MASTER OF SCIENCE THESIS

Neck muscle control patterns in 3D isometric experiments

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Delft University of Technology

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Contents

Abstract

The better understanding of neuromuscular control of the human neck is of critical importance to understand whiplash injury and neurological movement disorders. Isometric experiments using electromyography (EMG) are an appropriate method to study neuromuscular control patterns of neck muscles. As the human head-neck system is highly complex, it often exerts forces and moments simultaneously during isometric testing. However, literature generally shows no clear distinction between force and moment tasks in isometric experiments and no study tested forces and moments tasks separately in one experiment as the tasks given were ambiguous. The goals of this study were to test force and moment tasks separately in one experiment and analyse the differences in muscle control patterns. 12 healthy male subjects had surface electromyography (EMG) placed bilaterally on 4 neck muscles: sternocleidomastoid, splenius capitis, semispinalis capitis, trapezius. Isometric contractions were performed in a constrained helmet rigidly connected to an overhead loadcell. A new intuitive 3D visual feedback was applied in a neck isometric experiment which assisted subjects in separating force from moment tasks. Subjects performed force and moment tasks through sub-maximal voluntary contractions (sub-MVCs) in the anterior, posterior, and lateral directions. In a conventional 2DOFs task subjects received 2D feedback which only showed a target point while in a 3DOFs task subjects received an additional DOF feedback which showed a coupled moment in force tasks and a coupled force in moment tasks. Force and moment tasks with 2DOFs and 3DOFs visual feedback were compared. A consistent load coupling pattern was shown in 2DOFs task. Subjects performed force tasks coupled with consistent moment load and moment tasks coupled with force load, for instance, protraction force tasks coupled with extension moment; flexion moment tasks coupled with retraction force. With 3DOFs visual feedback, most subjects nullified the coupled load in the direction where the coupling DOF was displayed ($P<0.05$). The sternocleidomastoid and splenius capitis showed significantly different control patterns between force and moment tasks in the anterior (SCM: $P<0.005$, SPL: $P<0.05$) and lateral direction (SCM, SPL: $P<0.05$). Based on the findings we propose that force and moment tasks should be considered separately when performing neck isometric experiments on sternocleidomastoid and splenius capitis in the future research. The 3D visual feedback was a good method to separate force from moment tasks. The isometric load data along with EMG activity can be used to validate musculoskeletal neck models.

Keywords: Neck muscles, isometric, electromyography, visual feedback, muscle control patterns

Chapter 1 Introduction

The human head-neck system is highly complex. Deep cervical muscles are mainly for stabilizing our head position and superficial muscles are believed to produce multidirectional forces and moments (Blouin, Siegmund et al. 2007). This complex and redundant system requires a suitable control strategy to make them work smoothly. However, we still do not fully understand how humans control cervical muscles: how do muscle control patterns vary in different conditions? How well can subjects apply forces and moments independently with the neck? Is there any difference in muscle control patterns when performing force and moment tasks?

The neck plays a vital role in head movement. It allows the neck to flex and extend, bend laterally, rotate axially and move in translation. This enables our sensory organs like eyes, ears, mouth and nose to be oriented in the right direction.

However, our neck is fragile. It is a critical issue that chronic neck pain is highly prevalent and many people worldwide are suffering from neck pain with different causes (Cote, Cassidy et al. 1998, Falla 2004). There are many neck injuries such as whiplash, hernia, neck trauma, cervical spondlylosis and cervical dystonia. Whiplash is a serious neck injury resulting from rapid acceleration or deceleration occurred in vehicle accidents, especially obtained after a rear impact (Panjabi, Cholewicki et al. 1998). The human head is thrust back first and then forward beyond its normal range of motion. The ligaments and muscles supporting the spine are stretched or even torn. Symptoms of whiplash include stiff neck and neck, shoulder, or back pain, headaches, dizziness, limited mobility and it may also induce psychological problems (Siegmund, Winkelstein et al. 2009). With correct treatment, most patients can recover totally but some individuals may experience residual neck pain for a longer period of time.

The understanding of neuromuscular control of the human neck is of critical importance to understand mechanism of whiplash injury as well as for clinical revalidation purposes. Recently, the automotive industry has begun to use mathematical human models along with crash test dummies to simulate vehicle impacts. The biofidelity of crash dummies and neck models should be as accurate as possible so that the simulation can be regarded as a real impact. However, currently the models are lacking accurate neuromuscular control of the neck and detailed muscle activity and kinematic data for proper validation. Moreover, the knowledge on the neck muscle control is also critical in the clinical field where complex neurological movement disorders, like cervical dystonia (CD) affects specific muscles in the neck. Cervical dystonia (CD) is characterized by involuntary muscle contractions like twisting movements, tremor and abnormal postures (Delnooz and van de Warrenburg 2012). Patients have trouble performing movements correctly and compensate for the lack of control by changing muscle activation patterns. They use more co-contraction to perform the task which compensates overflow of electromyography (EMG) activity of inappropriate muscles. Even though treatments exist, neuromuscular disorders are generally impossible to cure and even the pathology is mostly unknown (Geyer and Bressman 2006, Elia, Lalli et al. 2010, Lehericy, Tijssen et al. 2013). More knowledge on the neuromuscular control of the neck will hopefully lead to better diagnosis and treatment of such neck disorders.

Three types of tests are frequently used to gain a better understanding of neck neuromuscular control. Dynamic tests (sled tests) are useful in observing neck muscle reflexes and simulating vehicle impacts (Siegmund, Blouin et al. 2007). Isokinetic tests are chosen to assess cervical strength using muscle strength testing devices like isokinetic dynamometers (Seng, Peter et al. 2002). But for the measurement of muscle EMG activity, both of two methods have limitation that it is difficult to get stable EMG recordings during muscle contraction. An alternative way is to use isometric test to measure subject strength in various directions along with EMG testing. The tested muscles can maintain contraction for a short time during isometric experiment, so muscle EMG activity is quite stable and have a close relationship with neck strength in the specific direction. It can be noted that recently the researches are interested in neck muscle control study using isometric experiment along with EMG testing (Keshner, Campbell et al. 1989, Ylinen, Rezasoltani et al. 1999, Chiu and Lo 2002, Garces, Medina et al. 2002, Kumar, Narayan et al. 2002, Vasavada, Peterson et al. 2002, Choi 2003, Ylinen, Nuorala et al. 2003, Gabriel, Matsumoto et al. 2004, O'Leary, Vicenzino et al. 2005, Blouin, Siegmund et al. 2007, Siegmund, Blouin et al. 2007, Almosnino, Pelland et al. 2009, Falla, Lindstrom et al. 2010). Kumar et al. (2002) studied the relationship between isometric force and EMG amplitudes in the sagittal, coronal and oblique planes. Hyeonki Choi et al. (2003) quantified the muscle co-contraction during isometric contractions influences the cervical spinal loads. Vasavada et al. (2002) and Gabriel et al. (2004) researched the neck muscle preferred activation direction during isometric contractions in spatial tuning and horizontal plane respectively. Blouin et al. (2007) identified the role of the deep and superficial neck muscles by performing isometric neck muscle contractions. Falla et al. (2010) studied the varied behavior of sternocleidomastoid motor units between healthy and patient subjects based on isometric experiment.

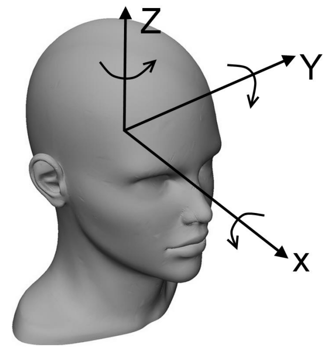


Figure 1.1 The coordinate system defined on human head

Generally, the neck is capable of performing head movement in 5 degrees-of-freedom (DOFs) according to the head coordinate (Figure 1.1). But in the isometric setup, the subject head is firmly locked and they only can apply loads towards a certain direction. The 5 degrees of freedom ($x, y, \widehat{x}, \widehat{y}, \widehat{z}$) defined in the isometric setup are that x, y represent force Fx (protraction/retraction) and Fy (lateral traction) along x,y direction and $\widehat{x}, \widehat{y}, \widehat{z}$ represent moment Mx (lateral bending), My (flexion/extension), Mz (axial rotation) around x,y,z axis. The majority of previous experiments quantified isometric efforts defined in the human head coordinate. The table 1.1 summarizes the DOFs of tasks of isometric experiments in the previous studies. Most experiments were 2 DOFs and a few did 3 DOFs. But no experiment can do 5DOFs completely so far. Moreover, the neck is so maneuverable and often exerts moment and force simultaneously. It is therefore important to know what the neck is doing exactly. Most experiments asked subjects to perform tasks, namely flexion/extension, right and left lateral bending and axial rotation. However, their measurements can be force or moment. It is problematic to distinguish between moment and force task as these tasks are coupled each other. For example, when the subjects perform flexion task against supporting pads placed before the subject's forehead, the subjects may prefer to perform protraction force than flexion moment or combined together (Almosnio 2009). Vasavada et al. (2002) analyzed the spatial tuning of neck muscle EMG activity. However, the spatial tuning of moment and force would be performed at the same time. Siegmund et al. (2007) didn't point out whether the task was the neck translational force or rotational moment. In the lateral direction, lateral traction force and lateral bending moment are coupled each other (Garces, Medina et al. 2002, Kumar, Narayan et al. 2002, Choi 2003). So far only two experiments: Chiu and Lo (2002) and Almosnino et al. (2009) tested force and moment task separately in the forward direction. Chiu and Lo (2002) used the medical instrument: The Multi Cervical Rehabilitation Unit (Hanoun Medical Inc.,Ontario) which can perform 4 DOFs isometric testing and took protraction/retraction into account (Chiu and Lo 2002). Another experiment Almosnino et al.(2009) reported to measure protraction by instructing subjects to push against the anterior padding of the helmet (Almosnino, Pelland et al. 2009). Unfortunately both of them did not record EMG so there was no information about the neck muscle EMG activity.

Table 1.1 Summary the degrees of freedom (DOFs) of task of isometric experiments in literature.

Paper	DOFs	Force x	Force y	Moment $\widehat{x}$	Moment $\widehat{y}$	Moment $\widehat{z}$	Tasks used in the paper	EMG testing
Thomas Tai Wing Chiu and Sing Kai Lo,2002	4	√		√	√	√	Flexion/extension; Right/left lateral bending; Protraction and retraction.	No
Keshner et al.,1989	3	√	√			√	Flexion/extension; Right/left lateral bending; Right/left axial rotation;	Yes
Vasavada et al.,2002	3			√	√	√	Flexion/extension; Right/left lateral bending; Right/left axial rotation;	Yes
Choi et al.,2002	3	√	√			√	Flexion/extension; Right/left lateral bending; Right/left axial rotation;	Yes
Almosnino et al.,2010	3	√		√	√		Extension/flexion; Protraction; Right/left lateral bending;	No
Kumar et al., 2002	2	√	√				Extension/flexion; Right/Left lateral bending	Yes
Gabriel et al.,2004	2	√	√				Flexion/extension; Right/left lateral bending;	Yes
Falla et al.,2010	2	√	√				Flexion/extension; Right/left lateral bending;	Yes
Blouin et al.,2007 Siegmund et al.,2007	2	√	√				8 directions (45° interval) in the horizontal plane	Yes
Ylinen et al.,1999 Ylinen et al.,2003	2	√				√	Flexion/extension; Right/left axial rotation;	No
Garces et al., 2002	1	√					Flexion/extension;	No
O'Leary et al.,2005	1				√		Flexion	No

In some previous studies, subjects were instructed to exert loads in a certain direction through voice commands (Kumar, Narayan et al. 2002, Seng, Peter et al. 2002, Choi 2003, Ylinen, Nuorala et al. 2003, Gabriel, Matsumoto et al. 2004). It is difficult to know which direction is actually subjects perform. Keshner et al. (1989) used visual feedback to assist subjects in maintaining a stable head position. The visual feedback of Falla et al. (2010) displayed the loads value to subject but no direction. 2D visual feedback was applied in the study of Vasavada et al. (2002) and Blouin et al. (2007) which showed the loads and directions in a screen. So far there is lack of a sufficient visual feedback to separate force and moment tasks towards the same direction.

A short summary of literature study results: no experiment measures isometric loads in force and moment task separately with EMG testing under the same condition. Also no report quantifies how well humans can do force and moment tasks respectively due to lacking a sufficient visual feedback. The gap of knowledge is muscle control patterns when performing force and moment tasks. It is very interesting to see whether they are different or not. If they are different, the results of previous studies had problems because they didn't consider that. If they are the same, it is not necessary to separate the force and moment task during isometric testing. Those questions will be answered in this report.

In this study, there are two research goals proposed:

- Design a new experiment setup that can separate force and moment tasks.
- Analyse the difference in neck muscle control patterns when performing force and moment tasks.

In order to achieve the research goals, a new isometric experiment was performed. An intuitive 3D visual feedback was developed to assist subjects perform force and moment tasks separately. Surface EMG testing was applied to compare muscle control patterns between the force and moment tasks.

The master thesis is organized as follows. Chapter 1 is the motivation to study neuromuscular control of neck and the research problems and finally the research goals are proposed. In Chapter 2, the experiment methods are described in detail. In Chapter 3, the experiment results are presented including the task execution and the effects of visual feedback and tasks on loads and EMG. Chapter 4 is making a discussion and comparison with previous results, limitations and recommendations. In Chapter 5, the conclusions and future work are proposed.

Chapter 2 Experimental Methods

2.1 Subjects

12 healthy male subjects with no history of physical neck muscle injuries involving control of the head and neck participated in this study (Table 2.1). 9 subjects participated in regular physical activity 2-4 hours per week in individual sports; none of these sports involved specific conditioning of the neck muscles as part of the training routines. The testing procedure was explained to the participants and their written consent was obtained prior to experiments. The experimental protocol was in accordance with the Declaration of Helsinki and was approved by the Human Research Ethics Committee at the Delft University of Technology.

Table 2.1 Subject information in neck isometric experiment. Mean (Standard Deviation) of data is shown. 12 subjects were tested, but one subject failed to perform the tests to the required degree and has been removed from the analysis (See Results-Task execution).

