isometric endurance and maximum voluntary isometric contraction force (MVC) of neck- and shoulder girdle muscles are known to be reduced in chronic WAD compared with controls [3-9]. For relatively unconstrained dynamic head movements, kinematic performance variables such as peak velocity are also lower than in healthy participants [10, 11] and the peak head movement displacement is typically reduced in people with chronic WAD [10-17]. Collectively, these alterations reduce the functional capacity of the head and neck in people with chronic WAD.

The causes for the reductions in peak kinematic performance variables in chronic WAD are less clearly understood. It has been shown that the activation of neck muscles is altered in chronic WAD as compared with healthy subjects [5, 18] and such changes may potentially affect the head kinematics. However, these results were obtained from studies of isometric neck muscle contractions at low to moderate muscle forces [5, 18]. It is therefore possible that these observations are not directly applicable to dynamic head movements. In a study of movement kinematics in chronic WAD and control participants, Sjölander [19] found no difference in peak movement velocity when taking movement displacement into consideration. Because of the close relationship between the kinematic parameters of displacement and peak velocity [20], it is therefore possible that reductions in head displacement may contribute to the reductions in peak head movement velocity in chronic WAD.

In addition to measures of peak performance, the regularity or smoothness of neck movements in people with chronic neck pain are observed to be reduced compared with healthy controls [11, 15, 19, 21]. Smooth movements are characterized by approximately bell-shaped and unimodal velocity profiles [22], while movements of reduced smoothness exhibit multi-peaked, irregular velocity profiles containing a series of accelerative and decelerative phases. Such irregular movement patterns have been suggested to be a consequence of motor control disturbance in people with persistent WAD[11, 19]. In a previous study, the irregularity of movement was shown to be strongly related to both the movement velocity and displacement across a series of different head movements in healthy participants [23]. Since it is known that people with chronic WAD perform with both lower movement velocity and less displacement compared with controls, it raises the question of whether the reduced smoothness of movements observed in people with chronic WAD may simply be caused by altered movement velocity and displacement and not altered movement control strategies.

In this study we compared head kinematics and muscle activation in relatively unconstrained neck movements at three different speeds in participants with and without chronic WAD. In addition comparisons were made taking both movement velocity and displacement into consideration.

Methods

Participants

We examined 15 patients (six men and nine women) suffering from chronic WAD (> 6 months), classified as grade 2 according to the Quebec Task Force classification [24] and which started less than 72 hours after the motor vehicle accident. In addition, six men and nine women matched with the WAD group for sex and age (± 5 years) served as controls. The following exclusion criteria were used: WAD grade 3-4, pregnancy, age ≤ 18 or ≥ 60 years, unsettled insurance claims, systemic inflammatory diseases, neurological disorders, tremor, regular usage of analgesics and strongly reduced vision/blindness or auditory defects. All patients were recruited from a local rehabilitation clinic and examined by a specialist in physical medicine or neurology and a manual therapist before inclusion. Descriptive data for the participant groups are given in Table 1. The study was approved by the Regional Committee for Medical and Health Research Ethics, and all participants signed an informed consent form for participation in the study in accordance with the Helsinki declaration.

Overview and procedures

In this study we examined the movement performance of unconstrained head movements in the sagittal plane at three different speeds in participants with and without chronic WAD. Head movement performance was assessed with respect to displacement, velocity and acceleration and measures of movement smoothness and symmetry. Neck muscle activity was measured by means of surface electromyography (EMG) of agonist and antagonist muscles. Descriptive measures of anthropometry and overall strength were taken as they may affect the outcome variables in the study. All experiments were performed in a standardized laboratory setting. All participants completed one separate training session in order to familiarize themselves with the testing procedures 1 - 2 weeks in advance of the experimant. Tests were

completed in the following order; 1) maximum handgrip strength, 2) evaluation of pain intensity, 3) tests of head movements and 4) re-evaluation of pain intensity. Participants were given pauses ad libitum.

Descriptive data

Anthropometrics and grip strength. The participants' body height (cm) and weight (kg) were measured and the body mass index (BMI (kg/m^2)) calculated. Head volume was measured for men and women as described by McConville [25] and Young [26], respectively and a density of 1.05 kg/l [27] was used to estimate the head mass. As a measure of overall muscle strength [28, 29], hand grip strength was tested on a hand dynamometer (Model 78010, Lafayette Instruments) adjusted individually. The base rested on the first metacarpal and the bar on the second to fifth medial phalanx. Participants were told to squeeze as hard as possible and to maintain the force for three to four seconds. Each hand was tested two to three times (60 s inter-test pause) and the highest value was used in further analysis.

Self-reported questionnaires. A numerical rating scale (1 - 10) was used to assess subjective pain intensity in the neck and head region at the time of measurement, where 1 represents absence of pain and 10 the worst imaginable pain. Participants rated the pain intensity in the head and neck immediately before and after completion of the neck movement testing. The neck disability index (NDI) was used as a measure of physical disability due to neck pain [30]. Fear of movement and of movement-related pain in work and physical activity in general was measured using the fear avoidance beliefs questionnaires (FABQ) subscales work (FABQW) and physical activity (FABQPA) [31]. In line with previous studies in people with neck pain [32], we modified the FABQ by replacing the word back with neck. The health-related quality of life (HRQOL) was assessed by the generic SF-36, version 1 [33]. The

questionnaire's mental and physical component summary measures (MCS and PCS) were calculated using Norwegian normative values [34], where the population norm score is defined as 50 ± 10 (SD) for both scales.

Head movements

Movement directions. Four head movements were completed in a custom designed chair as previously reported [23]. While sitting the participants were instructed to position themselves in their individual resting position with respect to their head when looking straight forward at a wall that was approximately 120 cm in front of them. This was defined as their neutral head position (NP). At the participant`s individual focus point on the wall, a 15mm diameter dark blue dot was applied as an individual reference for the NP. The participants completed four head movements in the sagittal plane, each corresponding to approximately half of their full range of motion: forward flexion from NP (FFN), extension back to NP (EBN), extension from NP (EFN) and flexion back to NP (FBN). Participants were asked to move their head and neck as far as possible when starting from the NP and to stop at NP when starting from the fully flexed or extended position. The order of the direction of movements was randomized for each participant. Examples of two movement directions are shown in the top of figure 1.

Movement speeds. The participants were tested in three different speed conditions. First, the participants were instructed to complete all movement directions in a pace corresponding to what they perceived as their normal speed and which was termed preferred speed (P). Thereafter they were instructed to move at about half of their preferred speed, termed slow speed (S) and finally with their maximum speed (M). To put as little constrains on the movements as possible, the participants were not given any feedback on their performance

during testing. The participants were allowed to practice the movement directions and speed conditions before the test started. The participants completed 3 trials per speed condition for each direction and these were averaged for further analysis. All trials were accepted, except if the participants expressed that the movements deviated from what they had intended to do, then retrials were performed.

Kinematics

Data sampling and analysis. Position data were sampled using an electromagnetic motion tracker (Liberty, Polhemus Inc.) at 240Hz as previously described in detail [23]. The signals, analyzed off-line in MatLab, were filtered using a quintic Woltring spline with a cutoff frequency of 6 Hz. The quintic spline additionally defines the higher order derivatives (velocity, acceleration and jerk). Movement onset and offset were defined to be 4% of the peak angular velocity [23]. If the signal fluctuated across this 4% threshold, the final crossing was used for the offset. Movement duration and displacement were respectively the time and angular position difference between the movement onset and offset. The overall smoothness of the movement was calculated as the normalized jerk cost (NJC) according to Teulings [35]. To further examine the regularity of the movement, the number of submovements was counted as described by Ketcham [36]. Movement symmetry for movements consisting of one submovement was measured by the velocity profile symmetry index [37], taken as the time to peak velocity divided by total movement time. Values less than or above 0.5 indicate asymmetry in the velocity profile. For movements consisting of more than one submovement, the spatial occurrence of the submovements was calculated as the relative number of submovements started in each of the two movement halves. The reliability of this setup and kinematic outcome measures have been previously examined and shown to be acceptable [23].

Electromyography

Muscles and sensor placement. Electromyographic signals were sampled bilaterally from the sternocleidomastoid (SCM) and the splenius muscles. The signals were detected and pre-amplified 10x using single differential active surface sensors consisting of two parallel 10 x 1 mm silver electrode bars (DE-2.1, Delsys Inc.). The sensor placement on the SCM muscle were marked on the skin using published suggestions [38], then examined by ultrasound (US) imaging using a 10 MHz, 5 cm linear array probe (Vingmed, General Electrics) and adjusted if necessary. After locations were established, the skin was first shaved and then firmly rubbed and washed with 70% isopropyl alcohol using electrode prep pads and the electrodes fastened using double adhesive tape. A 50 mm diameter ground electrode was placed over the left olecranon. From now on the SCM will be referred to as agonist during flexion movements and antagonist during extension movements. The opposite is done for the splenius muscle. See supplementary files for a more detailed description.