Mean(S.D.)	Age(years)	Height(cm)	Weight(kg)	Head circumference (cm)	Neck circumference (cm)
subjects (n=11)	25.6(2.5)	178.0(6.0)	73.1(7.3)	57.3(2.0)	37.1(2.5)

2.2 Experimental setup

The setup device was self-manufactured and made of steel (Figure 2.1). The whole structure was rigid. Subjects were seated in a rigid chair with a flat base and back and restrained by a safety belt. The 6 DOFs loadcell (MC3A-100, AMTI, US) was connected to the device through an adjustable joint which can tune the height according to the subjects sitting height. In order to protect subjects head, subjects were required to wear a skateboard helmet which was screwed on a connector board. The subjects head with helmet was coupled to the loadcell by a connector board. It can tune the length by positioning the connector board at different height. If a good position was found, two clamps would be tightened to lock the connector board. There were three sizes of cushion which can fit different subject head sizes inside helmet. Therefore the subject head was firmly locked in the helmet and it can be assumed that head was rigidly connected to the loadcell (Figure 2.2). Under this condition, subjects can push against the helmet to forward, backward, lateral direction, namely protraction, retraction, lateral traction translational force, and also rotate head around three axes to preform moment, namely flexion, extension, lateral bending moment. The axes of moment were defined as three orthogonal axes through the intersection of the sagittal plane of head and atlanto-occipital joint (O'Leary, Vicenzino et al. 2005). The loadcell can record three-dimensional forces and moments in real time. The force data was first sent to the amplifier (National Instruments) then stored in the hard disc by D-flow software (Motek medical, NL) while meantime it showed force and moment visually on the display. The visual feedback helps subjects perform the tasks.

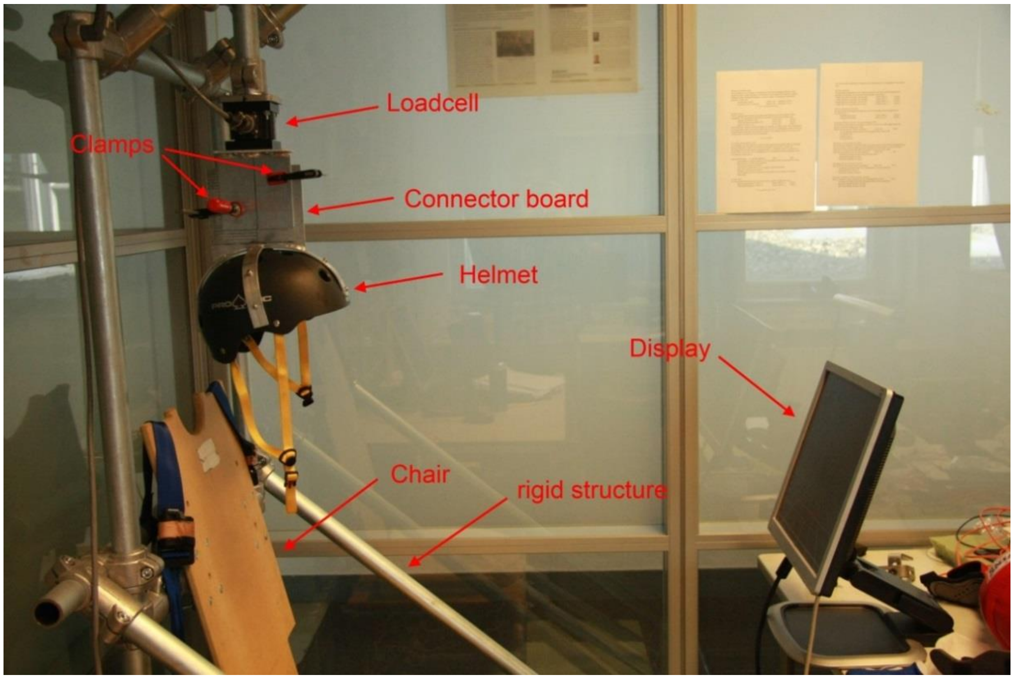


Figure 2.1 Experiment setup for neck isometric testing, helmet and loadcell are rigidly connected via a connector board using two clamps. The display in front of setup is for visual feedback. The whole structure is made of steel and very rigid.

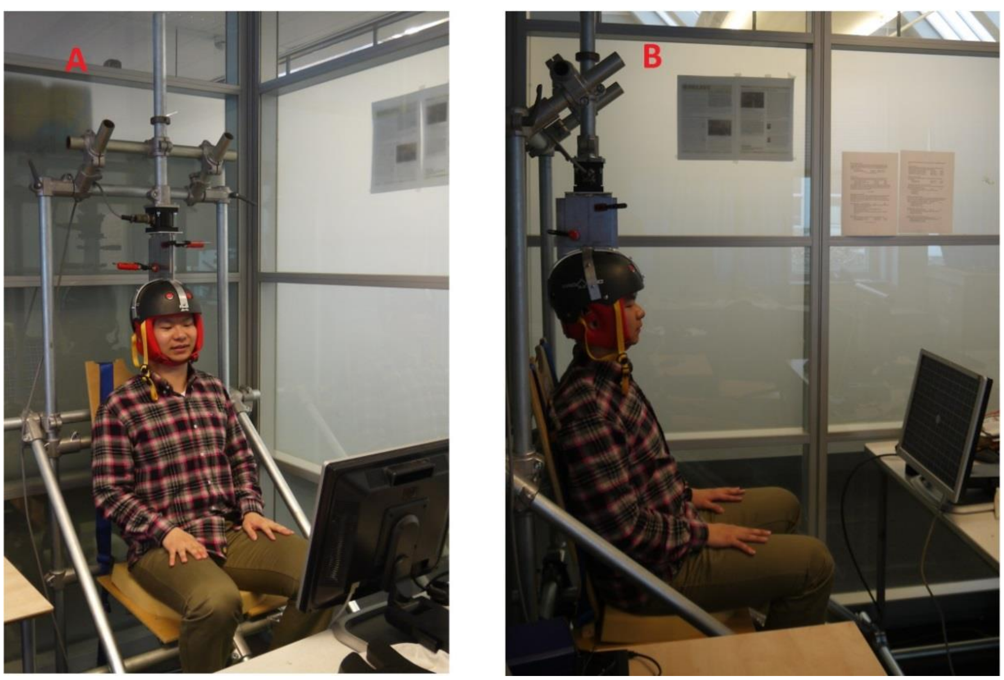


Figure 2.2 A: The subject wearing helmet locked in the device is performing the experiment. B: the side of view of the whole setup.

Surface EMG electrodes (TMSi, NL) were placed bilaterally on 4 well accessible neck muscles: sternocleidomastoid (SCM), splenius capitis (SPL), semispinalis capitis (SEMI), trapezius (TRAP) on each subject (Figure 2.3). The electrode placement was identified by correct palpation and verified by EMG signal. The electromyography (EMG) data was collected and recorded in TMSi software (Polybench) via Portilab at a sample rate of 2000Hz. The TMSi software and Portilab were synchronized by an external electric pulse from D-flow software.

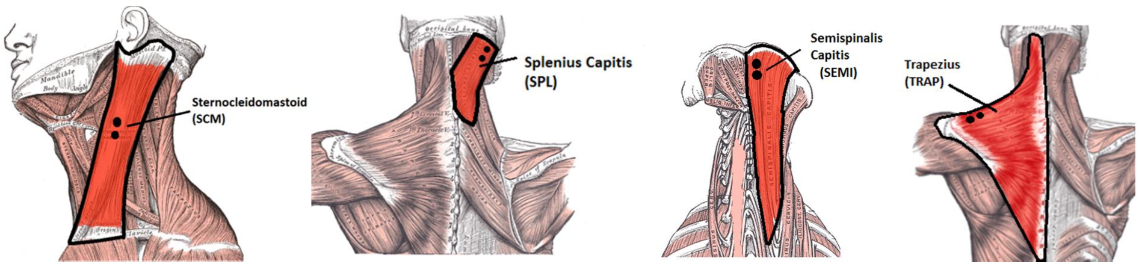


Figure 2.3 Muscle anatomy and placement of EMG surface electrodes (black dots). From left to right: sternocleidomastoid (SCM), splenius capitis (SPL), semispinalis capitis (SEMI), and trapezius (TRAP). All pictures are adapted from Gray's Anatomy (Gray 1977).

2.3 3D Visual feedback

In this experiment, the visual feedback is of critical importance. The head loads can be visualized to know it is force or moment. The requirement of visual feedback is that the experiment tasks displayed should be intuitive and clear. The D-flow software developed by Motek Medical BV was used to build the visual feedback. It displayed head loads on the monitor, stored data in the computer and sent a trigger to record EMG data.

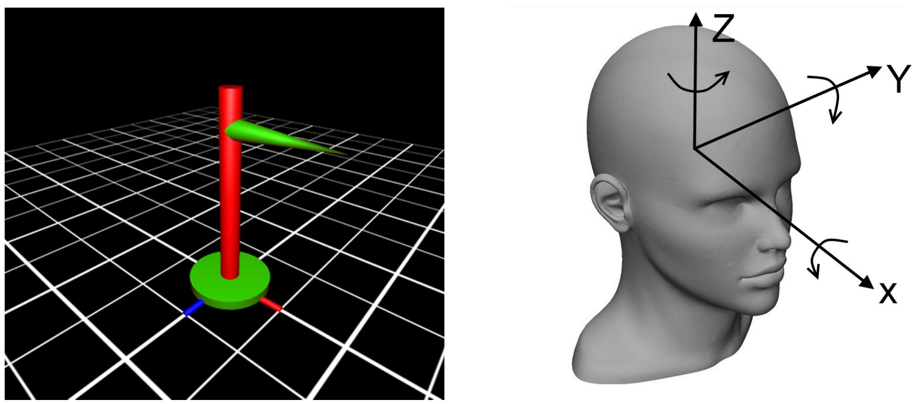


Figure 2.4 The visual object (left) built in the virtual environment consisting of circle (green),bar (red) and cone (green) represents 5DOFs of head coordinate system (right).

Table 2.2 Experiment tasks related to 5 degrees of freedom and visual objects. The sign indicates the task direction.

DOFs	Fx	Fy	Mx	My	Mz
Tasks	Protraction(+) Retraction(-)	Left lateral traction(+) Right lateral traction(-)	Right lateral bending(+) Left lateral bending(-)	Flexion (+) Extension(-)	Left axial rotation(+) Right axial rotation(-)
Objects	Circle		Cylinder bar		Cone

As already mentioned above, a coordinate system that describes the human head 5 DOFs is built. The table 2.2 shows the 5 DOFs and the corresponding task names. The visual object was designed to stimulate 5 degrees of freedom of the head when performing tasks (Figure 2.4). A visual object was made up of three objects: circle, cylinder bar and cone. The circle can translate along x and y axes which represent protraction/retraction and lateral traction force tasks respectively; the cylinder bar can rotate around x and y axes which represent flexion/extension and lateral moment tasks; the cone can rotate around z axis which represents axial moment task. Totally, three objects were combined into one that can show 5 DOFs corresponding to head coordinate system. There were two visual objects displayed during experiments (Figure 2.5). One was controlled by the subject which is named further as “subject”, the other was “target” which represents task primary load. For each experiment task, a certain number of visual feedbacks are given to subject. The subject job is to control “subject” object by exerting a certain load of force or moment to match “target” object. During the experiment, subjects may perform at most 5 different DOFs force and moment together, only the DOFs defined in the task are displayed and other DOFs aren’t shown but the values are recorded. The visual objects can have two colors: green color indicates two objects were matched each other; red color means two objects weren’t matched.

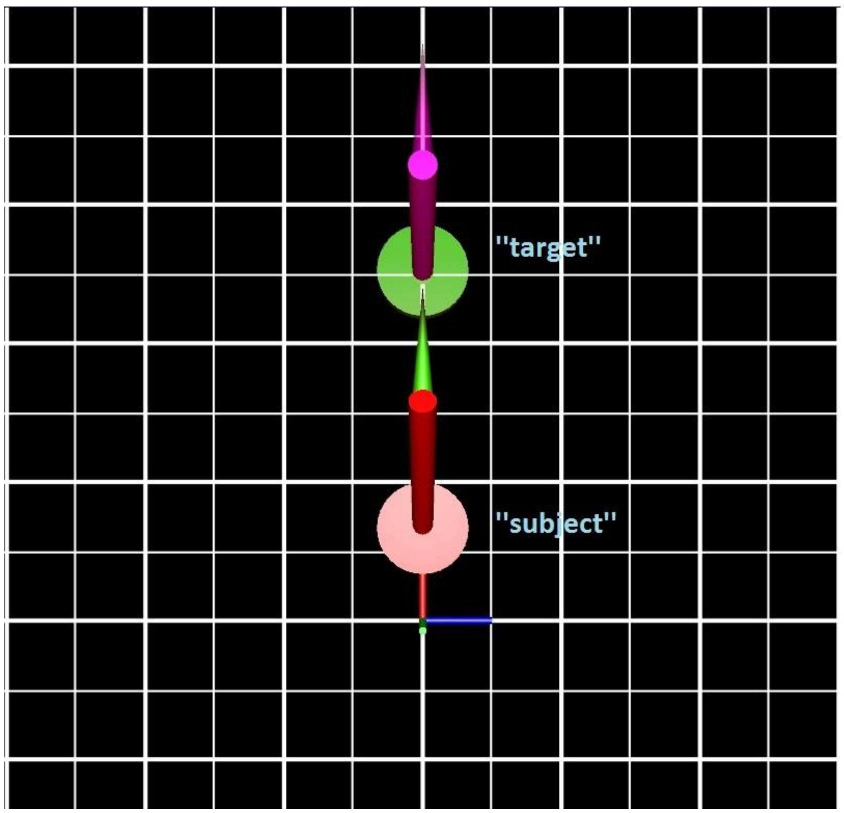


Figure 2.5 Subjects control “subject” object to match “target” object during the experiment.

2.4 Experimental tasks

The design of experiment tasks includes the task type (MVC or sub-MVC), the number of DOFs visual feedback and task loads.

The experiment contained two parts: the first part consisted of the maximal voluntary contraction (MVC) tasks for muscle EMG normalization (Figure 2.6); the second part consisted of the fixed load sub-MVC tasks. The MVC tasks required subjects to perform force or moment as hard as they could. There were 5 tasks, namely retraction for normalizing semispinalis capitis (SEMI), left twist and right twist for sternocleidomastoid (SCM), splenius capitis (SPL), semispinalis capitis (SEMI), left and right shoulder lift for trapezius (TRAP). Retraction and twist repeated two times and shoulder lift only once. The visual feedback displayed only the value of force or moment related to the task.

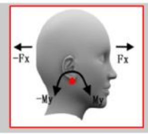
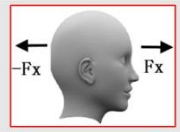
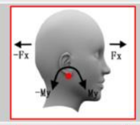
MVC task	Visual feedback	Rep	Hold on time [s]	Rest time [s]	comments
Retraction MVC	Fy	2	5	8	Normalize SEMI
Left Twist MVC	Mz	2	5	8	Normalize SCM, SPL, SEMI
Right Twist MVC	Mz	2	5	8	Normalize SCM, SPL, SEMI
Left Shoulder lift		1	5	8	Normalize TRAP
Right Shoulder lift		1	5	8	Normalize TRAP

Figure 2.6 The maximum voluntary contraction (MVC) task for muscle EMG normalization.

The second part consisted of sub-MVC tasks. Compared to the MVC tasks, the muscles can contract consistently for longer time and subjects can control loads direction more accurately and with less effects of fatigue. There are two options of sub-MVC task. One is the percentage of sub-MVC tasks (Edo de Bruijn et al., draft paper). The task load is different for everyone and it requires performing the MVC task per each direction for normalization and MVC calculation should be online. Another option is the fixed load tasks, the advantages are tasks are the same for everyone and muscle EMG activity is easy to compare. However, the disadvantage is the difficulty level of task is different to every subject which means each subject has a different feeling: easy or hard for the fixed load. It requires subjects have similar physical strength level. Due to simplifying tasks and short experiment duration, the fixed load sub-MVC task was chosen.

The experiment tasks consisted of protraction/retraction, flexion/extension, (left/right) lateral traction and (left/right) lateral bending. 3 subjects had a pilot test with 4DOFs visual feedback and 2 subjects had a pilot test with 5DOFs visual feedback. The tasks were very difficult to perform because too many DOFs to control and no one succeeded in all tasks. 2DOFs and 3DOFs tasks were quite doable.The figure 2.7 below shows the design of experiment tasks with visual feedback. The first type task was with 2 DOFs visual feedback that gave subjects the first DOF corresponding to the task load direction and the second DOF that subjects should control to the minimum. It can make sure subjects perform to the correct direction. For example, the 2DOFs visual feedback were Fx and Fy for protraction/retraction and lateral traction force tasks, My and Fy for flexion/extension moment task, Mx and Fx for lateral bending moment task. The second type task was 3 DOFs visual feedback that maintained the former 2DOFs and added another DOF to visually display the coupling load in the target direction. For protraction/retraction force tasks, the visual feedback added My which was coupled with force Fx; For lateral traction force tasks, two 3DOFs tasks would perform: one is with Mx and the other is with Mz additional visual feedback which both were coupled with Fy. The visual feedback for flexion moment task took Fx into account. The lateral bending moment task added Fy visual feedback.

How does the visual feedback work? For example, when the subject performs protraction force with 2DOFs visual feedback Fx,Fy he would push forward motivated by Fx visual feedback and meanwhile he may also generate a few moment My which is coupling moment. It wouldn't show that in 2DOFs task. However, with 3DOFs visual feedback, additional My visual feedback would inform how much flexion moment (My) he performed. The subject can control it to the minimum. Therefore, subjects are expected to perform protraction task only with translational force Fx. Other tasks also do the same thing with visual feedback.

Task	Load direction	2nd VFB	3rd VFB	Demonstration
Protraction/ Retraction	Fx	Fy		
Protraction/ Retraction	Fx	Fy	My	
Flexion/ Extension	My	Fy		
Flexion/ Extension	My	Fy	Fx	

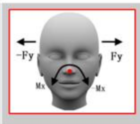
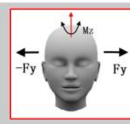
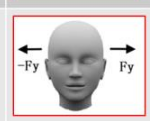
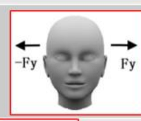
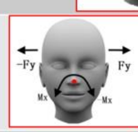
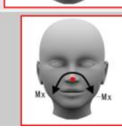
Task	Load direction	2nd VFB	3rd VFB	Demonstration
Lateral traction	Fy	Fx		 
Lateral traction	Fy	Fx	Mx	
Lateral traction	Fy	Fx	Mz	
Lateral Bending	Mx	Fx		
Lateral Bending	Mx	Fx	Fy	

Figure 2.7 The experiment tasks with 2DOFs and 3DOFs visual feedback. The additional third visual feedback is marked red colour.

The task loads were set as 30N for force task and 3Nm for moment task. Determine of task loads performed a pilot test on 5 subjects set from 50N, 5Nm then lowered down gradually until all subjects can handle that. The goal was a large load set point to ensure a good signal-to-noise ratio of EMG and minimize slipping of helmet. Moreover, subjects would not feel very difficult to perform the task and less effect of fatigue. If the loads were set too low, the muscle EMG activity may not show the significant difference. Besides, subjects cannot exert certain loads very precisely. The tolerances for force and moment load were tuned in the pilot experiments for 3 subjects. Three levels: 5%, 10%, 15% were tested for force and moment task respectively. The goal was as the minimal tolerance as possible. 3 subjects succeeded all force and moment tasks as the tolerance 10% for force and 15% for moment.

2.5 Experiment procedures

The whole experiment for one subject lasted about 2 hours. After a short introduction about this experiment and testing procedure, subjects were asked to fill a questionnaire form and sign a consent form to participate in this research. Then a suitable helmet was chosen to subject and it should be very tight but not hurt subject head. Wearing the helmet, subjects sat on the chair in the experiment setup. Tune the height of loadcell and monitor position so that subjects felt comfortable and in a neutral position that is self-selected by the subject. After that, surface electrodes were put on subject neck muscles bilaterally: sternocleidomastoid (SCM), splenius capitis (SPL), semispinalis capitis (SEMI), trapezius (TRAP), In order to check the EMG signals, subjects were asked to perform tasks like shoulder lift, retraction, twist. Then subjects were required to tighten themselves to the chair using the safety belt and place their feet on a foot pedal, bend knees slightly and place their hands on their lap. They were instructed to place their head and neck in a comfortable and natural position, while focusing visually on a monitor 0.5m away at the approximate height of the subject's eyes. Finally, subjects were locked in the helmet connected to the loadcell by two clamps and EMG wires connected to Portilab. Set initial parameters of D-flow visual feedback and EMG software. In order to get familiar with visual feedback before doing formal experiment, subjects were asked to do a short training, free to try some experiment tasks. The visual feedback was calibrated. When all preparation was done, subjects were ready to perform experiment tasks.

First of all, subjects would perform the MVC tasks. They were required to exert the maximum effort for 5 seconds and then had an 8 seconds rest. After the MVC tasks, subjects would perform the fixed load tasks with visual feedback. There were totally 18 types of tasks, each task repeat 2 times. So in total, there were 36 trials. One fixed load trial would last the maximum 60 seconds no matter whether the task is success or not. In order to succeed, subjects should exert 30N for force or 3Nm for moment to control the visual object to match target loads. The tolerance for force task was 10% and for moment was 15%.

The success load ranges for force and moment task were:

$$F \le [27 \quad 33]\,N$$
$$M \le [2.55 \quad 3.45]\,Nm$$

The error tolerance for coupled force and moment were:

$$F_e \le [-3 \quad 3]\,N$$
$$M_e \le [-0.45 \quad 0.45]\,Nm$$

When two objects were matched which means the force or moment was in the success load range, and also other coupled DOFs loads were in the error tolerance, the visual object color would change to green and a timer would countdown. Subjects should hold on 5 seconds until a “Have a Rest” word popped out and this task was success and subjects had a 6 seconds rest. If they only hold on less than 5 seconds which either the object came out of the loads range or unwanted DOFs loads were out of error tolerance, the timer would reset and the object would change back to red color. Subjects should try again until objects were matched again. If subjects failed to do some tasks, they would get a second chance to repeat after all tasks finished. During the experiment, subjects were allowed to stop or pause even came out of helmet to have a rest if necessary. EMG data and loadcell data were stored in the computer and well labelled subject number.

After all the experiment tasks performed, subjects can leave the chair and get rid of EMG electrodes from the neck and clean their neck by medical alcohol. The experiment procedure checklist is shown in the Appendix B.

2.6 Data collection and analysis

The loadcell signals were passed through an analogue low-pass filter (2nd order, critically damped at 1024Hz) and sampled at 2000Hz. In the D-flow software, the loadcell data was recorded as sample rate 304Hz and applied 10ms window to calculate the mean of loads. After that the data was transformed to the loads of head coordinate by multiplied a transformation matrix (Appendix A). The data text was selected labeled as a success task and extracted the last 5 seconds of samples. The data of the failed tasks were not used with a replacement of NaN. The mean of samples for Fx,Fy,Mx,My,Mz were calculated in one trial. Each task repeated two times. Then the mean of two repeats was calculated for one task (some tasks may only have one success repeat) and finally the mean and standard error of 11 subjects were calculated for each task (Matlab, Mathworks Inc., USA).

The EMG data were sampled at 2000Hz, extracted the last 5 seconds of samples, changed from unipolar to bipolar and removed mean value. A 3rd order notch filter was implemented to remove the influence of 50Hz noise from the network. A high-pass filter, 4th order Butterworth filter at 20Hz, was applied to remove kinematic artifacts (De Luca, Gilmore et al. 2010). Finally the EMG was full wave rectified. Ideally, the last 5 seconds of samples should be extracted after the filtering to avoid the swing-up of the filter. However, errors due to the current filter over were lower than 6% overall so we kept the order above. EMG data during all trials EMG_{trial} were normalized with respect to their maximum value EMG_{mvc}. EMG_{mvc} was determined as the highest mean EMG of a 500ms window during any of the MVC tasks for each muscle. Mean and standard error of EMG were calculated for each task over all subjects.

Statistical analysis used the two-tailed Student's *t*-test for two sample data. The mean of the loadcell data Fx,Fy,Mx,My,Mz and the EMG data for each muscle in two paired tasks were checked the significant difference. The significance level was set to 0.05. The two paired tasks can be the same task with 2DOFs and 3DOFs visual feedback or the force and moment task in the same direction with the same type of visual feedback.

Chapter 3 Results

The data obtained consists of forces and moments from the loadcell and simultaneously recorded EMG data. Loadcell data is used to ensure correct task performance and to check whether the setup with visual feedback can separate force and moment tasks. The normalized EMG data shows the muscle control patterns during the isometric tasks. In order to evaluate the differences between force and moment tasks, three comparisons are done in the chapter:

- Loadcell results of the same task with 2DOFs and 3DOFs visual feedback.
- Loadcell results between force and moment tasks in the same direction.
- Muscle control patterns between force and moment tasks in the same direction.

3.1 Task execution

The MVC results are shown in table 3.1. Subjects exerted the effort as hard as they could. Subject No.8 had a relatively low strength: 94.1N for retraction, 5Nm and 6.2Nm for left and right twist. Subject No.2 had the maximum strength in the retraction force which was 221.5N and No.6 had the maximum twist strength which was 16.2Nm and 18.8Nm for left and right respectively.

Table 3.1 The MVC tasks results for 12 subjects and the mean (standard deviation) over 12 subjects and over 11 subjects where subject No.8 was removed respectively.

Subjects	MVC: Retraction [N]	MVC: Left twist [Nm]	MVC: Right twist [Nm]
No.1	-155.0	11.2	-11.7
No.2	-221.5	12.7	-13.1
No.3	-168.8	10.7	-11.0
No.4	-125.1	8.4	-9.8
No.5	-132.8	7.5	-8.9
No.6	-187.1	16.2	-18.8
No.7	-216.8	9.6	-8.4
No.8	-94.1	5.0	-6.2
No.9	-188.9	16.1	-16.5
No.10	-165.2	10.6	-12.8
No.11	-186.0	12.2	-13.5
No.12	-169.0	10.0	-11.1
Mean(S.D.) (12 subjects)	-167.5(37)	10.9(3.2)	-11.8(3.5)
Mean(S.D.) without No.8	-174.2(30.3)	11.4(2.8)	-12.3(3.1)

Subjects had different feelings during the fixed load experiment. Subjects No.4, No.5, No.7 and No.8 felt the tasks were difficult to perform. Subject No.4 thought the task load was hard, especially moment tasks with 3DOFs visual feedback. Subject No.5's had comments about slightly sliding inside the helmet when doing lateral bending tasks. Subject No.7's head didn't fit the helmet very well so some tasks with 3DOFs visual feedback failed. Subject No.8 had a difficulty to do lateral bending even without being in the device. Some felt tired and required a longer rest after 30 seconds trial time. Other subjects felt the task was doable and fitted well in the device.

The table 3.2 shows the results of task completion. 7 out of 12 subjects finished all tasks and subject No.4, No.5, No.7, No.8 and No.12 failed one or more tasks, as shown in the table. Each task required subjects to repeat twice. Only if both repeats failed, the task would not count as a success task. The success rate was calculated by the number of successful subjects divided by the total number of subjects. The task with 2 DOFs visual feedback has a higher success rate than the 3 DOFs. The lowest success rate of task is protraction with 3DOFs visual feedback and there were 5 subjects failed in this task. Another two difficult tasks are 3DOFs flexion and 2DOFs left lateral bending tasks which the success rates are 66.67% and 75% respectively. Other task success rates are above 80%.

Table 3.2 the results of subject execution and task success rate.

DOFs	Task name	Visual feedback*			Repetition 1 failed Sub. No.	Repetition 2 failed Sub. No.	Success rate (%)
2	Protraction	**<u>Fx</u>**	Fy				100
3	Protraction	**<u>Fx</u>**	Fy	My	4,5,7,8,12	4,5,7,8,12	58.33
2	Retraction	**<u>Fx</u>**	Fy				100
3	Retraction	**<u>Fx</u>**	Fy	My			100
2	Flexion	**<u>My</u>**	Fy		4	4	91.67
3	Flexion	**<u>My</u>**	Fy	Fx	4,5,7,8	4,5,7,8	66.67
2	Extension	**<u>My</u>**	Fy		7		100
3	Extension	**<u>My</u>**	Fy	Fx			100
2	Left Lateral traction	**<u>Fy</u>**	Fx				100
3	Left Lateral traction	**<u>Fy</u>**	Fx	Mx			100
3	Left Lateral traction	**<u>Fy</u>**	Fx	Mz	7,8	8	91.66
2	Right Lateral traction	**<u>Fy</u>**	Fx		7		100
3	Right Lateral traction	**<u>Fy</u>**	Fx	Mx		7	100
3	Right Lateral traction	**<u>Fy</u>**	Fx	Mz	5	7	100
2	Left Lateral Bending	**<u>Mx</u>**	Fx		4,5,7,8	4,7,8	75
3	Left Lateral Bending	**<u>Mx</u>**	Fx	Fy	4,8	4,7,8	83.33
2	Right Lateral Bending	**<u>Mx</u>**	Fx		4,5,8	4,8	83.33
3	Right Lateral Bending	**<u>Mx</u>**	Fx	Fy	7	4,5,8	100

***The bold underscored variable provides the primary task loads for which the target point is set.**

The load levels of the tasks were fixed for every subject: 30N for force task and 3Nm for moment task. It can be assumed that the same task is performed by each subject as long as there is no large variability in strength in the subject group. Relatively weak subjects would require a large percentage of MVC to apply the same load, which then ultimately would no longer be a sub-MVC task. To ensure similar task performance, the subject data should be selected to remove outliers.The criterion is that anyone whose 30% MVC load is lower than the fixed task loads will be removed from the results. One holds on the load exceeding 30%MVC for 5 seconds will be extremely tired and not healthy. We found subject No.8 was relatively weak as shown in MVC tasks (Table 3.1). The MVC of retraction is 94.1N and 30%MVC is 28.23N which is lower than force task load 30N and the twist MVC is also much lower than others which are 46% and 52.5% of the mean for left and right twist respectively. The MVC twist task is to normalize three muscles SCM, SPL and SEMI. If these three muscles weren't strong enough, the fixed load task was relatively strenuous for this subject. Moreover, Subject No.8 was remarked that had a difficulty performing lateral bending moment task and he failed 6 tasks (Table 3.2). Therefore, subject No.8 is removed from the dataset for further analysis.