Data sampling and analysis. The pre-amplified signals were passed to a main amplifier (Bagnoli-16, Delsys), amplified 1000x, band-pass filtered between 20 - 450 Hz with a built-in analog filter, AD-converted (NI-DAQ 6220, National Instruments) and sampled at 1 KHz. EMG signals were offset-adjusted and the running root mean squares (rms) were calculated in window lengths of 50 ms with 49 ms window overlap using an EMG software package (EMGworks 3.7). Baseline EMG was subtracted from the reference- and movement rmsEMG signals. EMG epochs covering the entire movement as defined by the kinematic start and stop procedures ± 200 ms were subsequently normalized to the median rmsEMG accomplished at reference contractions (see supplementary files for descriptions) and further analyzed. A few trials containing large spiked artifacts were excluded. The signal obtained during movement was separated into two epochs; one beginning at the start of movement as defined above for

the position data and ending at the time point of peak velocity was defined as the accelerative phase, and one epoch starting at peak velocity and ending at the stop of movement was defined as the decelerative phase. The signals of bilateral muscle pairs were averaged for further analysis. Due to very low EMG activity during the S and P speed conditions for the gravity-assisted movements (EBN and FFN), the EMG was analyzed for the movements completed against gravity, i.e. the flexion and extension back to neutral position (FBN and EBN).

Statistics

Graphical displays were used to assess the distribution of the data. After log-transformation of right-skewed distributions, the data were found to be approximately normally distributed. The WAD and the control group were compared using independent samples t-tests. Differences within the groups between speed test conditions within a given movement direction were examined using ANOVA for repeated measures.

Possible effects of velocity and displacement on the NJC and number of submovements were also examined by comparing groups using general linear models (GLM) with velocity and displacements as covariates. As both displacement and velocity affects the EMG amplitude [39], the rmsEMG data were compared using the same model and covariates. Since peak movement velocity is strongly related to the displacement of movement [20], we also compared groups for peak velocity and acceleration at the M speed conditions using displacement as a covariate.

To test for differences between groups in the spatial distribution of submovements and of the velocity profile symmetry index we used a mixed factor GLM with participants as random factor. Bivariate correlations were performed using Pearson's correlation coefficient. The scores of NDI, FABQ and pain intensity were analyzed against movement displacement, peak

velocity and acceleration and rmsEMG amplitude of the P and M speed condition for all movement directions. Tests are two-sided and p-values less than 0.05 were considered statistically significant. Statistical analyses were performed using the SPSS 18 and JMP 9.0 statistical packages.

Results

Group characteristics

The chronic WAD group and the control group were not significantly different with respect to age, anthropometrics or grip strength (Table 1). The control group scored about the same as the Norwegian normative values for the SF-36 measure of health related quality of life PCS and MCS. The WAD group displayed statistically significantly lower values of both summary scores than the control group did (p-values < 0.05). According to the scale of Vernon [30], the mean absolute NDI score of 22 for the WAD group was in the upper part of the range (15 - 24) defining moderate physical disability due to neck pain. The fear avoidance of the WAD group related to physical activity (FABQPA) and work (FABQW) were similarly moderate.

Kinematics

All movement variables for head and neck kinematics showed differences between participants with- and without chronic WAD and the detailed results are presented in Figure 2 and Table 2. In summary, the mean values for displacement were numerically lower for the WAD group compared to controls in all comparisons across all movement directions; in 8 of 12 cases the differences were statistically significant (p-values < 0.05). Similar results were also found for both peak and average velocity as 16 of 24 comparisons were significantly lower for the WAD group (p-values < 0.05). The peak acceleration and deceleration were significantly lower in the WAD group in 14 of 24 cases (p-values < 0.05). Peak and average velocity and peak acceleration and deceleration were significantly lower in the WAD group compared to the control group for all movement directions for the M speed condition (p-values < 0.01). Also, for the preferred test speed, the peak and average velocity and peak acceleration and deceleration were lower in the WAD group for the EFN and FBN movement.

The differences between groups in peak velocity and acceleration at the M speed conditions were also evident after using displacement as a covariate (p-values < 0.05).

Mean values for NJC and number of submovements were numerically consistently higher in the WAD group than the control group (table 2), although the large variation between individuals implied that the difference was significant ($p<0.05$) only for one and two test conditions, respectively. However, when displacement and velocity were used as covariates, no differences were found between groups for either NJC or number of submovements at any test velocity for any movement direction (Figure 3). We found no statistically significant differences between groups in the spatial distribution of submovements in either of the two movement halves (both $p = 0.91$). For the WAD group, 54 ± 17% of the submovements started in the first half of the movement displacement compared to 57 ± 18% in the control group. Nor did we find any significant difference in the velocity profile symmetry for the movements consisting of one submovement only ($p = 0.81$; figure 4). In summary, we detected no difference in either the smoothness or the symmetry of movement between the two groups.

Electromyography

In the sitting position prior to testing, the absolute baseline rmsEMG amplitude (μV) was not significantly different between groups for any muscle studied (Table 3, p-values > 0.25). Similarly, we found no group differences in absolute rmsEMG amplitude (μV) values during the reference contractions for the muscles (p-values > 0.11).

There was an overall effect of increased movement velocity as assessed by the separate test speed conditions on both the agonistic and antagonistic muscle rmsEMG amplitude for the two phases of both movement directions analyzed (14 of 16 comparisons were statistically significant, p-values < 0.05). For the acceleratory phase of the M speed condition for all

movement directions, the relative rmsEMG amplitude of both the agonistic and antagonistic muscles were significantly lower for the WAD group compared with the controls (p-values < 0.01, figure 5). For the decelerative phases of these movements, only the antagonistic muscles displayed lower amplitude for the WAD group (p-values < 0.01). For the FBN direction, reduced muscle activity in the WAD group was also found for the accelerative phase at the P speed condition in both the agonist and antagonistic muscles and at the S speed condition for the antagonistic muscles (p-values < 0.05). No group differences were found for the EBN direction at either the S or P speed (p-values > 0.38).

When the EMG data was compared between groups while controlling for velocity and displacement, all statistically significant differences between groups in rmsEMG amplitude for the agonist and the antagonist muscles vanished (p-values > 0.18) with one exception: the activity in the antagonistic SCM muscle was significantly different between groups in the acceleratory phase of the EBN movement at the M speed condition ($p < 0.05$).

Association between kinematics, EMG and self-reported data in the WAD group

We did not find any significant relationships between the self-reported pain intensity at baseline and the kinematics or rmsEMG amplitude (r value range -0.44 to 0.42, all p-values > 0.10). The NDI correlated only with the antagonistic splenius rmsEMG amplitude during the accelerative phase of the P speed at the FBN movement ($r = -0.59$, $p < 0.05$).

The FABQ physical activity component correlated significantly with displacement for the P and M speed condition at the EFN and FBN movement directions (r value range -0.55 to -0.65, p-values < 0.05), and with peak velocity and acceleration at the M speed condition for the EFN and FBN movements (r value range -0.52 to -0.59, p-values < 0.05).

For the FBN movement the FABQ physical activity correlated with the rmsEMG amplitude for the agonist muscle at both the accelerative and decelerative phase for the P and M speed tests (r value range -0.67 to -0.77, p-values < 0.01).

Supplementary data

Participant groups were additionally examined using extra loading (+25% of head mass) at the P speed test only. The results for each group were similar to that of the unloaded P speed condition and the data are therefore shown in the supplementary files.

Discussion

The finding in the present study of generally reduced displacement, peak acceleration, deceleration and velocity at the M speed conditions for the WAD group compared to controls are in close agreement with a number of previous studies examining participants with chronic WAD [10-17]. For the EFN and FBN movements we also found reduced displacement, peak acceleration, deceleration and velocity at the preferred movement speed to be different between groups, which is consistent with previous observations [14]. Thus, even though the WAD participants held a large reserve capacity in movement velocity as displayed by the result of the M speed test, they preferred to move at a lower velocity than the controls for the P speed test. Differences in movement velocity and displacement at both the maximum and preferred speed between the participants with chronic WAD and controls therefore seem to be a general and robust finding.

The lower peak velocity and acceleration at the M speed condition for the WAD group compared with the controls also persisted after controlling for movement displacement. There are several possible explanations for such a group difference including muscle morphological and muscle activation strategies. Since we measured neither single cell- nor gross muscle area in the present study, we cannot exclude muscle atrophy as a possible factor for reductions in peak acceleration or velocity. However, when using magnetic resonance imaging, previous studies have not detected atrophy of the total cervical muscle cross-sectional area in chronic WAD participants area as assessed by case-control studies [40-42] or in a 6-month follow-up study of WAD participants [43]. Thus, group differences in neck muscle size seem to have limited explanatory strength for differences in head kinematics in the present study. As the maximum shortening velocity of a muscle is strongly dependent upon its fiber type composition [44], an increase in the proportion of slow muscle fibers of the neck muscles

could possibly reduce the head movement velocity. However, the result from an uncontrolled, cross-sectional study of participants with neck pain of various etiologies on the contrary indicates a possible, minor increase in the fast fiber type direction [45]. Also, the reported type 1 fiber proportion in the neck muscles from the participants with post-traumatic etiology in the study of Uhlig [45] is almost identical to that found in presumably healthy participants [46]. Thus, it seems that the most reasonable explanation for the altered kinematics in the WAD participants would be the muscle activation patterns. We found a large reduction in agonist rmsEMG amplitude at the M speed test in the WAD group compared with the controls, which supports the interpretation that the reductions in peak acceleration and velocity at the M speed tests are a result of lowered muscle activation. This reduced activation found in the M speed test may in turn be partly explained by fear of pain since we found significant negative associations between the FABQPA and both peak acceleration, velocity and agonist muscle rmsEMG amplitude in the M speed test. It is therefore possible that peak exertion is voluntarily reduced to sub-maximal levels partly because of pain and/or fear of pain. It is also possible that the peak muscle activation is reduced because of motor inhibition by pain afferents [47, 48]. The amplitude of motor evoked potentials induced by transcranial magnetic stimulation has been shown to be reduced in experimental pain [49], suggesting the cortical level as site of inhibition. The reduction in neural drive at the M speed test may also be a function of both sub-maximal voluntary activation and motor inhibition.