3.2 Effects of visual feedback and task on loads

The different types of task and visual feedback influence subjects performing task loads. From the comparison of tasks with 2DOFs and 3DOFs visual feedback, we can study effects of the visual feedback. From the comparison of force and moment tasks, we can quantify their differences on loads.

3.2.1 Effects of visual feedback

The results of the same task with 2DOFs and 3DOFs visual feedback are compared. Differences in load coupling are shown in Table 3.3, where the sign defines the load direction as shown in the table 2.2. The performance of tasks with 2DOFs visual feedback shows the coupling effects which reflect the subjects' natural behavior. Any coupled load that is larger than the error tolerance (force is 3N; moment is 0.45Nm) averaged over subjects is taken into account as coupling element. Subjects perform protraction force (Fx) coupled with extension moment (My) but retraction force without coupling element. Flexion and extension moment (My) are coupled with retraction force (Fx). Lateral traction force (Fy) coupled with lateral bending moment (Mx) in the opposite direction, axial rotation moment (Mz) in the same direction. Lateral bending moment (Mx) coupled with lateral traction force (Fy) in the same direction. In addition, right lateral bending moment coupled with extension moment

(My) and left axial rotation moment (Mz). Added the coupled visual feedback, the results of 3DOFs visual feedback show the coupling load is reduced below the error tolerance. However, task right lateral traction added Mx visual feedback, except for Mx reducing; Fy and Mz are also changing significantly. Task left lateral bending with additional Fy visual feedback shows right axial rotation moment Mz increases significantly. There is no significant difference in retraction task with and without My visual feedback. The detail results are shown in the following figures (Figure 3.1-Figure 3.8). The red bars indicate mean values of force; the blue bars indicate mean values of moment. The standard error of the mean boundary is depicted by the vertical bar. The *p*-value indicates significantly different loads.

Table 3.3 Summary of coupling effects in 2DOFs and 3DOFs tasks. Mean coupled loads of subjects are given in brackets.

2DOFs task	Mean of coupled force(N) or moment(Nm)	
Force tasks(30N)	**Secondary force(N)**	**Secondary moment (Nm)**
Protraction	Na	Extension(2.91)
Retraction	Na	Na
Left lateral traction	Na	Extension(0.77)
		Right lateral bending(1.21)
		Left axial rotation (1.55)
Right lateral traction	Na	Left lateral bending(1.16)
		Right axial rotation (2.40)
Moment tasks(3Nm)	**Secondary force(N)**	**Secondary moment (Nm)**
Flexion	Retraction(8.91)	Na
Extension	Retraction(25.40)	Na
Left lateral bending	Left lateral traction (16.50)	Na
Right lateral bending	Right lateral traction(11.58)	Left axial rotation(0.78)
		Extension(0.96)
3DOFs task		
Force tasks(30N)	**Secondary force(N)**	**Secondary moment (Nm)**
Protraction	Na	Na
Retraction	Na	Na
Left lateral traction (Mx)	Na	Left axial rotation (1.21)
Right lateral traction(Mx)	Na	Right axial rotation (1.14)
Left lateral traction (Mz)	Na	Right lateral bending(2.37)
Right lateral traction(Mz)	Na	Left lateral bending(1.47)
Moment tasks(3Nm)	**Secondary force(N)**	**Secondary moment (Nm)**
Flexion	Na	Na
Extension	Na	Na
Left lateral bending	Na	Right axial rotation (1.95)
Right lateral bending	Na	Extension(0.77)
		Left axial rotation(1.75)

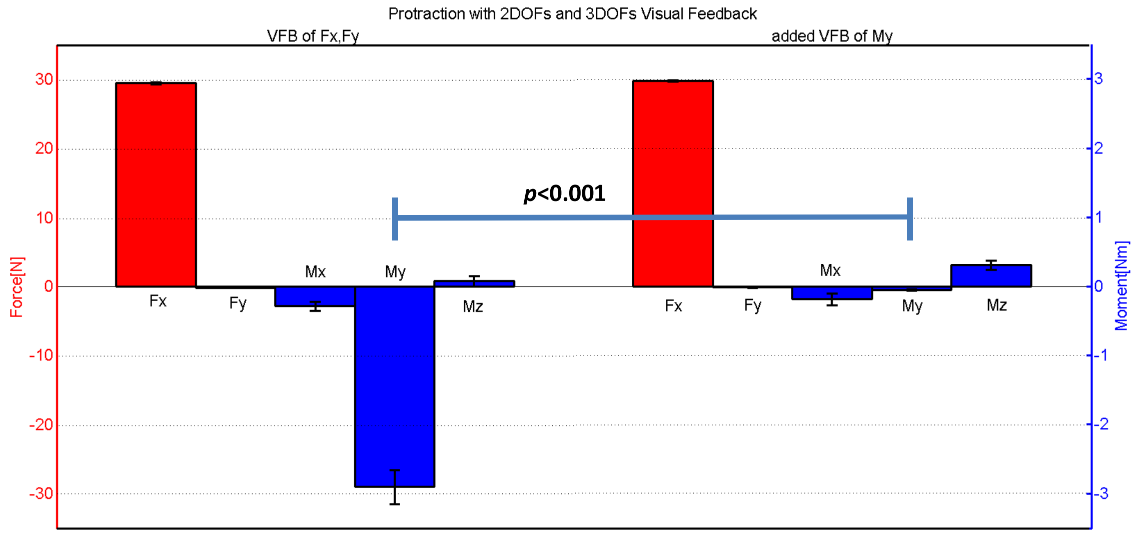


Figure 3.1 Protraction force task with 2DOFs (left) visual feedback Fx,Fy and 3DOFs (right) visual feedback Fx,Fy,My. The red bars indicate mean values of force; the blue bars indicate mean values of moment. The standard error of the mean boundary is depicted by the vertical bar. The coupled extension moment My is strongly reduced ($p<0.001$) when giving My feedback while other forces and moments show no difference.

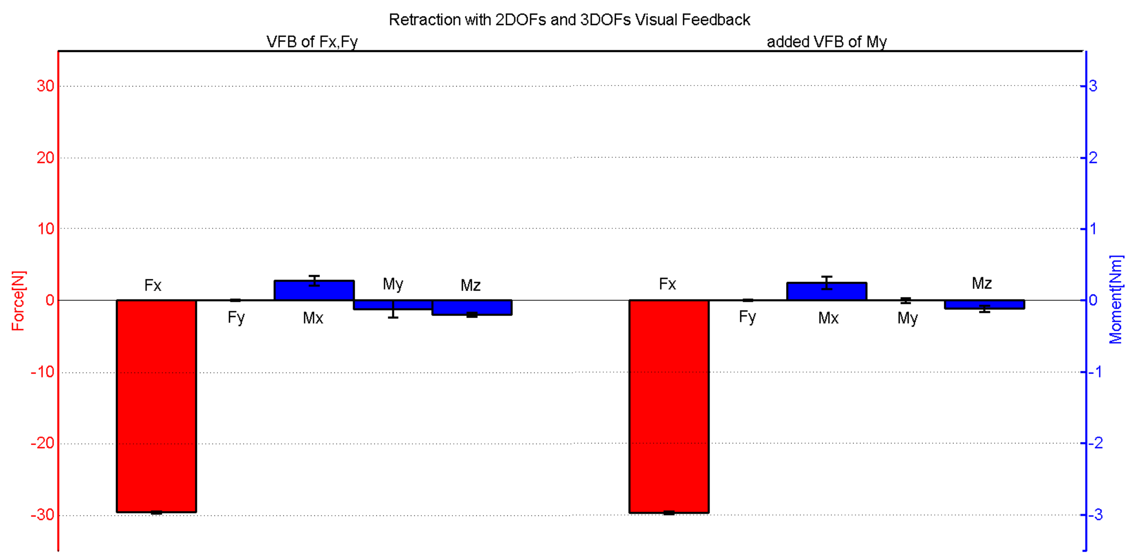


Figure 3.2 Retraction force task with 2DOFs (left) visual feedback Fx,Fy and 3DOFs (right) visual feedback Fx,Fy,My. The red bars indicate mean values of force; the blue bars indicate mean values of moment. The standard error of the mean boundary is depicted by the vertical bar. There is no significant difference when adding My as visual feedback.

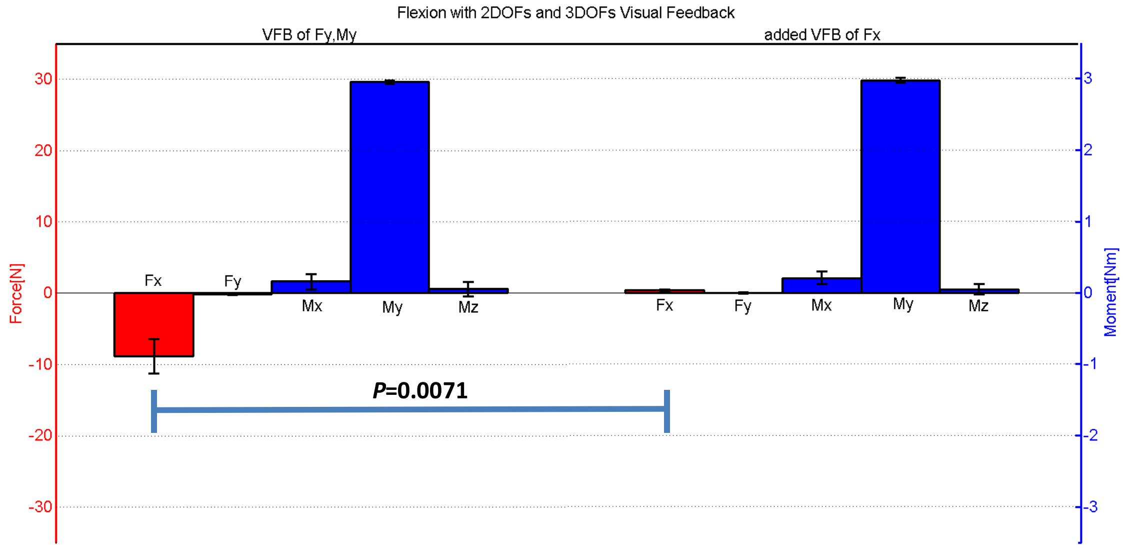


Figure 3.3 Flexion moment task with 2DOFs (left) visual feedback Fy,My and 3DOFs (right) visual feedback Fx,Fy,My. The red bars indicate mean values of force; the blue bars indicate mean values of moment. The standard error of the mean boundary is depicted by the vertical bar. The coupled retraction force Fx is strongly diminished (p=0.0071) when subjects are provided with Fx feedback. Other forces and moments show no difference.

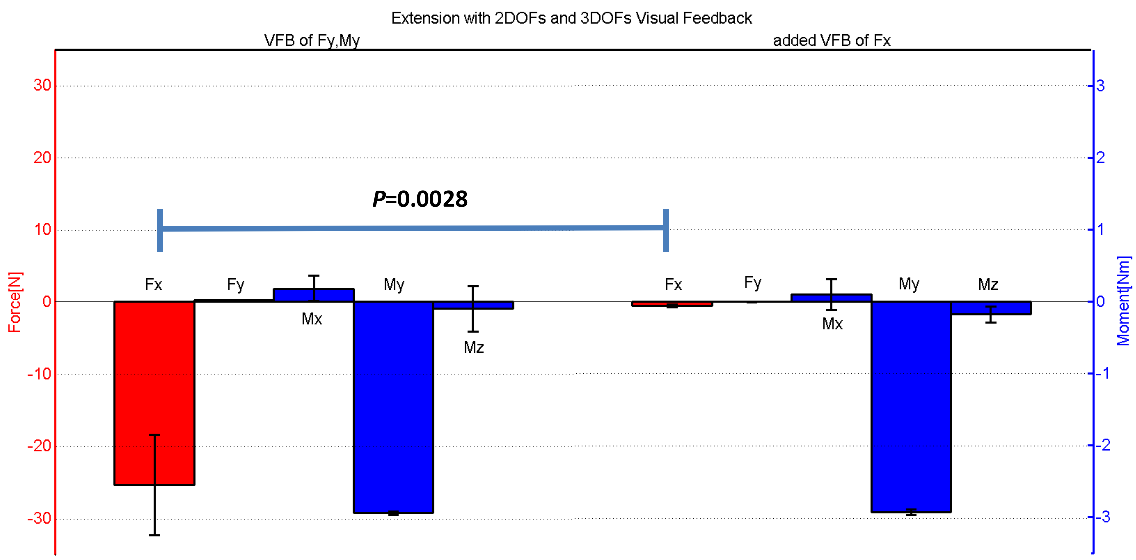


Figure 3.4 Extension moment task with 2DOFs (left) visual feedback My,Fy and 3DOFs (right) visual feedback My,Fy,Fx. The red bars indicate mean values of force; the blue bars indicate mean values of moment. The standard error of the mean boundary is depicted by the vertical bar. The coupled retraction force Fx is strongly reduced (p=0.0028) when subjects are provided with Fx feedback. Other changes of forces and moments are not significant.

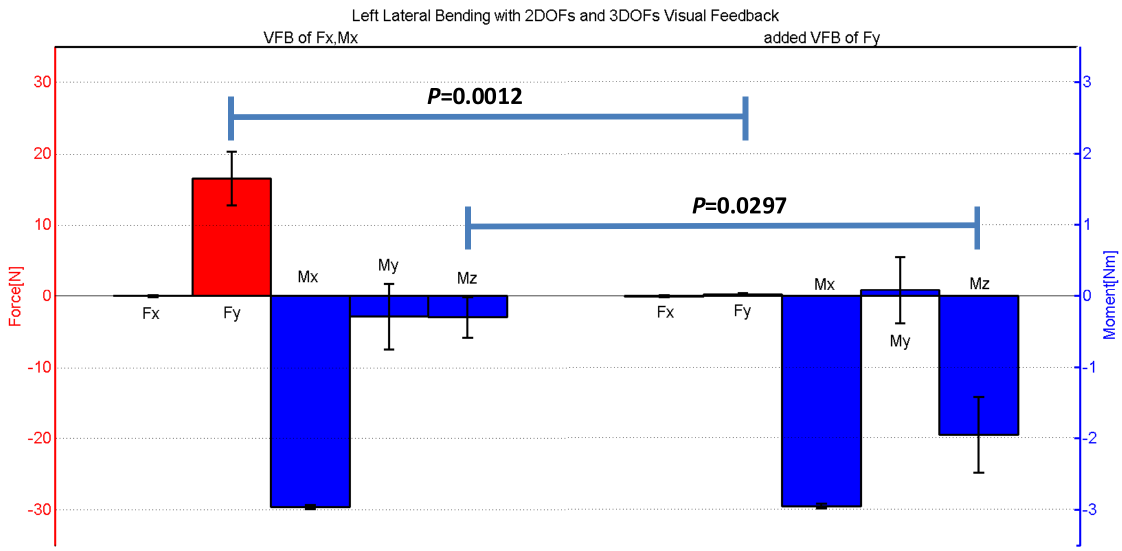


Figure 3.5 Left lateral bending moment task with 2DOFs (left) visual feedback Mx,Fx, and 3DOFs (right) visual feedback Mx,Fx,Fy. The red bars indicate mean values of force; the blue bars indicate mean values of moment. The standard error of the mean boundary is depicted by the vertical bar. The left lateral force Fy is strongly reduced (p=0.0012) when giving Fy feedback. Right axial rotation moment Mz is significantly increased (p=0.0297).