The electromyographic activity of the agonist and antagonist muscles during both the acceleratory and deceleratory phases of the movement was on the other hand not different between groups when movement velocity and displacement were taken into consideration. Thus, the results of the present study suggest that for a given velocity and displacement of dynamic neck movements, the chronic WAD participants activated the involved muscles to

the same degree as healthy controls. Although we are not aware of any studies that have examined neck muscle activation during dynamic unconstrained neck movements in WAD participants, one study examining participants with chronic non-specific neck pain and controls reported no group difference in EMG amplitude of the cervical erector spinae muscles at a duration-controlled EBN movement [50]. These data are in keeping with our data, but they contrast somewhat with previous trials using isometric contractions [5, 18]. For example, Schomacher [5] found the average EMG activity (μV) of the semispinalis muscle to be significantly lower in participants with chronic WAD compared with controls during circular isometric contractions at standard force levels (15 and 30 N). Their data strongly indicate that other neck muscles, either synergistic or antagonistic, must have altered their activity in parallel with that of semispinalis to generate the resultant forces. There were no indications of such a rearrangement of intermuscular activation patterns in the present study since we found no difference in the rmsEMG amplitude between groups after controlling for velocity and displacement for either the splenius or the SCM muscles in any movement direction. It is possible that such differences may be attributed to the muscle contraction types examined and/or the relative voluntary effort used in tests.

The smoothness and regularity of movement did not differ between groups after the movements were controlled for velocity and displacement. As indicated in figure 3, the WAD group in fact tended to move more smoothly for a given velocity than the controls. This contrast between groups can however be explained by differences in movement displacement, since a movement of a given velocity becomes smoother by reductions in displacement [23] and this has not been taken into account in the figure. Thus, across a large range of head movement velocity, chronic neck pain due to WAD does not seem to alter the smoothness of movements compared with controls. This finding therefore contradicts the conclusions drawn

from previous studies that did not control for movement velocity that implicitly suggested that movement smoothness in unconstrained movements is altered *per se* for participants with chronic neck pain [11, 15, 19, 21]. Also, to further assess the dynamic movement strategies, we also examined the symmetry of movements and the spatial occurrence of submovements and found no significant group differences. These findings indicate that chronic WAD neither lead to a rearrangement of intermuscular activation patterns nor resultant movement patterns *per se* in relatively simple, unconstrained dynamic head movements. This conclusion is also somewhat in contrast to other studies that have found increased irregularity of velocity-controlled and constrained motion paths in chronic WAD compared with healthy participants [51, 52]. The head movements used in both these studies were highly spatially constrained by the imposition of visual trajectory tracking [51, 52]. As several [53-56], although not all [57] studies have found reduced eye-movement control in chronic WAD, it is possible that the different conclusions made may be related to the dependence on visual involvement in the movement tests used.

A key question relates to the external validity of the study. Are the two groups of participants comparable for variables not related to neck pain? And are the chronic WAD participants representative for patients with chronic WAD group I and II? While there were no group differences with respect to descriptive data for age, anthropometrics or grip strength, the WAD group scored significantly poorer than the controls for both the MCS and the PCS summary measures of the SF-36, reflecting limitations in physical ability and psychological distress. Such reductions in scores of SF-36 seem to be a common finding in people with chronic musculoskeletal diseases [58].

The WAD group displayed moderate physical disability due to neck pain as measured by the NDI. The mean score for the NDI are comparable to the participants with chronic WAD grade

I-II in a series of studies [4, 7, 41, 59], all displaying absolute NDI values very similar to our study (20 - 25.6). The findings in the present study should be treated with some caution due to the limited number of observations in this study. However, despite the moderate sample size, we found a number of statistically significant group differences. These findings were also seen across four different movements which further strengthens the findings.

Conclusion and clinical implications

During simple, relatively unconstrained head movements, participants with chronic WAD move with less velocity and displacement compared with healthy controls. When taking these variables into consideration we found no difference in either rmsEMG amplitude or movement smoothness between the groups. People with chronic WAD do not seem to display signs of altered motor control patterns during unconstrained dynamic head movements. We suggest that while reductions in movement velocity and displacement are robust changes and may be of clinical importance in chronic WAD, movement smoothness of unconstrained dynamic movements are not.

List of abbreviations

A.u.	Arbitrary units
EBN	Extension back to the neutral head position
EFN	Extension from the neutral head position
FABQ	Fear avoidance beliefs questionnaire
FBN	Flexion back to the neutral head position
FFN	Forward flexion from the neutral head position
M	Maximum movement speed
NDI	Neck disability index
NJC	Normalized jerk cost
NP	Neutral head position
P	Preferred movement speed
rmsEMG	Root mean square electromyography
S	Slow movement speed
SCM	Sternocleidomastoid
SF-36	Short form-36
WAD	Whiplash associated disorders

Competing interests

The authors declare that they have no known competing interests.

Authors' contributions

HV designed the study, processed the data, performed statistical analyses, drafted and revised the manuscript and participated in data sampling. ESB sampled the data, and participated in the design of the study and in the drafting of the manuscript. KL performed statistical analyses, participated in data processing and revised the manuscript. SRE sampled the data and participated in drafting the manuscript. NKV designed the study, participated in data processing and revised the manuscript.

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Figure legends

Figure 1. Example of two movement directions (EFN and FBN, top row) completed at the P speed condition and the accompanying data for position (second row), angular velocity (third row) and rectified EMG (μV) for the left SCM (forth row) and splenius muscles (bottom row). Note the differences in Y axis scaling between muscles. Dashed and solid vertical lines depict start and stop of movements, respectively. The participant scored about average for the kinematics and rmsEMG amplitude for both movements.

Figure 2. Average (± SD) kinematic data for the three speed conditions (S, P, M) in the four movement directions (column EFN, FBN, FFN and EBN) for the WAD (filled circles, n = 15) and control (open circles, n = 15) groups. Significant group differences; * $p < 0.05$, ** $p < 0.01$, ***, $p < 0.0005$. Y axis scaling is identical across the rows.

Figure 3. Relationship between average velocity ($\log_{10}$) and NJC(-10) ($\log_{10}$) across all speed conditions for all movement directions pooled for the WAD (filled circles, n = 15, 180 trials) and the control (open circles, n = 15, 180 trials) groups.

Figure 4. Velocity profile symmetry index (scale) versus average angular velocity (°/s) for the WAD (filled circles, n = 15, 55 trials) and control (open circles, n = 15, 73 trials) group. Solid vertical line indicates symmetric movements (value 0.5). Long and short dashed lines indicate the average values (0.427 ± 0.082 and 0.416 ± 0.087, p = 0.81 for group differences) for the WAD and control groups, respectively.

Figure 5. RmsEMG amplitude (%) of the SCM, splenius (SPL) muscle at the accelerative and decelerative phase of the three different speed conditions (S, P and M) for the FBN (upper panels) and EBN (lower panels) movements for the WAD (filled circles, n = 15) and control (open circles, n = 15) groups. The data are average and error bars standard deviation. Statistically significant group differences; * $p<0.05$, ** $p<0.01$, ***, $p<0.0005$. Note the differences in Y axis scaling among the separate test conditions.

Table 1. Descriptive data for the chronic WAD and control groups (six men and nine women in each group). Results are average (SD). For the duration of symptoms the results are median (interquartile range). Statistically significant difference from the control group; * $p < 0.05$, ** $p < 0.0005$. Statistically significant difference from the pre-value within group; # $p < 0.0005$.

Variable	Chronic WAD	Control
Age (yrs)	40.1 (8.7)	38.7 (8.8)
Height (cm)	170.5 (8.5)	173.2 (7.6)
Weight (kg)	78.3 (13)	75.8 (13.9)
BMI (kg/m^2)	26.9 (4.2)	25.1 (3.2)
Head mass (kg)	4.33 (0.34)	4.53 (0.30)
Hand grip strength, dominant (kg)	45.3 (11.4)	50.1 (12.6)
non-dominant (kg)	41.8 (11.8)	47.3 (12.1)
SF-36, PCS (0-100)	33.4 (9.7)**	54.4 (5.0) (n = 14)
MCS (0-100)	45.3 (15.0)*	55.2 (4.8) (n = 14)
Duration of symptoms (months)	22 (98)	-
Pain intensity (1-10), pre-test	3.1 (1.4)	-
post-test	5.6 (2.0)#	-
NDI (0-50)	21.7 (5.6)	-
FABQ W (0-42)	22.3 (10.2)	-
PA (0-24)	10.5 (4.5)	-

Abbreviations; BMI – body mass index, SF-36, short form-36, PCS – physical component summary, MCS – mental component summary, NDI – neck disability index, FABQ – fear avoidance beliefs questionnaire, W – work, PA – physical activity.

Table 2. Average (SD) angular velocity (°/s), normalized jerk cost (a.u.) and number of submovements for the three speed conditions in the four movement directions for the chronic WAD (n = 15) and control group (n = 15). Statistically significant difference from the control group; * $p < 0.05$, ** $p < 0.01$.