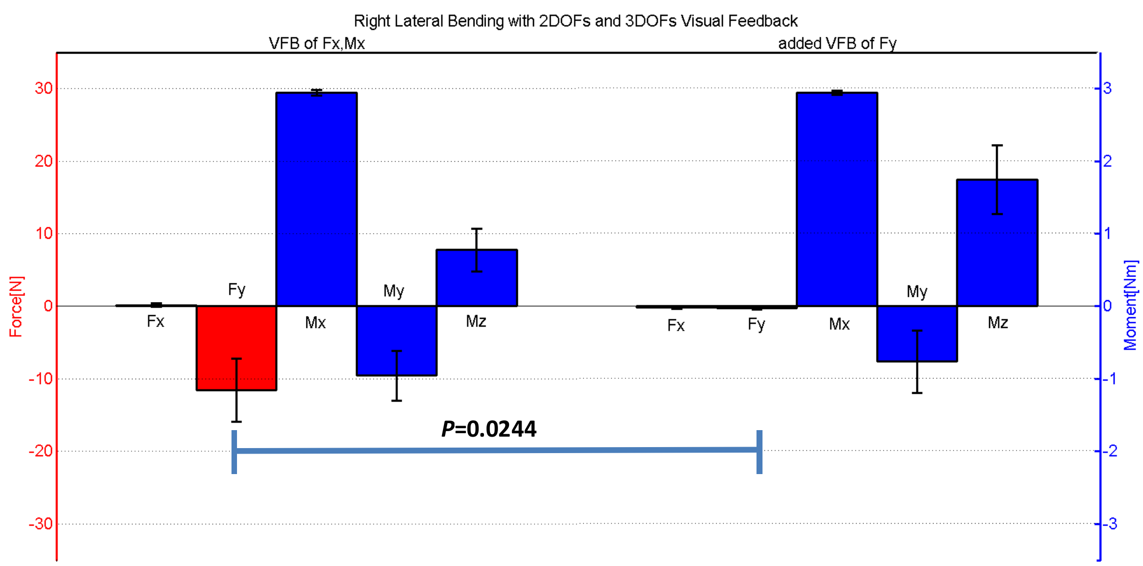


Figure 3.6 Right lateral bending moment task with 2DOFs (left) visual feedback Mx,Fx and 3DOFs (right) visual feedback Mx,Fx,Fy. The red bars indicate mean values of force; the blue bars indicate mean values of moment. The standard error of the mean boundary is depicted by the vertical bar. The right lateral force Fy is reduced (p=0.0244) when giving Fy feedback. Other changes of forces and moments are not significant. Both are coupled with extension moment My and left axial rotation moment Mz.

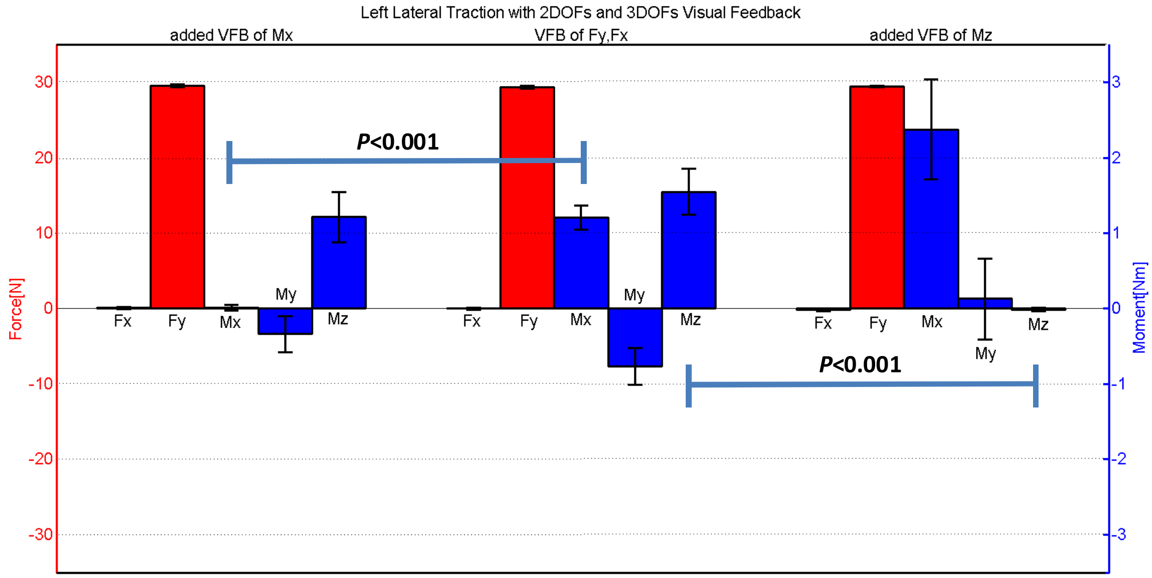


Figure 3.7 Left lateral traction force task with 2DOFs (middle) visual feedback Fy,Fx and 3DOFs (left) Fy,Fx,Mx and 3DOFs (right) Fy,Fx,Mz. The red bars indicate mean values of force; the blue bars indicate mean values of moment. The standard error of the mean boundary is depicted by the vertical bar. The coupled right lateral moment Mx is strongly reduced (p<0.001) when giving Mx feedback. The left axial rotation moment Mz is significantly decreased (p<0.001) with Mz feedback added.

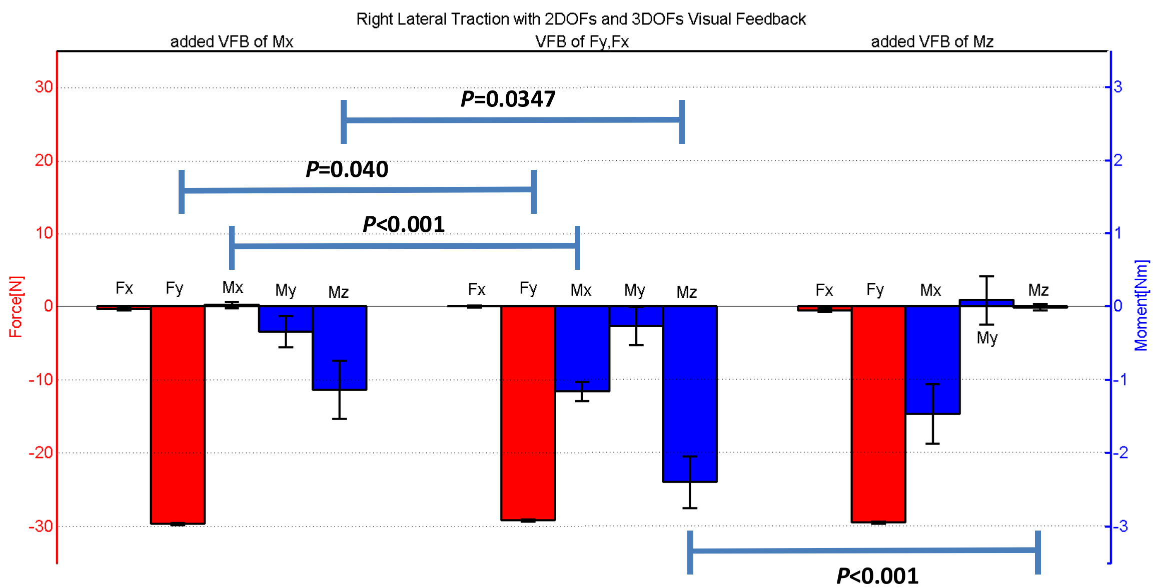


Figure 3.8 Right lateral traction force task with 2DOFs (middle) visual feedback Fy,Fx and 3DOFs (left) Fy,Fx,Mx and 3DOFs (right) Fy,Fx,Mz visual feedback. The red bars indicate mean values of force; the blue bars indicate mean values of moment. The standard error of the mean boundary is depicted by the vertical bar. Left lateral moment Mx is strongly reduced (p<0.001) when giving Mx feedback. Meanwhile lateral traction force Fy increased significantly (p=0.04) and right axial rotation moment Mz is reduced (p=0.0347). Another comparison shows the coupled right axial rotation moment Mz is significantly decreased (p<0.001) with Mz feedback added. Other changes of forces and moments are not significant.

3.2.2 Effects of force versus moment task

The load results of force and moment tasks with 3DOFs visual feedback in the same direction are compared below. Results for 2DOFs tasks are quite comparable and shown in the Appendix C. As described above all task loads were adequately achieved but even with the 3DOFs task some additional coupled loads were generated (Table 3.3). There are four task directions: the forward, backward, leftward and rightward with respect to subject sitting position, and resulting 5 force and moment loads: Fx, Fy, Mx, My, Mz .The force tasks: protraction, retraction, left and right lateral traction corresponding to the forward, backward, leftward and rightward direction. The moment tasks like flexion, extension, left and right lateral bending can be described as the forward, backward, leftward, rightward direction. The results show three of five loads are significantly different between force and moment tasks in the forward, leftward and rightward direction, but only two loads Fx and My were different in the backward direction (retraction/extension). For lateral direction, lateral bending moment task was compared with lateral traction force added Mx and Mz visual feedback respectively. The red bars indicate mean values of force; the blue bars indicate mean values of moment. The standard error of the mean boundary is depicted by the vertical bar. The *p*-value indicates significantly different loads in the figures (Figure 3.9-Figure 3.12).

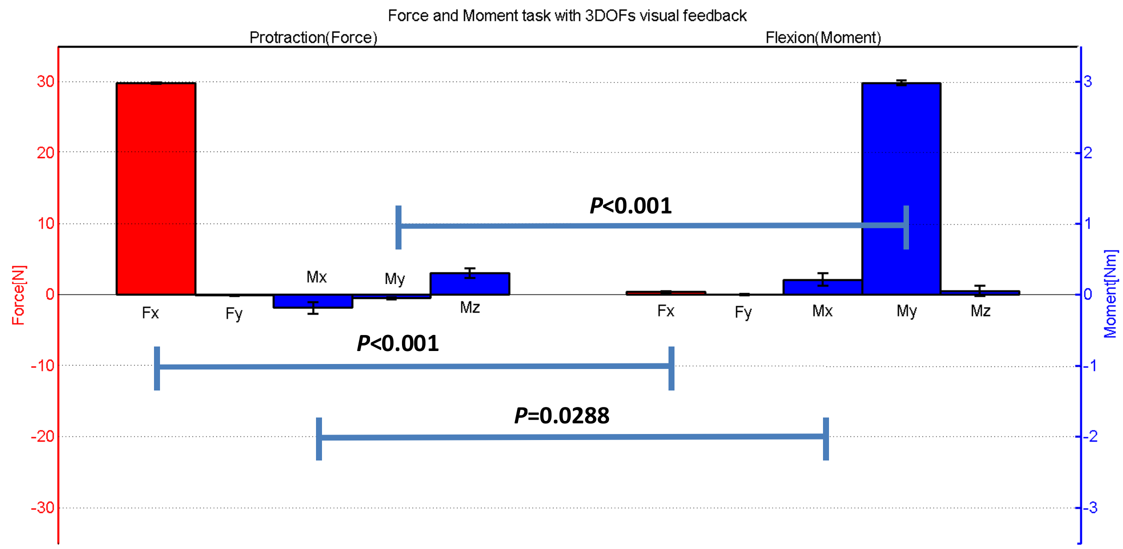


Figure 3.9 In the forward direction, the Fx force task: protraction (left) and My moment task: flexion (right) with 3DOFs visual feedback Fx,Fy,My. The red bars indicate mean values of force; the blue bars indicate mean values of moment. The standard error of the mean boundary is depicted by the vertical bar. Task loads Fx and My are significantly different (p<0.001). Besides, Mx is also significantly different (p=0.0288).

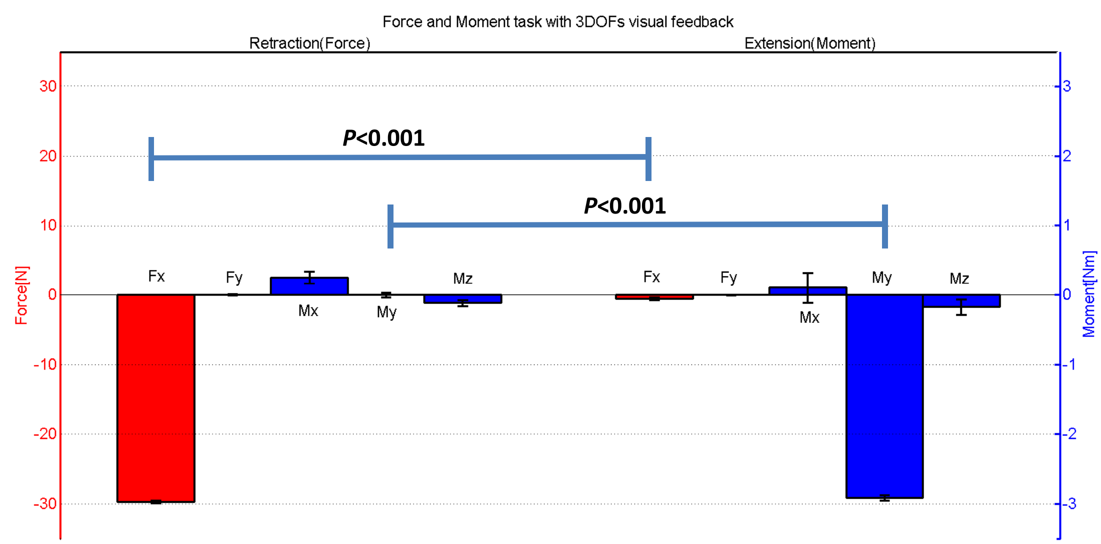


Figure 3.10 In the backward direction, the Fx force task: retraction (left) and My moment task: extension (right) with 3DOFs visual feedback Fx,Fy,My. The red bars indicate mean values of force; the blue bars indicate mean values of moment. The standard error of the mean boundary is depicted by the vertical bar. Task loads Fx and My are significantly different (p<0.001).

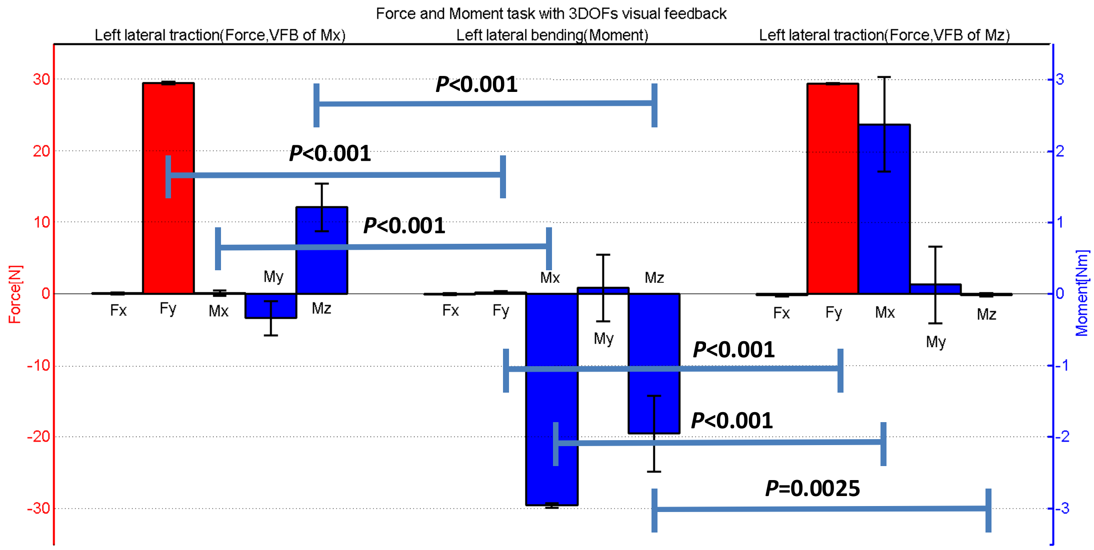


Figure 3.11 In the leftward direction, Comparison of the lateral traction task with 3DOFs visual feedback Fy,Fx,Mx (left) to the lateral bending with 3DOF visual feedback Mx,Fx,Fy (middle). The red bars indicate mean value of force; the blue bars indicate mean value of moment. The standard error of the mean boundary is depicted by the vertical bar. Fy, Mx and Mz are significantly different (p<0.001). Another comparison of the lateral traction task added Fy,Fx,Mz visual feedback(right) to the lateral bending (middle). Fy, Mx and Mz are significantly different (Fy: p<0.001, Mx: p<0.001, Mz: p=0.0025).

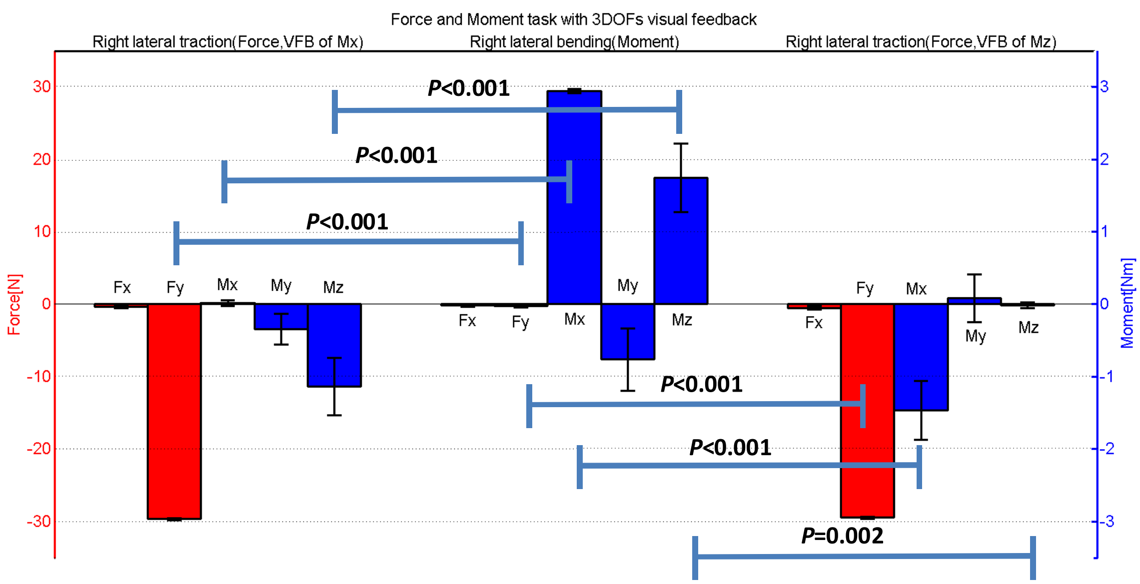


Figure 3.12 In the rightward direction, Comparison of the lateral traction task with 3DOFs visual feedback Fy,Fx,Mx (left) to the lateral bending with 3DOFs visual feedback Mx,Fy,Fx (middle). The red bars indicate mean value of force; the blue bars indicate mean value of moment. The standard error of the mean boundary is depicted by the vertical bar. Fy, Mx and Mz are significantly different (p<0.001). Another comparison of the lateral traction task with 3DOFs visual feedback Fy,Fx,Mz (right) to the lateral bending (middle). Also Fy, Mx (p<0.001) and Mz (p=0.002) are significantly different.

3.3 Effects of force versus moment task on EMG

Four pairs of neck muscles, sternocleidomastoid (SCM), splenius capitis (SPL), semispinalis capitis (SEMI), trapezius (TRAP) were tested during the isometric experiment. The electromyography (EMG) activities of muscles are plotted as a polar curve which the angle 0^o, 90^o, 180^o, -90^o represent the task direction: forward, rightward, backward, leftward. The figure 3.13 defines four directions according to the top view of subject head when performing isometric experiment. The normalized EMG mean and standard error (colour shaded area) over 11 subjects in force and moment tasks are put in one plot. Each plot consists of left and right side muscle and the tasks with 2DOFs and 3DOFs visual feedback respectively. Blue lines represent force task with 2DOFs visual feedback; Green lines represent moment task 2DOFs visual feedback; Red lines represent moment task with 3DOFs visual feedback; Cyan lines represent force task with 3DOFs visual feedback added Mx to leftward and rightward; Magenta lines represent force task with 3DOFs visual feedback added Mz to leftward and rightward. The highest EMG activity level in four directions indicates the preferred activation direction of muscle. The student *t*-test is to check the results significant level between force and moment task for each direction (Figure 3.14–Figure 3.17).

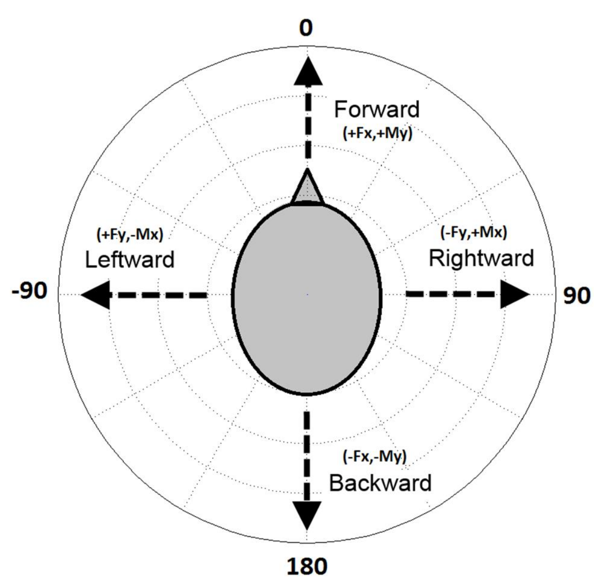


Figure 3.13 Four directions are defined with respect to the top view of subject head performing isometric experiment.

3.3.1 Sternocleidomastoid

The sternocleidomastoid (SCM)'s preferred activation direction is forward during a force task, but shifts to the lateral direction in a moment task with 2DOFs visual feedback. The preferred lateral direction is consistent with the SCM anatomical location. The left side is more active in leftward and the right side is in rightward direction in moment task. Compared to 2DOFs tasks, the curve indicating the preferred activation of direction is more sharp and clear in 3DOFs task. For moment task, the direction is the same as SCM location which means left SCM points to leftward direction and right SCM points to rightward direction. For force task, there are two preferred activation directions: the forward and lateral directions that are the same as the SCM anatomical location. They have approximately equal EMG activity level. The significant differences are found in forward ($p<0.001$) and left directions ($p=0.0096$) for left SCM and forward direction ($p=0.0033$) and rightward direction ($p<0.001$) for right SCM in 2DOFs task. The unsymmetrical pattern is shown in 3DOFs task. The forward ($p<0.001$) and left direction ($p=0.0276$ for added Mx and $p=0.0188$ for added Mz visual feedback) are significantly different between force and moment task for left SCM. But right SCM shows the difference in forward direction ($p=0.0019$) but not in rightward direction.

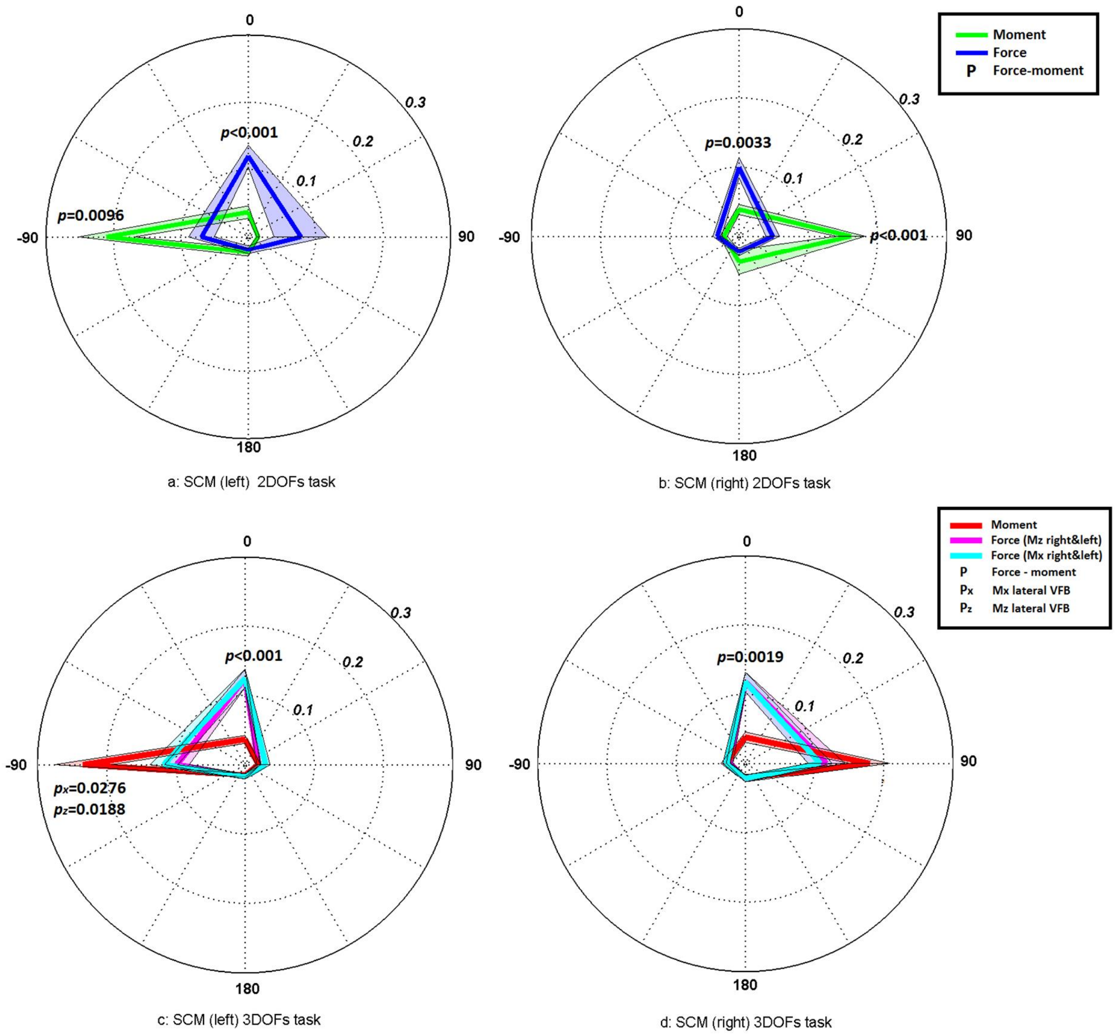


Figure 3.14 a,b: Sternocleidomastoid (SCM) force and moment task with 2DOFs visual feedback. The thick line indicates the mean normalized EMG and the standard error is depicted by the shaded areas. Left and right SCM in force task have a higher activation than in moment task in the forward direction (left: $p<0.001$ and right: $p=0.0033$). Left SCM is more active in moment task then force task in leftward direction ($p=0.0096$) while right SCM shows the same pattern in rightward direction ($p<0.001$).

c,d: Sternocleidomastoid (SCM) force and moment task with 3DOFs visual feedback. Two kinds force tasks are shown, with additional My in pro/retraction tasks and with additional Mx or Mz visual feedback in lateral force tasks. The EMG activity of left and right SCM is significantly higher than in force task than moment task in forward direction (left: $p<0.001$ and right: $p=0.0019$). Left SCM is more active in moment task than two kinds of force task in leftward direction ($p_x=0.0276$, $p_z=0.0188$). Right SCM doesn't show the significant difference in rightward direction.

3.3.2 Splenius capitis

The result shows splenius capitis (SPL) preferred active direction is the lateral direction in force and moment task with 2DOFs visual feedback which is consistent with their anatomical position. SPL is more active in the lateral direction in moment task with 3 DOFs vsiual feedback. In the force task with added Mx feedback (cyan line), the preferred activation directions are the forward and the lateral direction that is the same as the SPL anatomical location. However, the result of the force task with added Mz feedback is not that obvious (magenta line). The EMG level of four directions are almost equal. The EMG activity level of 2DOFs force task in forward direction is higher than the moment task in the left SPL (p=0.0206). However, the right side doesn't show the difference. The forward direction in 3DOFs task is significantly different between the force and moment tasks in both sides (p=0.0241 for left and p=0.0081 for right). For right SPL, the EMG activity level of the moment task is significantly higher than the force task with added Mx feedback in leftward direction (p=0.0405) and also higher than the force task with added Mz feedback in rightward direction (p=0.0259).