		EFN		**FBN**		**FFN**		**EBN**	
		WAD	Control	WAD	Control	WAD	Control	WAD	Control
Av. vel.	S	10.8 (6.7)**	18.2 (7.8)	13.4 (9.0)*	22.4 (10.6)	12.5 (6.7)	16.7 (7.7)	14.2 (6.9)	19.1 (7.2)
(°/s)	P	23.6 (12.2)**	40.0 (13.2)	27.6 (15.4)**	45.9 (12.7)	37.3 (21.1)	42.8 (13.9)	35.3 (18.9)	38.5 (11.1)
	M	66.6 (44.9)***	133.2 (42.6)	76.1 (56.3)**	136.8 (33.7)	87.1 (44.7)**	139.6 (36.7)	81.8 (45.6)**	131.6 (30.1)
NJC	S	1541 (2933)	335 (269)	824 (1502)	319 (250)	969 (1318)	467 (521)	704 (1171)	275 (287)
(a.u.)	P	134 (173)	58 (43)	95 (134)	42 (24)	79 (117)	45 (30)	74 (107)	47 (19)
	M	33 (22)	27 (14)	42(40)**	19 (5)	24 (12)	20 (11)	30 (15)	25 (8)
Subm.	S	14.6 (12.4)	9.4 (3.9)	11.3 (7.0)	9.3 (5.7)	14.6 (12.6)	11.4 (7.5)	12.9 (8.8)	9.5 (6.8)
(no.)	P	3.9 (2.9)	2.4 (1.6)	3.2 (2.4)*	1.6 (0.8)	2.6 (2.3)	1.8 (1.0)	1.9 (1.3)	1.5 (0.6)
	M	1.5 (0.7)*	1.1 (0.2)	1.4 (0.9)	1.0 (0.0)	1.1 (0.2)	1.0 (0.1)	1.3 (0.5)	1.0 (0.1)

Abbreviations; NJC – normalized jerk cost, a.u. – arbitrary units, Subm. – submovement, no. – number, Av.vel. – average velocity, NP – neutral head position, EFN – extension from NP, FBN – flexion back to NP, FFN – flexion from NP, EBN – extension back to NP, S – slow movement speed, P – preferred movement speed, M – maximum movement speed.

Table 3. Average (SD) rmsEMG amplitude (μV) for the SCM and splenius muscle at rest and at reference contractions (rest values subtracted) for the chronic WAD (n = 15) and control (n = 15) participants. There were no statistically significant differences between the groups.

	Rest		**Reference contractions**	
Muscle	WAD	Control	WAD	Control
SCM	2.75 (0.26)	2.74 (0.19)	40.12 (17.36)	51.79 (21.61)
Splenius	2.73 (0.69)	2.52 (0.17)	11.42 (5.12)	10.95 (3.24)

Abbreviations; SCM – sternocleidomastoid.

FIGURE 1

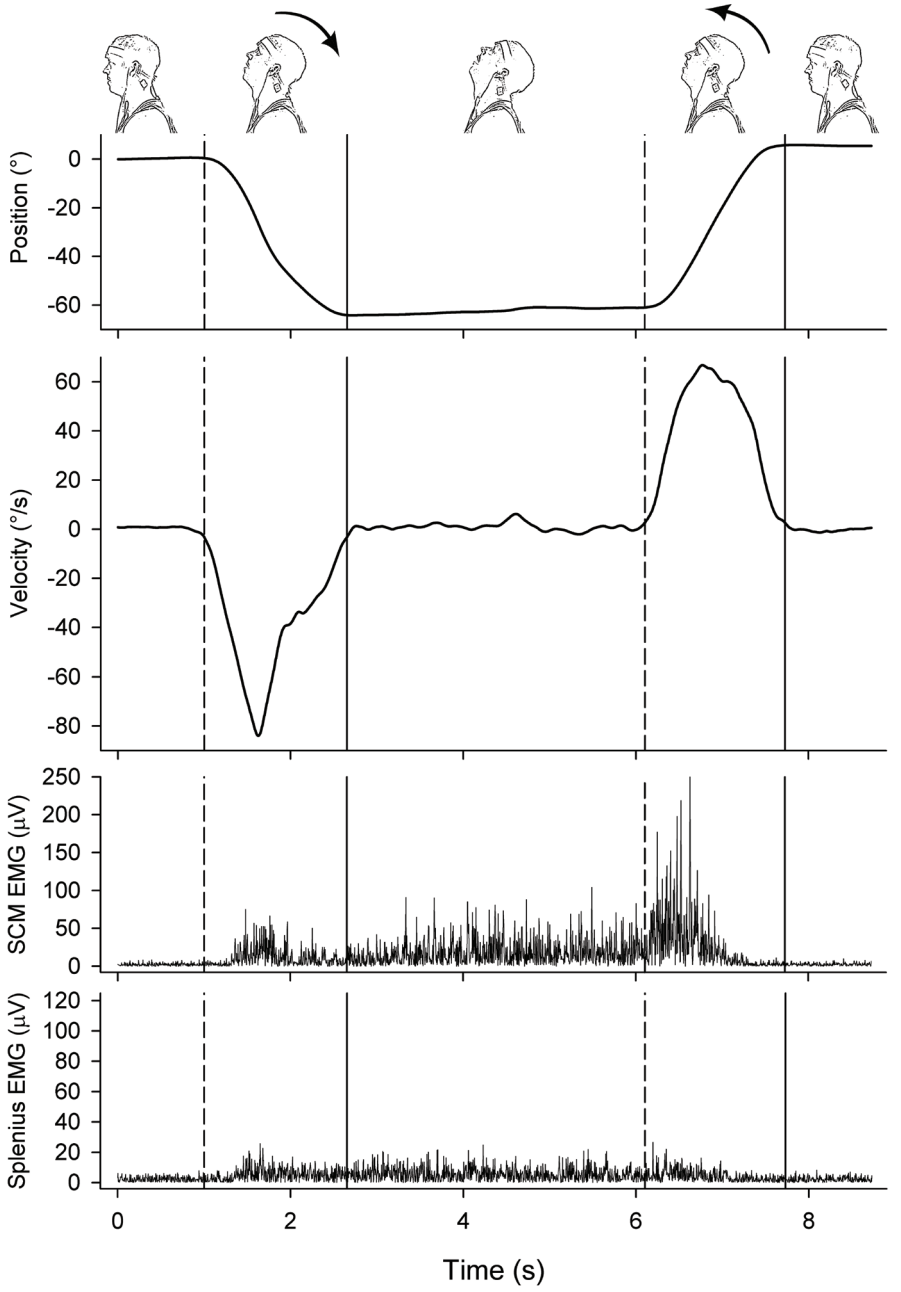

Position (°)
0
-20
-40
-60
Velocity (°/s)
60
40
20
0
-20
-40
-60
-80
SCM EMG (μV)
250
200
150
100
50
0
Splenius EMG (μV)
120
100
80
60
40
20
0
0
2
4
6
8
Time (s)

FIGURE 2

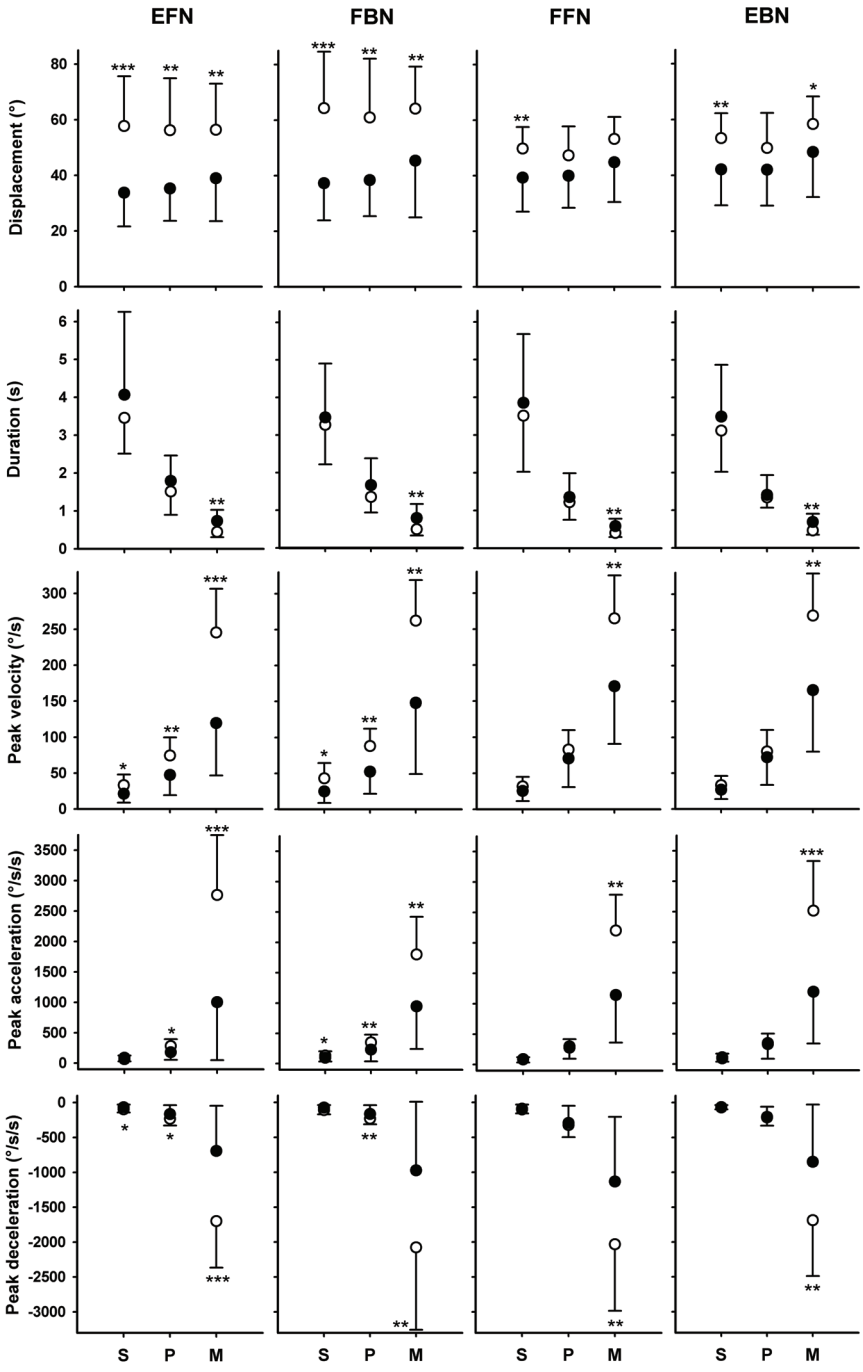

EFN
FBN
FFN
EBN
Displacement (°)
Duration (s)
Peak velocity (°/s)
Peak acceleration (°/s/s)
Peak deceleration (°/s/s)
S
P
M