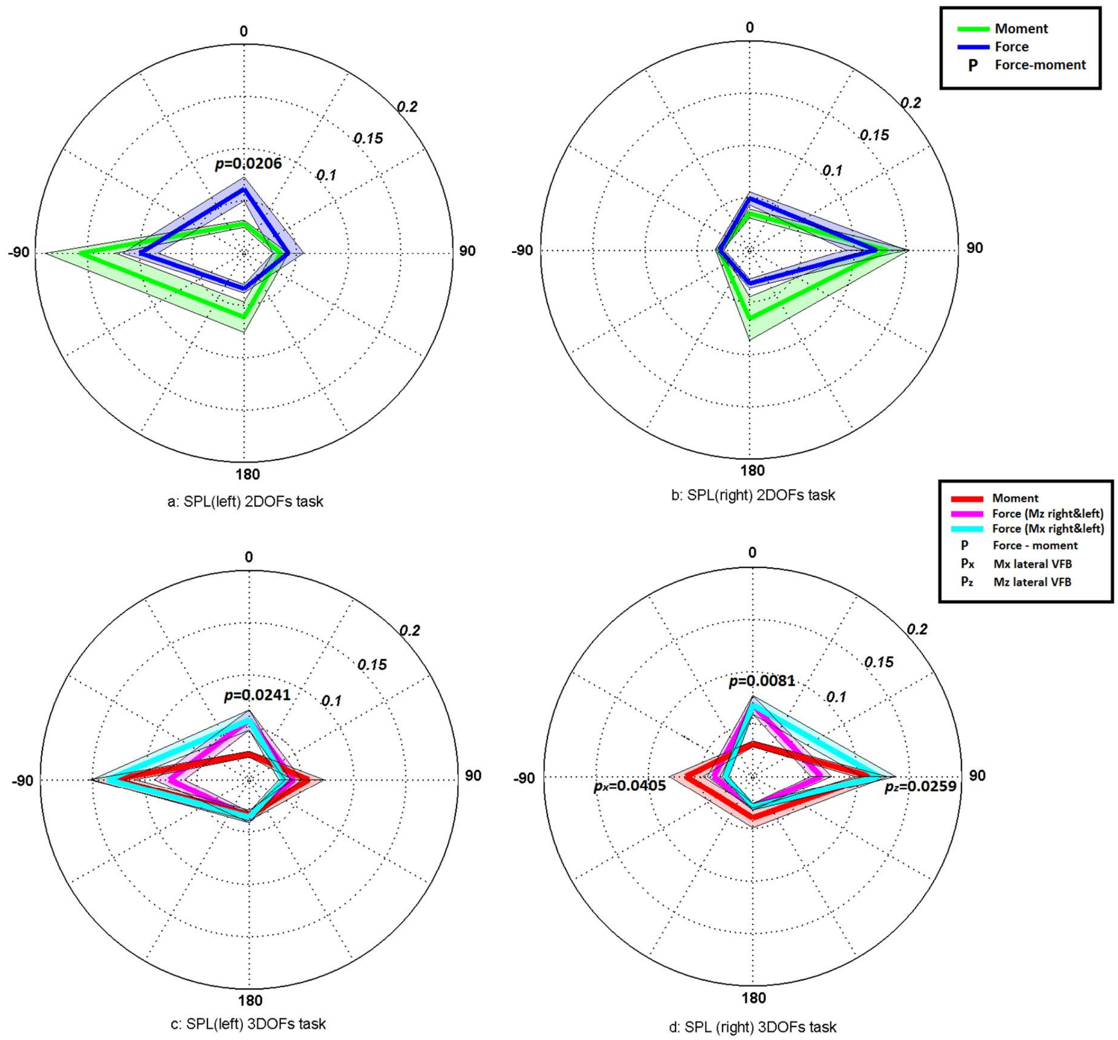


Figure 3.15 a,b: Splenius capitis (SPL) force and moment task with 2DOFs visual feedback. The thick line indicates the mean normalized EMG and the standard error is depicted by the shaded areas. Left SPL in the forward direction is significantly different between force and moment task (p=0.0206).

c,d: Splenius capitis (SPL) force and moment task with 3DOFs visual feedback. Two kinds force tasks are shown, with additional My in pro/retraction tasks and with additional Mx or Mz visual feedback in lateral force tasks. SPL has significant difference in forward direction for both sides (left: p=0.0241, right: p=0.0081). Right SPL in the moment task has higher EMG level than Mx force task in the leftward direction (p_x =0.0405) and Mz force task in the rightward direction (p_z=0.0259).

3.3.3 Semispinalis capitis

Semispinalis capitis (SEMI) is more active in the backward direction than other directions both in the moment and force task with 2DOFs visual feedback. Note that the right SEMI in force task has dramatically high EMG activity level in the rightward direction but left SEMI doesn't show that in the leftward direction. The SEMI's preferred active directions in the moment and force task with 3DOFs visual feedback are quite similar which are lateral and backward direction.There is no significant difference between force and moment task with 2DOFs and 3DOFs visual feedback for each direction.

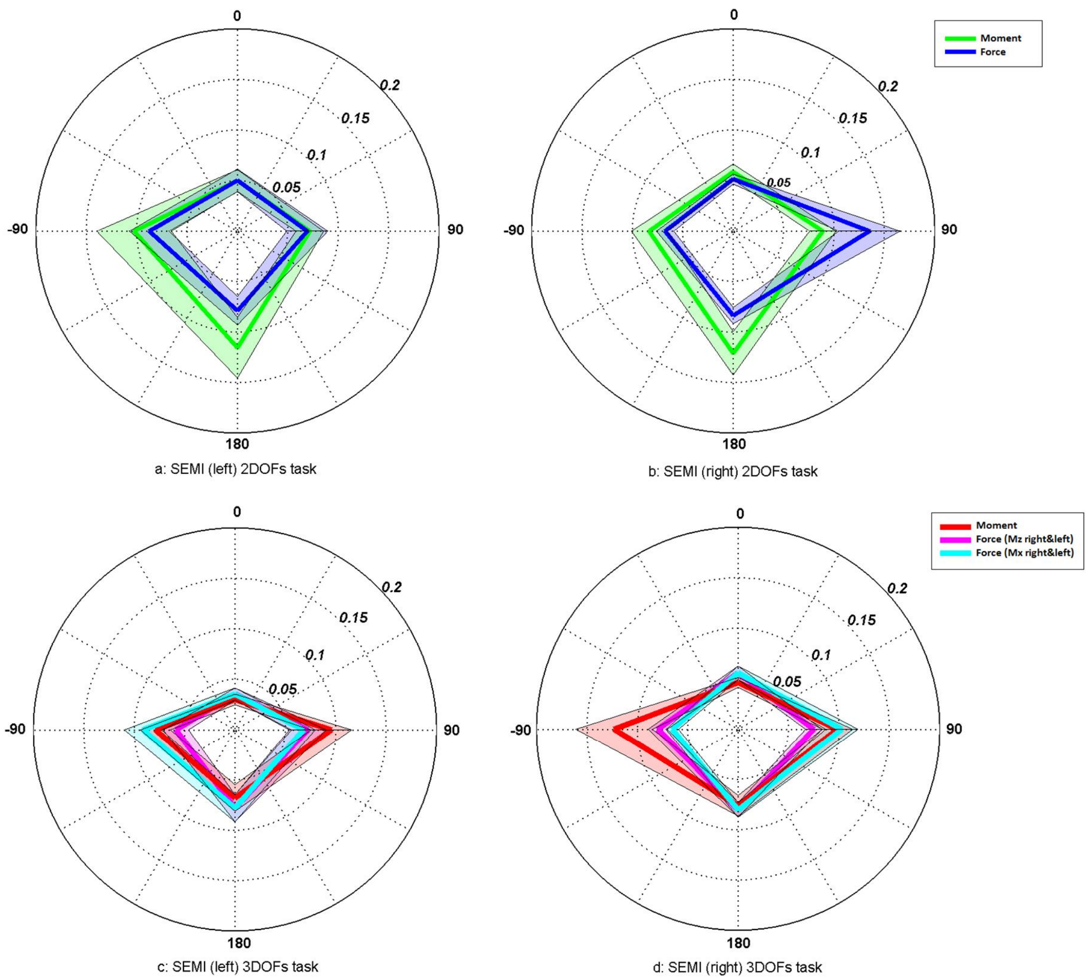


Figure 3.16 a.b: Semispinalis capitis (SEMI) force and moment task with 2DOFs visual feedback. The thick line indicates the mean normalized EMG and the standard error is depicted by the shaded areas. No significant difference between force and moment task for each direction.

c,d: Semispinalis capitis (SEMI) force and moment task with 3DOFs visual feedback. No significant difference between force and moment task for each direction. The preferred active direction is the lateral and backward direction.

3.3.4 Trapezius

The left trapezius (TRAP) in moment task with 2DOFs visual feedback shows very high EMG activation level 10%MVC in the leftward direction. But in other directions the EMG level is very low only about 5%MVC. The results of 3DOFs tasks also show similar low EMG level. No significant difference is found between the force and moment task in four directions.

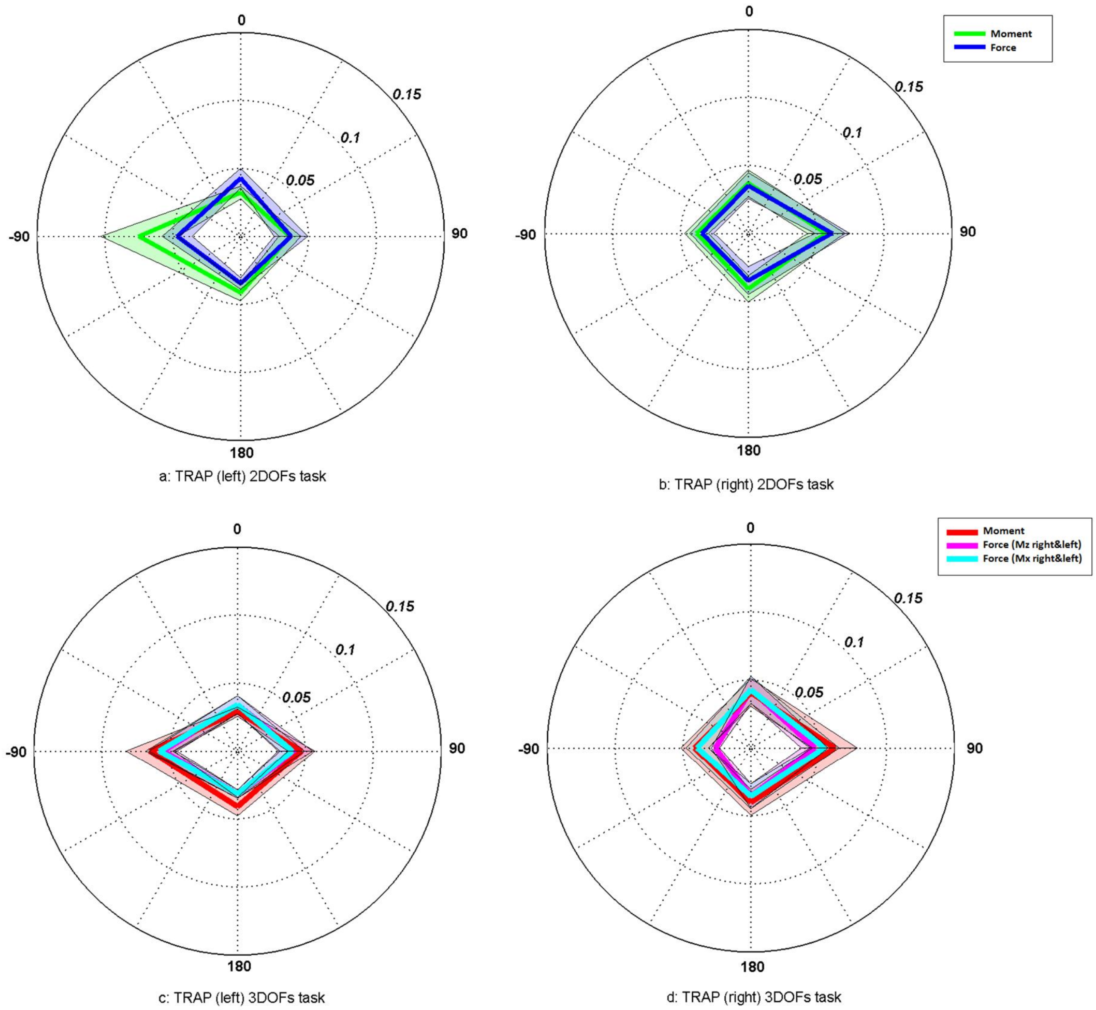


Figure 3.17 a,b: Trapezius (TRAP) force and moment task with 2DOFs visual feedback. The thick line indicates the mean normalized EMG and the standard error is depicted by the shaded areas. The EMG activation level is very low. No significant difference between force and moment task for each direction.

c,d: Trapezius (TRAP) force and moment task with 3DOFs visual feedback. The EMG activation levels are almost equal in four directions for force and moment task. Similarly, there is no significant difference between force and moment task for each direction.

Chapter 4 Discussion

In this study an isometric experiment was performed where force and moment tasks were executed with 2DOFs and 3DOFs visual feedback. With 2DOFs visual feedback subjects generated consistent coupling loads. The 3D tasks with additional visual feedback improved subjects' performance by significantly reducing the coupling loads. EMG activity presented varying neck muscle control patterns between force and moment task in the same direction for the sternocleidomastoid (SCM) and splenius capitis (SPL) muscles. It is recommended to consider force and moment tasks separately when performing isometric experiments on SCM and SPL.

4.1 Effects of force versus moment task

The literature study shows most researches didn't make a specific distinction between force and moment tasks. Either the measurement was varied as force and moment or they measured coupled loads due to insufficient constraints. This study shows that it is important to separate force from moment tasks. Comparison of loads during force and moment tasks in the same direction shows large differences in responses. The primary task loads are significantly different and another load reflecting subject unexpected behavior is also different. Three of five loads are significantly different both in 2DOFs and 3DOFs visual feedback between force and moment tasks except for retraction force task.