FIGURE 3

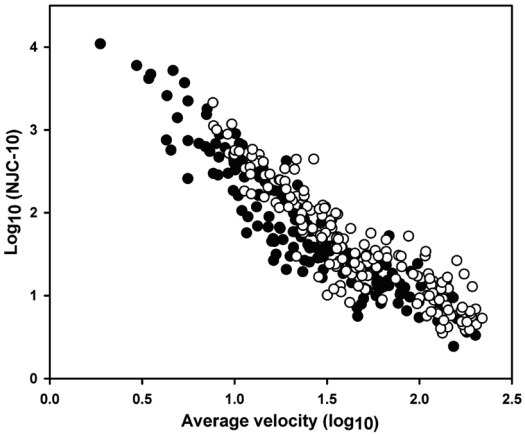


FIGURE 4

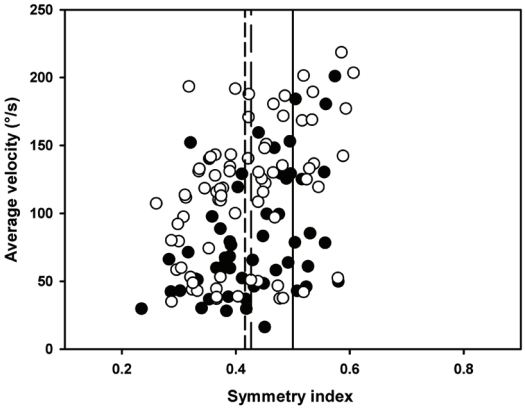
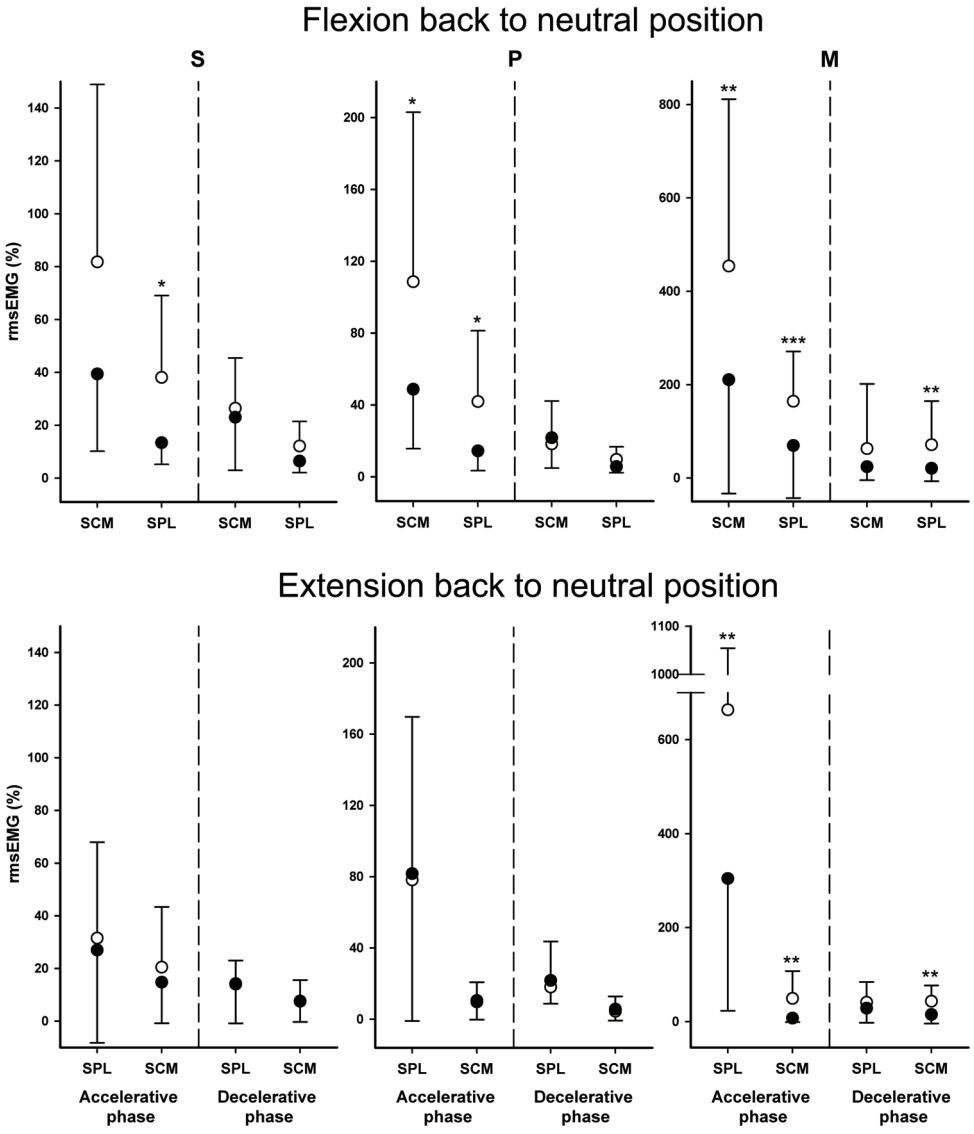

250
200
150
100
50
0
Average velocity (°/s)
0.2
0.4
0.6
0.8
Symmetry index

FIGURE 5


Flexion back to neutral position
S
P
M
rmsEMG (%)
SCM
SPL
Extension back to neutral position
Accelerative phase
Decelerative phase

Supplementary data

Data for movements at preferred speed with an additional load of 25% of head mass

Methods

Following the movement tests under different speed conditions, subjects completed the movements in the four directions with additional loading corresponding to 25% of the head mass at their preferred speed only (P25). Modified pilot helmets (HGU-55/P, Gentex) were worn as a base for the supplementary head loading. Load plates, manufactured from polytetrafluoroethylene (PTFE), were put on PTFE -bars attached to the helmet on an axis parallel to the frontal plane passing approximately through the combined center of gravity of head and helmet. The center of gravity were calculated for the helmet and for 11 subjects according to the procedures of McConville [1] and Young [2], and projected on calibrated 2D profile images. The weighed combined center of gravity was calculated and marked on the 2D images of the helmet. The PTFE bars were then attached to each side of the helmet at this point. Measurements were completed using image software (ImageJ, version 1.37; Rasband, W.S, National Institute of Health). The chronic WAD group received an extra total load of a mean of 1.08 ± 0.1 kg (24.9 ± 0.9% of head mass). The corresponding value for the control group was 1.14 ± 0.08 kg (25.1 ± 1.2%). Kinematic and electromyograpic data were analyzed using the same procedures as described in the main document.

Results and discussion

Head kinematics with an additional head mass of 25% (1.1 ± 0.09 kg) were examined at the P speed only (supplementary table 1), and for both groups, the kinematics of these movements were remarkably similar to those of the unloaded condition. Thus, the statistical differences

found between groups using two sample t-tests were also similar to those found for the unloaded P speed condition. After controlling for movement velocity and displacement using GLM analysis, there were no differences between the groups in NJC or number of submovements, with the exception of the FBN movement where the statistical difference for the number of submovements persisted ($p < 0.01$).

Differences between groups in muscle activity in the accelerative phase were found between the groups in the extra load condition in both the agonist and antagonistic muscles in the FBN direction (all $p < 0.05$, supplementary table 2). Additionally, increased antagonistic muscle activity in the control group as compared to the WAD group was found in the deceleratory phase in the FBN direction ($p < 0.05$). No differences were found between the groups in the EBN direction for the extra load condition. After using displacement and velocity as covariates, there were no significant differences in muscle activity between the groups for any muscle in any movement direction for the loaded test condition. In conclusion, the completion of movements with an additional 25% extra load was similar to that of the unloaded condition in both groups.

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Table 1 supplementary. Average (SD) kinematic and movement smoothness data for the extra load condition (P25) in the four movement directions for the chronic WAD (n=15) and control (n=15) group. Group differences are tested by two-sample t-tests. Statistically significant different from the control group; * $p < 0.05$, ** $p < 0.01$.

	EFN		**FBN**		**FFN**		**EBN**	
	WAD	Control	WAD	Control	WAD	Control	WAD	Control
Displacement (°)	34.5 (15.2)**	55.6 (19.4)	39.1 (16.9)**	62.5 (20.9)	41.6 (14.1)	47.7 (8.3)	43.9 (14.3)	50.9 (11.1)
Duration (s)	2.29 (2.67)	1.56 (0.46)	1.79 (0.93)	1.35 (0.38)	1.65 (0.88)	1.31 (0.46)	1.73 (0.81)*	1.22 (0.25)
Peak vel. (°/s)	45.2 (32.5)*	70.4 (30.8)	51.8 (35.1)**	95.2 (36.1)	60.0 (38.3)	77.2 (30.3)	59.5 (31.0)*	84.1 (28.2)
Average vel. (°/s)	23.5 (16.3)*	38.3 (16.2)	27.3 (19.0)**	48.1 (17.0)	32.0 (20.0)	41.6 (16.9)	29.6 (14.3)**	43.7 (12.5)
Peak acc. (°/s/s)	172.0 (140.0)	257.0 (156.1)	215.0 (179.4)**	391.1 (199.6)	216.3 (158.1)	286.3 (174.7)	250.8 (181.6)*	366.5 (188.9)
Peak dec. (°/s/s)	-147.1 (140.2)*	-203.1 (122.0)	-160.7 (120.8)**	-251.0 (128.0)	-235.5 (208.6)	-304.9 (191.6)	-166.1 (120.3)	-223.7 (109.8)
NJC (a.u.)	808.0 (2784.0)	52.1 (28.6)	129.6 (179.0)*	41.7 (19.6)	96.5 (106.3)	49.0 (34.2)	101.2 (111.7)**	33.5 (11.4)
Submov. (no.)	6.5 (12.6)	2.3 (1.2)	4.2 (3.8)**	1.6 (0.9)	3.6 (3.2)	2.1 (1.2)	3.0 (2.7)*	1.4 (0.6)

Abbreviations; Vel. – velocity, Acc – acceleration, Dec. – deceleration, NJC – normalized jerk cost, a.u. – arbitrary units, Submov. – submovements, no. – number, NP – neutral head position, EFN – extension from NP, FBN – flexion back to NP, FFN – flexion from NP, EBN – extension back to NP.

Table 2 supplementary. Average (SD) EMG amplitude values (%) for the SCM and splenius muscle for the WAD (n=15) and control (n=15) groups for the accelerative and decelerative phases during loaded movements in the FBN and EBN movements. Note the differences in the ordering of muscles between movement directions. Statistically significant differences between the groups were found by two-sample t-tests; * $p < 0.05$, ** $p < 0.01$. These statistically significant differences between the groups vanished when using displacement and velocity as covariates in the analysis of covariance.

		Accelerative phase		**Decelerative phase**	
Direction	Muscle	Chronic WAD	Control	Chronic WAD	Control
FBN	SCM	86.1 (92.1)**	153.3 (69.5)	28.9 (27.4)	28.0 (23.0)
	Splenius	31.5 (46.2)**	71.8 (66.2)	8.6 (8.0)*	20.6 (22.4)
EBN	Splenius	100.9 (101.0)	132.2 (116.0)	23.9 (19.3)	21.6 (14.0)
	SCM	11.3 (12.5)	6.5 (10.1)	6.1 (7.0)	4.9 (6.5)

Abbreviations; NP – neutral head position, FBN – flexion back to NP, EBN – extension back to NP, SCM – sternocleidomastoid.

Supplementary methodological description

Electromyography

Muscles and sensor placement. After localizing and inspecting the areas for placement of the EMG sensors, the parallel electrode bars of the sensors were subsequently oriented at a right angle to the fascicles of the muscles as visualized by ultrasound imaging. In accordance with Joines [1], we found that some of the participants did not display a gap between the SCM and trapezius muscles large enough to access the deeper lying splenius muscle with the entire sensor. In those cases we chose to place the sensor closer to, or in a few cases, one of the electrode bars above the trapezius muscle. This was done to avoid possible cross-talk from the SCM, as prior pilot experiments had shown that the SCM muscles were more active during head movements than the trapezius. EMG activity was also recorded bilaterally from the upper trapezius muscle using previous suggested sensor placement [2]. In accordance with previous studies groups [3-5] we found very low EMG activity for this muscle (not exceeding 8.5 % in the EBN movement in the M speed test) in both groups and have therefore not reported the data.

Data sampling and EMG normalization procedures. Baseline EMG was recorded for each muscle when sitting with the head in the NP as defined in the manuscript. The median running rmsEMG (window length 100ms, 99ms overlap) value obtained for the lowest 2 seconds was defined as the baseline value. The procedures for obtaining reference contractions of the different muscles were as follows; For the SCM muscle, the participants sat with back and head support adjusted to 45° to the vertical plane. Participants lifted and held the head slightly off the head support. For the splenius muscles, participants lay horizontally on their side on a

bench with head support that was adjusted to align the cervical and thoracic column in all three planes. The participants then lifted and held the head slightly off the head support in the vertical direction. The participants did three isometric contractions for each test. Each contraction lasted about 10 s and the first and last 2 s epochs were removed from analysis. The median running rmsEMG signal (100 ms window/99 ms overlap) was calculated for each muscle and the median value of the three trials was used as reference signal.

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Appendices

Appendix 1

List of muscles analyzed for intermuscular relationship of the four sets of data from Weber et al.[121], own data from study I, Garrett et al.[220] and Johnson et al.[69] reported in study I. The muscles are listed in alphabetical order for each separate set of data. For muscles where mean is given in parenthesis indicate that the value used is the mean of several samples from the muscle. "n" depict the number of individuals included in the studies.

No.	Weber (n = 21)	Own data (n = 12)	Garrett (n = 10)	Johnson (n = 6)
1.	Omohyoid	Scalenus medius	Adduktor magnus	Abductor digiti minimi
2.	Sternocleidomastoid	Splenius	Biceps femoris, long head (mean)	Abductor pollicis brevis
3.		Sternocleidomastoid	Biceps femoris, short head	Adductor magnus (mean)
4.		Trapezius	Rectus femoris	Adductor pollicis
5.		Vastus lateralis	Semimembranosus (mean)	Biceps brachii (mean)
6.			Semitendinosus (mean)	Biceps femoris
7.			Vastus intermedius	Brachioradialis
8.			Vastus lateralis	Deltoid (mean)
9.			Vastus medialis	1st Dorsal interosseus
10.				Erector spinae (mean)
11.				Extensor digitorum
12.				Extensor digitorum brevis
13.				Flexor digitorum brevis
14.				Flexor digitorum profundus
15.				Frontalis
16.				Gastrocnemius (mean)
17.				Gluteus maximus
18.				Iliopsoas
19.				Infraspinatus
20.				Latissimus dorsi
21.				Orbicularis oculi
22.				Pectoralis major (mean)
23.				Peroneus longus
24.				Rectus abdominis
25.				Rectus femoris (mean)
26.				Rhomboid
27.				Sartorius
28.				Soleus (mean)
29.				Sternomastoid
30.				Supraspinatus
31.				Temporalis
32.				Tibialis anterior (mean)
33.				Trapezius
34.				Triceps (mean)
35.				Vastus lateralis (mean)
36.				Vastus medialis (mean)

Appendix 2

Mean kinematic data (SD) for the three speed conditions in each of the four small amplitude (A, EFN; B, FBN; C, FFN and D, EBN) and large amplitude movements (E, EF and F, FF) in 26 respectively 12 subjects. Statistically significant different for all subjects from the P speed condition; *** $p < 0.001$; ** $p < 0.01$. Statistically significant different from the men; §§§ $p < 0.0005$; §§ $p < 0.01$; § $p < 0.05$.

A. EFN

	Test	Duration (s)	Displ. (°)	Peak vel. (°/s)	Mean vel. (°/s)	Peak acc. (°/s/s)	Peak dec. (°/s/s)
All	S	3.72 (1.27)***	56.8 (14.5)	31.9 (14.6)***	17.3 (7.3)***	84.4 (37.1)***	94.1 (42.2)***
Women		4.03 (1.19)	64.6 (13.7)§§	32.3 (13.5)	17.7 (6.7)	86.2 (36.9)	86.9 (28.0)
Men		3.36 (1.32)	47.8 (9.6)	31.5 (16.4)	16.7 (8.2)	82.5 (39.0)	102.5 (54.5)
All	P	1.47 (0.57)	55.9 (15.3)	78.7 (26.6)	41.4 (12.9)	309.5 (161.4)	248.4 (119.9)
Women		1.70 (0.59)§	63.0 (16.0)§§	74.8 (25.6)	40.2 (13.7)	282.2 (112.8)	213.4 (96.2)
Men		1.20 (0.43)	47.7 (9.7)	83.2 (28.0)	42.7 (12.2)	341.4 (205.2)	289.1 (135.5)
All	M	0.47 (0.14)***	57.3 (14.5)	249.1 (66.9)***	133.4 (48.7)***	2880.0 (976.1)***	1747.0 (960.7)***
Women		0.50 (0.16)	62.9 (15.0)§	251.2 (73.5)	139.1 (57.2)	2636.9 (918.9)	1887.8 (1265.4)
Men		0.42 (0.11)	50.9 (11.1)	246.7 (61.3)	126.8 (38.0)	3163.7 (1002.3)	1582.6 (388.0)

B. FBN

	Test	Duration (s)	Displ. (°)	Peak vel. (°/s)	Mean vel. (°/s)	Peak acc. (°/s/s)	Peak dec. (°/s/s)
All	S	3.62 (1.27)***	62.4 (16.3)	39.1 (18.5)***	20.1 (9.5)***	125.4 (60.4)***	99.9 (50.0)***
Women		3.94 (1.35)	71.6 (14.9)§§	42.7 (20.3)	21.2 (10.0)	137.5 (65.6)	101.5 (45.6)
Men		3.23 (1.11)	51.7 (10.4)	34.8 (15.9)	18.8 (9.1)	111.3 (53.0)	98.1 (56.6)
All	P	1.37(0.48)	60.8 (17.2)	91.6 (26.0)	47.0 (13.4)	392.9 (171.3)	235.5 (92.8)
Women		1.61 (0.46)§§	69.1 (17.6)§§	86.1 (23.3)	44.9 (13.6)	326.8 (110.8)§	198.6 (79.2)§
Men		1.09 (0.32)	51.1 (11.0)	98.1 (28.5)	49.3 (13.4)	470.1 (200.3)	278.5 (91.5)
All	M	0.50 (0.17)***	63.4 (14.3)	265.5 (69.0)***	135.6 (41.0)***	1889.6 (715.1)***	2027.5 (1111.8)***
Women		0.59 (0.18)§§	68.3 (15.6)	245.8 (67.6)	124.0 (42.2)	1640.1 (735.4)	1446.7 (639.4)§§
Men		0.40 (0.09)	57.7 (10.6)	288.8 (65.8)	149.2 (36.5)	2180.7 (592.8)	2705.0 (1181.6)

C. FFN

	Test	Duration (s)	Displ. (°)	Peak vel. (°/s)	Mean vel. (°/s)	Peak acc. (°/s/s)	Peak dec. (°/s/s)
All	S	3.74 (1.50)***	49.6 (7.4)	30.5 (13.2)***	15.6 (7.1)***	86.1 (32.6)***	95.4 (49.2)***
Women		3.95 (1.55)	49.5 (7.3)	27.5 (10.0)	14.3 (5.8)	73.1 (21.1)§	82.2 (34.8)
Men		3.49 (1.46)	49.8 (7.8)	33.9 (16.0)	17.2 (8.4)	101.2 (37.7)	110.8 (59.9)
All	P	1.17 (0.41	48.9 (9.4	88.6 (30.6	46.0 (15.7	334.7 (149.5)	328.2 (185.6)
Women		1.30 (0.43)	48.0 (8.5)	78.0 (24.0)	40.4 (13.1)§	276.2 (103.1)§	262.7 (137.8)§§
Men		1.01 (0.32)	50.0 (10.6)	101.1 (33.7)	52.6 (16.3)	403.0 (169.7)	404.6 (209.9)
All	M	0.39 (0.09***	55.5 (10.9**	278.8 (76.5***	148.7 (43.9***	2339.3 (776.2)***	2080.2 (948.2)***
Women		0.42 (0.10)§	52.8 (11.9)	248.3 (79.4)§	131.4 (46.0)§	1997.1 (718.0)§	1746.6 (907.4)§
Men		0.35 (0.05)	58.8 (8.9)	314.3 (57.3)	169.0 (32.6)	2738.6 (661.2)	2469.3 (873.7)

D. EBN

	Test	Duration (s)	Displ. (°)	Peak vel. (°/s)	Mean vel. (°/s)	Peak acc. (°/s/s)	Peak dec. (°/s/s)
All	S	3.35 (1.28)***	53.4 (8.0)	32.0 (13.6)***	18.5 (7.7)***	102.2 (50.9)***	68.1 (29.0)***
Women		3.60 (1.33)	53.5 (7.0)	30.1 (12.0)	16.8 (6.2)	94.4 (46.1)	58.1 (23.1)
Men		3.05 (1.21)	53.3 (9.2)	34.2 (15.5)	20.4 (9.1)	111.2 (56.7)	79.9 (31.8)
All	P	1.28 (0.29)	51.4 (11.2)	88.0 (33.7)	42.9 (15.5)	407.2 (221.4)	222.5 (124.9)
Women		1.40 (0.23)§	51.1 (9.6)	76.3 (22.9)	37.9 (10.3)	332.1 (125.0)	169.2 (57.0)§
Men		1.14 (0.30)	51.8 (13.3)	101.6 (39.8)	48.8 (18.8)	494.7 (278.2)	284.7 (154.2)
All	M	0.43 (0.10)***	60.0 (12.8)***	292.7 (81.8)***	144.1 (41.3)***	2843.4 (1081.1)***	1911.0 (894.4)***
Women		0.48 (0.10)§§	58.7 (14.3)	262.6 (82.3)§	126.1 (39.2)§	2417.0 (1028.5)§	1563.2 (861.2)§
Men		0.38 (0.05)	61.6 (11.1)	327.9 (68.6)	165.0 (34.3)	3340.9 (951.3)	2316.8 (779.9)

E. EF

	Test	Duration (s)	Displ. (°)	Peak vel. (°/s)	Mean vel. (°/s)	Peak acc. (°/s/s)	Peak dec. (°/s/s)
All	S	6.42 (2.97)***	106.0 (12.0)	36.6 (15.6)***	20.1 (8.4)***	109.5 (53.3)***	92.7 (44.8)**
Women		8.03 (3.36)	106.9 (12.9)	30.2 (13.0)	15.9 (7.5)	84.2 (30.5)	86.2 (55.8)
Men		5.27 (2.23)	105.4 (12.3)	41.2 (12.3)	23.1 (8.1)	127.5 (60.6)	97.3 (39.3)
All	P	1.62 (0.50)	108.5 (12.6)	141.8 (49.3)	74.1 (26.1)	603.9 (290.7)	328.5 (180.0)
Women		1.80 (0.40)	109.7 (18.0)	132.9 (54.2)	66.9 (32.0)	590.1 (330.5)	282.0 (211.5)
Men		1.49 (0.56)	107.6 (8.6)	148.2 (48.9)	79.2 (22.2)	613.8 (286.1)	361.8 (162.6)
All	M	0.54 (0.16)***	115.2 (15.9)	429.6 (93.5)***	228.4 (70.4)***	3580.4 (1151.4)***	2174.6 (935.2)***
Women		0.62 (0.22)	117.4 824.6)	410.4 (146.7)	216.9 (113.0)	3221.1 (1675.1)	2315.2 (1490.1)
Men		0.48 (0.05)	113.5 (7.1)	443.4 (33.7)	236.5 (19.5)	3837.2 (612.8)	2074.2 (307.8)

F. FF

	Test	Duration (s)	Displ. (°)	Peak vel. (°/s)	Mean vel. (°/s)	Peak acc. (°/s/s)	Peak dec. (°/s/s)
All	S	6.16 (2.63)***	106.7 (12.7)	38.4 (16.9)***	20.5 (8.6)***	117.0 (49.9)	104.8 (41.3)**
Women		7.48 (2.70)	105.8 (14.2)	29.9 (10.3)	15.9 (5.7)	97.4 (37.6)	80.7 (19.0)
Men		5.22 (2.32)	107.3 (12.6)	44.6 (18.7)	23.9 (9.1)	131.0 (55.4)	122.0 (45.4)
All	P	1.48 (0.44)	107.5 (12.1)	144.2 (43.8)	78.7 (23.1)	574.6 (275.4)	407.7 (237.9)
Women		1.70 (0.39)	107.3 (17.1)	122.1 (46.2)	66.9 (23.4)	464.5 (242.6)	273.3 (103.2)
Men		1.31 (0.43)	107.7 (8.5)	159.9 (37.4)	87.1 (20.4)	653.3 (287.2)	503.7 (266.2)
All	M	0.56 (0.19)***	114.5 (17.1)	410.8 (115.4)***	221.3 (71.4)***	2583.4 (987.7)	2413.8 (1097.5)***
Women		0.66 (0.26)	117.0 (25.3)	385.8 (172.3)	205.3 (108.2)	2397.5 (1401.2)	2291.1 (1710.6)
Men		0.49 (0.05)	112.7 (9.8)	428.8 (61.0)	232.8 (34.1)	2716.2 (655.9)	2501.4 (486.0)

Abbreviations; Displ. – displacement, Peak vel. – peak velocity, Peak acc. – peak acceleration, Peak dec. – peak deceleration, NP – neutral head position, EFN – extension from NP, FBN – flexion back to NP, FFN – flexion from NP, EBN – extension back to NP, EF – full extension, FF – full flexion, S – slow movement speed, P – preferred movement speed, M – maximum movement speed.

Appendix 3

Normalized jerk cost (a.u.) and number of submovements for the three speed conditions in each of the four small amplitude (A, EFN; B, FBN; C, FFN and D, EBN) and large amplitude movements (E, EF and F, FF) in 26 respectively 12 subjects. Results are mean (SD). Statistically significant different from the P speed test; *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$. Statistically significant different from the men; § $p < 0.05$.

A. EFN

	Test	NJC (a.u.)	Submovements (no.)
All	S	407.4 (329.6)***	10.5 (5.6)***
Women		446.2 (367.5)	11.4 (5.5)
Men		362.2 (288.4)	9.5 (5.8)
All	P	53.8 (36.5)	2.2 (1.4)
Women		67.2 (41.9)§	2.7 (1.7)
Men		38.0 (21.4)	1.6 (0.9)
All	M	32.0 (20.6)*	1.2 (0.4)**
Women		31.6 (21.4)	1.1 (0.2)
Men		32.5 (20.6)	1.3 (0.5)

B. FBN

	Test	NJC (a.u.)	Submovements (no.)
All	S	413.7 (339.2)***	10.5 (6.0)***
Women		479.7 (401.7)	11.1 (6.1)
Men		336.6 (242.4)	9.9 (6.0)
All	P	45.2 (28.2)	1.6 (0.9)
Women		54.9 (32.9)	1.8 (1.1)
Men		33.8 (16.3)	1.4 (0.6)
All	M	21.4 (8.5)***	1.0 (0.1)**
Women		23.4 (9.0)	1.0 (0.1)
Men		19.1 (7.5)	1.0 (0.1)

C. FFN

	Test	NJC (a.u.)	Submovements (no.)
All	S	534.5 (528.1)***	12.1 (7.3)***
Women		558.8 (587.8)	12.2 (6.9)
Men		506.1 (473.1)	12.0 (8.1)
All	P	39.3 (24.8)	1.7 (0.8)
Women		44.7 (28.1)	1.9 (0.9)
Men		33.0 (19.5)	1.4 (0.6)
All	M	17.7 (8.6)***	1.0 (0.1)**
Women		19.4 (11.2)	1.0 (0.1)
Men		15.8 (3.4)	1.0 (0.1)

D. EBN

	Test	NJC (a.u.)	Submovements (no.)
All	S	327.7 (325.8)***	10.4 (7.6)***
Women		366.5 (383.8)	10.1 (6.7)
Men		282.5 (251.1)	10.8 (8.8)
All	P	43.8 (18.0)	1.4 (0.5)
Women		46.7 (18.5)	1.4 (0.6)
Men		40.4 (17.6)	1.4 (0.5)
All	M	22.9 (6.2)***	1.0 (0.1)**
Women		25.3 (6.6)[§]	1.0 (0.1)
Men		20.2 (4.6)	1.0 (0)

E. EF

	Test	NJC (a.u.)	Submovements (no.)
All	S	1225.1 (1316.8)*	21.3 (14.2)**
Women		1940.1 (1862.0)	26.1 (16.0)
Men		714.3 (624.8)	18.0 (12.9)
All	P	52.4 (22.1)	2.0 (0.6)
Women		64.4 (21.8)	2.3 (0.4)
Men		43.9 (19.4)	1.7 (0.7)
All	M	23.7 (16.2)**	1.1 (0.3)**
Women		30.0 (24.6)	1.2 (0.4)
Men		19.3 (4.3)	1.0 (0.0)

F. FF

	Test	NJC (a.u.)	Submovements (no.)
All	S	1193.2 (1240.4)*	19.6 (11.8)**
Women		1674.4 (1635.2)	24.1 (11.8)
Men		849.6 (841.2)	16.3 (11.5)
All	P	45.8 (22.2)	1.9 (0.9)
Women		55.6 (27.3)	2.3 (1.0)
Men		38.7 (16.3)	1.6 (0.7)
All	M	19.4 (9.6)**	1.1 (0.3)*
Women		24.4 (13.7)	1.3 (0.5)
Men		15.8 (2.6)	1.0 (0.0)

Abbreviations; NJC – normalized jerk cost, a.u. – arbitrary units, no. – number, NP – neutral head position, EFN – extension from NP, FBN – flexion back to NP, FFN – flexion from NP, EBN – extension back to NP, EF – full extension, FF – full flexion. S – slow movement speed, P – preferred movement speed, M – maximum movement speed.

Appendix 4

Adjusted mean (SD) kinematic and movement smoothness data for the three speed conditions in each of the four small amplitude (A, EFN; B, FBN; C, FFN and D, EBN) and large amplitude movements (E, EF and F, FF) in 26 respectively 12 subjects. Velocity and acceleration are adjusted for movement displacement. NJC and submovements are adjusted for velocity and displacement. Statistically significant different from the men; *** p < 0.001; ** p < 0.01; * p < 0.05. P values between 0.1 and 0.05 are given; ^.

A. EFN

	Test	Peak vel. (°/s)	Mean vel. (°/s)	Peak acc. (°/s/s)	NJC (a.u.)	Submovements (no.)
Women	S	25.6 (13.7)^	14.9 (6.8)^	72.5 (35.8)	432.3 (239.5)	10.6 (3.3)
Men		38.2 (13.9)	20.0 (7.0)	98.4 (36.4)	378.4 (244.4)	10.5 (3.4)
Women	P	68.2 (26.0)^	36.5 (12.1)*	264.2 (174.0)	51.3 (21.4)	2.0 (0.9)
Men		90.9 (26.3)	47.1 (12.2)	362.3 (176.0)	56.6 (21.7)	2.5 (0.9)
Women	M	231.4 (51.9)^	124.3 (36.5)	2459.6 (917.8)*	31.1 (18.6)	1.1 (0.4)^
Men		269.8 (52.3)	144.1 (36.7)	3370.5 (924.7)	33.1 (18.8)	1.4 (0.4)

B. FBN

	Test	Peak vel. (°/s)	Mean vel. (°/s)	Peak acc. (°/s/s)	NJC (a.u.)	Submovements (no.)
Women	S	33.7 (15.3)^	16.8 (8.4)^	114.2 (58.4)	459.5 (238.6)	10.1 (3.2)
Men		45.4 (15.6)	23.9 (8.6)	138.5 (59.5)	360.1 (244.3)	10.9 (3.3)
Women	P	78.4 (24.1)**	40.3 (11.7)**	299.1 (166.6)**	41.4 (21.4)	1.4 (0.8)
Men		107.1 (24.4)	54.7 (11.9)	502.3 (168.7)	49.6 (21.9)	1.8 (0.8)
Women	M	229.4 (51.8)***	115.1 (32.8)**	1512.1 (607.0)**	20.0 (7.4)	1.0 (0.1)
Men		307.9 (52.1)	159.7 (33.0)	2330.0 (210.5)	23.1 (7.6)	1.0 (0.1)

C. FFN

	Test	Peak vel. (°/s)	Mean vel. (°/s)	Peak acc. (°/s/s)	NJC (a.u.)	Submovements (no.)
Women	S	27.7 (11.9)	14.4 (6.3)	73.3 (28.6)*	473.3 (353.9)	10.9 (3.9)
Men		33.8 (11.9)	17.1 (6.3)	101.0 (28.6)	605.8 (354.6)	13.6 (4.0)
Women	P	79.7 (23.1)*	41.2 (11.6)*	282.0 (126.9)*	36.6 (17.4)	1.6 (0.5)
Men		99.1 (23.1)	51.6 (11.6)	396.2 (127.0)	42.4 (17.6)	1.7 (0.5)
Women	M	263.4 (41.1)^	140.2 (23.3)^	2098.9 (596.0)*	17.1 (7.7)	1.0 (0.1)
Men		296.6 (41.2)	158.7 (23.4)	2619.8 (597.9)	18.5 (7.8)	1.1 (0.1)

D. EBN

	Test	Peak vel. (°/s)	Mean vel. (°/s)	Peak acc. (°/s/s)	NJC (a.u.)	Submovements (no.)
Women	S	30.0 (11.4)	16.8 (6.1)	94.1 (44.7)	294.5 (210.4)	8.2 (3.7)**
Men		34.3 (11.4)	20.5 (6.1)	111.5 (44.7)	366.5 (211.3)	13.0 (3.7)
Women	P	76.9 (21.1)**	38.2 (10.5)*	335.2 (177.8)*	42.0 (16.5)	1.3 (0.5)
Men		100.8 (21.1)	48.5 (10.5)	491.2 (177.8)	45.8 (16.7)	1.5 (0.5)
Women	M	268.9 (48.3)*	129.1 (24.3)**	2470.2 (874.9)*	23.4 (5.5)	1.0 (0.1)
Men		320.5 (48.3)	161.5 (24.3)	3278.8 (875.4)	22.4 (5.6)	1.0 (0.1)

E. EF

	Test	Peak vel. (°/s)	Mean vel. (°/s)	Peak acc. (°/s/s)	NJC (a.u.)	Submovements (no.)
Women	S	29.9 (15.4)	15.8 (8.0)	84.9 (52.7)	1477.8 (831.8)	19.1 (6.3)
Men		41.5 (15.3)	23.2 (8.0)	127.1 (52.7)	1044.6 (814.6)	22.9 (6.2)
Women	P	129.8 (41.1)	65.5 (22.5)	575.9 (277.9)	57.7 (11.0)	2.2 (0.5)
Men		150.4 (41.1)	80.2 (22.5)	624.0 (277.8)	48.7 (10.9)	1.8 (0.5)
Women	M	398.8 (50.1)^	208.6 (43.6)	3105.1 (844.1)	25.3 (12.1)	1.1 (0.3)
Men		451.6 (50.1)	242.5 (43.5)	3920.0 (843.0)	22.6 (11.9)	1.0 (0.3)

F. FF

	Test	Peak vel. (°/s)	Mean vel. (°/s)	Peak acc. (°/s/s)	NJC (a.u.)	Submovements (no.)
Women	S	30.1 (16.3)	16.0 (8.0)	97.5 (51.8)	1146.3 (897.0)	18.0 (6.6)
Men		44.4 (16.3)	23.7 (8.0)	131.0 (51.8)	1226.8 (877.3)	20.7 (6.4)
Women	P	122.4 (39.0)	67.0 (20.3)	465.7 (269.9)	46.2 (16.3)	2.0 (0.7)
Men		159.7 (39.0)	87.0 (20.3)	652.4 (269.9)	45.4 (15.9)	1.8 (0.7)
Women	M	370.7 (59.6)^	196.1 (39.0)^	2267.7 (513.0)^	20.7 (6.4)	1.2 (0.2)
Men		439.5 (59.5)	239.3 (39.0)	2808.9 (512.2)	18.5 (6.2)	1.1 (0.2)

Abbreviations; Peak vel. – peak velocity, Peak acc. – peak acceleration, NJC – normalized jerk cost, a.u – arbitrary units, no. – number, NP – neutral head position, EFN – extension from NP, FBN – flexion back to NP, FFN – flexion from NP, EBN – extension back to NP, EF – full extension, FF – full flexion, S – slow movement speed, P – preferred movement speed, M – maximum movement speed.