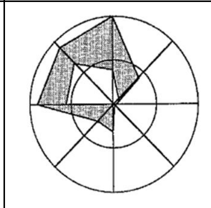
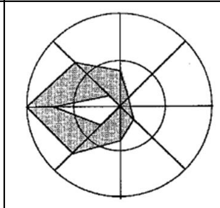
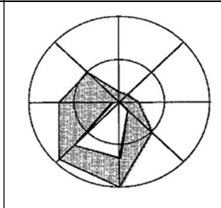
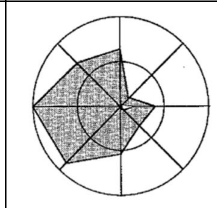
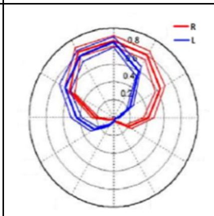
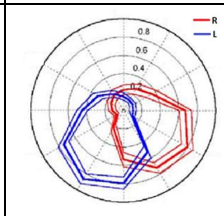
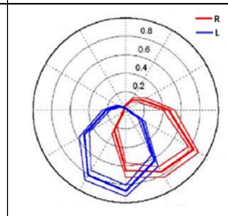
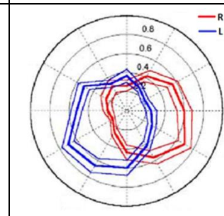
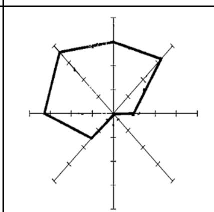
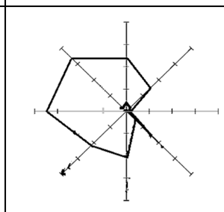
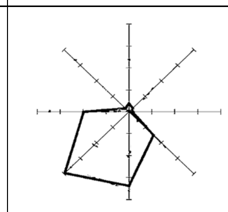
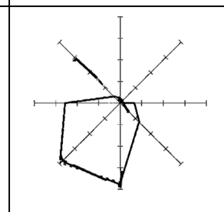
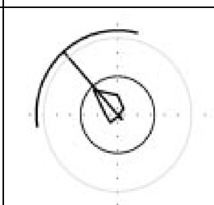
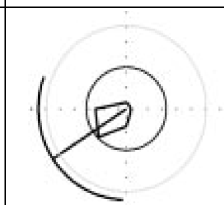
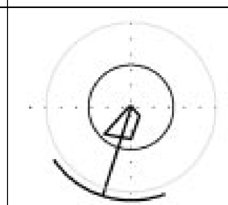
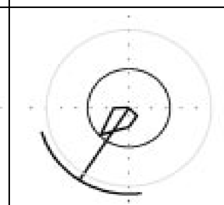
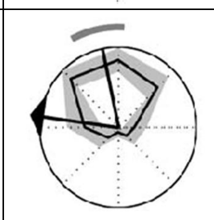
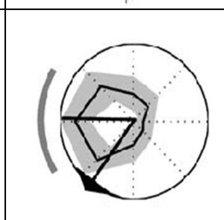
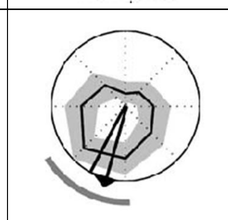
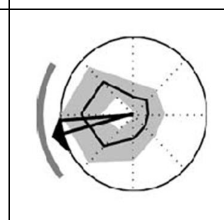
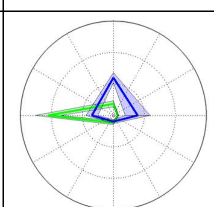
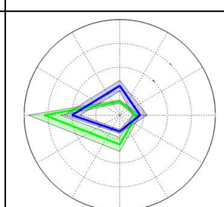
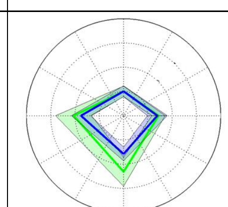
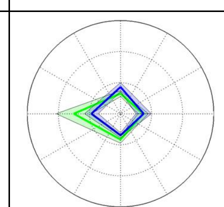
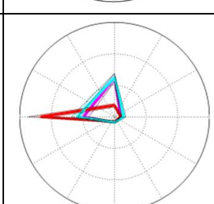
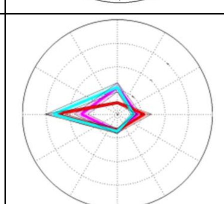
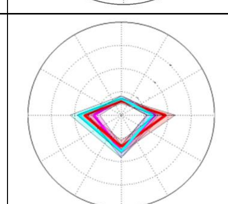
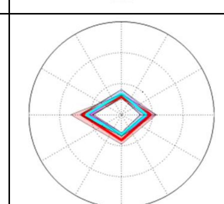
As force and moment tasks in the same direction are different, neck muscles require a distinctive control pattern which shows a different muscle mechanical function. The 3DOFs task results show that in the forward direction SCM is more active in protraction force task than flexion moment task. Similarly, SPL is also more active in force task than moment task in the forward direction. It is reasonable when thinking from anatomical view. SCM originates from the sternum and clavicle and inserts on the mastoid process which is in the anterolateral position of the neck. SCM contracts bilaterally to pull the head forwards. However, it can't ensure horizontal direction and the head may rotate down and up. SPL, connecting the base of the skull to vertebrae in the neck and upper thorax, is posterior cervical muscle (Keshner, Campbell et al. 1989) form a "V" shape. SPL is mainly for head rotation anterior and lateral direction bilaterally (Keshner, Campbell et al. 1989). It acts as an extensor to control head rotation. Protraction force task with 3DOFs visual feedback requires subjects push forward meanwhile control the moment. SCM activation is to generate force forward and SPL is active bilaterally to control head rotation. However, in the flexion moment task with

3DOFs visual feedback, subjects needn't generate force in forward direction. Therefore, SPL is less active due to SCM is silence.

Another difference is in the lateral direction. Left SCM is more active in left lateral moment task than the left lateral force task in 3DOFs task. The contraction of SCM unilaterally can bend head to the same direction which can generate lateral moment. SPL acts as lateral mover of the head mainly active in lateral force task. SCM is primarily active during 3DOFs lateral moment task and SPL is active bilaterally to control coupling lateral force. While during 3DOFs lateral force task, SPL is primarily active to push neck to lateral direction and SCM assists to control coupling lateral or axial moment to minimum. Note that SPL is almost equally active in force (3DOFs with added Mx) and moment task. There is a high coupling force generated in moment task that requires SPL more effort to control. However, the coupling lateral moment is not so high that SCM is less active in lateral force task. Right SCM didn't show the same pattern which is asymmetrical. The probable reason can be not enough statistical power because the *p*-value is 0.0549 (3DOFs with added Mx) that is quite close to significant level. Muscle SEMI and TRAP didn't show the significant difference between force and moment task for each direction.

The previous studies showed a varying control pattern because there were many influential factors: different experiment setups, task type and loads, EMG testing method and electrodes placement, definition of moment axes and etc. Also no experiment tested force and moment tasks separately in one experiment. The most important was the task given was ambiguous: force, moment task or force and moment coupled task. Therefore, it was quite difficult to compare those results between force and moment task. In this experiment, force and moment tasks were tested separately under the same condition. The comparison of the result is reasonable and acceptable.

Table 4.1 Muscle control patterns in EMG tuning curves reported by previous studies. The muscle compared here is left side.

Paper	Task Type	SCM	SPL	SEMI	TRAP
Keshner et al. 1989[a]	force				
Gabriel et al. 2004[b]	force				
Siegmund et al.,2007[c]	force				
Blouin et al.,2007[d]	force				
Vasavada et al.2002[e]	moment				
This study resutls[f]	2DOFs Moment Force				
	3DOFs Moment Force(Mz R&L) Force(Mx R&L)				

[a]Muscles analyzed here are right side but flipped horizontally which can be regarded as left side due to the symmetry of muscles. Mean and standard deviation (shaded area) are shown. [b]The mean (thick line) is bounded by the standard error

(thin line). [c] **The mean EMG is shown.** [d]**The black and gray lines originating from the center of the circle represent the mean resultant vector (preferred direction) of the muscle tuning curves, and the arcs illustrate the angular deviation of the resultant vectors.** [e]**The bold line is the mean resultant vector and the gray arc is the angular deviation .The arrow indicates the mean and range of moment arm directions calculated from a musculoskeletal model.** [f]**The mean normalized EMG and the standard error (shaded area) are shown (See Results).**

In this study results were compared with previous studies on EMG tuning curves (Table 4.1). The patterns of EMG tuning curves are quite similar. In general, our results are within the range of results in earlier studies. Analyzing the preferred activation direction of muscle showed a difference in SCM and SPL control patterns in the forward and lateral direction. The main reason was previous studies didn't consider force and moment task separately. Force task was coupled with moment load and moment task was coupled with force load. Therefore, it is necessary to separate force task from moment task in SCM and SPL isometric testing in the future study. The results of SEMI and TRAP were in line with previous studies.

4.1.1 Sternocleidomastoid

This study results showed SCM's preferred activation direction was varied as task type. In the force task, it was forward and lateral direction which was quite similar with the previous force tasks results: anterolateral direction (Keshner, Campbell et al. 1989, Gabriel, Matsumoto et al. 2004, Blouin, Siegmund et al. 2007, Siegmund, Blouin et al. 2007, Falla, Lindstrom et al. 2010). It can be assumed that their tasks were primarily force task without coupled moment loads. However, in the moment task, it was lateral direction which was quite different from Vasavada et al. (2002) moment task results: primarily anterior direction. Vasavada's results were more like force tasks. It can be assumed Vasavada's moment task was coupled with amounts of force loads mainly in the anterior direction. In Vasavada's study, the axes of flexion/extension and lateral bending moments were defined as the horizontal axes through the midpoint of the line between the spinous process of C7 and the sternal notch. The anatomical location was much lower than our study definition which was atlanto-occipital joint (O'Leary, Vicenzino et al. 2005). Subjects would perform more coupling loads by the axis defined in Vasavada's study.

4.1.2 Splenius capitis

In this study, the SPL was preferentially activated in the lateral direction during moment tasks, in line with results from Vasavada et al. (2002) and Keshner et al. (1989). It means Vasavada's tasks were pure moment tasks in lateral direction while Keshner's coupled with moment loads in lateral direction. In the force task, the result was primarily lateral and anterolateral direction which was similar to Siegmund et al. (2007). However, Gabriel et al. (2004) and Blouin et al. (2007) showed the SPL was mainly active in the posterolateral direction. It can be explained by the differences of the EMG method and placement of electrodes. Gabriel et al. (2004) used intramuscular wire electrodes which were placed in an area midway between the occipital protuberance and the midpoint of the trapezius ridge in the neck. Blouin et al. (2007) also used intramuscular electrodes which were placed at C4/C5 level.

4.1.3 Semispinalis capitis

This study showed the SEMI's preferred activation direction was posterior direction which was consistent with its anatomical location. It was the same as the previous study results. SEMI was found unexpected activation during the lateral task. It was caused by subjects also performed a little coupled extension moment. The SEMI is not necessary to test force and moment tasks separately.

4.1.4 Trapezius

TRAP was equally active for each four directions as 5%MVC EMG activation level. However, previous studies reported its preferred activation direction was not very apparent but approximately towards posterolateral direction which was the same as its anatomical location. The reason was the surface electrodes were placed in the different location of TRAP muscle (Keshner, Campbell et al. 1989, Vasavada, Peterson et al. 2002, Gabriel, Matsumoto et al. 2004).

4.2 Effects of 3D visual feedback

In this study, the 3D visual feedback was applied in an isometric neck experiment for the first time. With that, the head loads can be visualized to know it is force or moment. 2DOFs were used to set a target point and a third DOF was used to reduce the expected coupling in the target loading direction. Subjects are able to generate the requested head forces in the force tasks, and moments in the moment tasks. In the 2DOFs force task subjects received 2D force feedback and in the 2DOFs moment task, subjects received 2D moment feedback. With 3DOFs visual feedback, the coupled load was reduced significantly and almost completely in which direction the coupling DOF was displayed. Therefore, only primary force load presented in force tasks and moment load presented in moment tasks. Force and moment tasks were decoupled by 3D feedback. All subjects found that the tasks were intuitive and clear.

In 2DOFs tasks subjects generated the coupled loads consistently in the same direction. All tasks have such coupled effects except for retraction (Table 3.3). There is one coupled load in the forward direction and there are more than two coupled loads in the lateral direction. Subjects performed force tasks coupled with consistent moment load and moment tasks coupled with consistent force load, for instance, protraction force tasks coupled with extension moment; flexion moment tasks coupled with retraction force. By making good use of 3DOFs visual feedback, the tasks in the forward direction had virtually no more coupling in other loading directions. However, the tasks in the lateral direction still coupled with some unwanted loads because there was no visual feedback available to account for all coupling directions. The method of increasing to 4DOFs task and including all coupled loads Fy, Mx, Mz of visual feedback into lateral tasks made the tasks very difficult to perform. The main reasons are that these overly constrained tasks and complex visual feedback felt unnatural to the subjects. More extensive training may be helpful to improve their performance. It can be concluded that the 3D visual feedback was necessary to distinguish force from moment tasks and it effectively minimized all coupling in protraction, retraction, flexion and extension tasks. In the lateral directions coupling still existed in the direction where no visual feedback was present.

An important implication of 2DOFs task results can be used to validate neck musculoskeletal models. Subjects performed the task loads in a consistent coupling pattern (Table 3.3). The EMG activity corresponding to the coupling loads performance can be used to validate neck musculoskeletal models. The EMG activity of the 3DOFs task provides a more intuitive validation where force and moment tasks are separated. However, If only 2DOFs visual feedback is available, the consistent coupling loads measured in all directions should be taken into account using 2DOF task data from this study or other studies to validate musculoskeletal models.

The 3D visual feedback doesn't influence muscle control patterns much (Appendix D). It is reasonable that the primary task load determines muscle EMG activity most. Minimizing coupled loads wouldn't change the EMG activity too much. The results show only SCM right side shows the significantly higher EMG activation level in 3DOFs force task than 2DOFs force task in the right direction. Because SCM is more active unilaterally to minimize coupling lateral moment Mx or Mz in 3DOFs force task when adding Mx and Mz feedback. Left SCM didn't show the same pattern which is asymmetrical. The probable reason can be not enough statistical power.

4.3 Task difficulty

Two factors influence task difficulty: helmet constraints and complex visual feedback. There is a balance between helmet constraints and subject performance. Subjects had to wear a helmet to exert force and moment loads inside the helmet during experiment. The helmet should be very tight so that the moment generated can be transformed to the loadcell; Otherwise subject's head is sliding or slipping in the helmet during experiment. It is particularly of importance to moment tasks like flexion/extension and lateral bending. However, if it is too tight, subjects may get hurt and pain on the head which is not allowed. There are some methods to tighten the helmet with head to increase friction: rubber cap, soft cushion and boxing cap used individually or combined together. Chin strap or pad at undersurface of mandible is to generate flexion moment (O'Leary, Vicenzino et al. 2005, Almosnino, Pelland et al. 2009). Due to the different individual head dimension and irregular shape, subjects were asked to try different combination caps and found a reasonable way to tighten the helmet. The complex 3D visual feedback is another factor. It induces subject unnatural posture and feeling. It is because that human neck has the habit of performing coupled force and moment. In other words, humans can't easily control force and moment individually. With visual feedback, a coupled force or moment was visualized to control which is quite different from the human natural behaviour. So subjects had a strange feeling.

Some unexpected results are found in this experiment. Protraction 2DOFs task is coupled with extension moment which is not expected as flexion moment in the same direction (Figure 3.1). It is because the helmet is partly constrained in front of face. Subjects can only push the up edge of helmet so the head tends to rotate backward which leads to extension moment. There is no coupling moment in the retraction force task (Figure 3.2). The rear of head is fully constrained by the helmet so that subjects can push backward horizontally to exert only retraction force. Flexion task is coupled with retraction force which is not expected protraction force (Figure 3.3). Subjects were in an effort to rotate their heads forward inside helmet and unconsciously the rear part of their neck pushed the back edge of helmet so as to generate a little retraction force. The right lateral traction task with 2DOFs and 3DOFs visual feedback showed unexpected results (Figure 3.8). The task added visual feedback Mx not only significantly lowered lateral moment Mx but also showed a significant increase in retraction force Fy and decrease in right axial rotation Mz. It is because the exerting force point of subjects is varied inside helmet. This point or area will be at the lower position when doing 2DOFs lateral traction compared to 3DOF task because no Mx visual feedback presents. The lateral force Fy is difficult to perform when subjects push lower side of helmet because part of effort is to generate

Mx moment. After added Mx visual feedback, subjects tend to control lateral moment Mx and head push lateral direction horizontally. So they can generate higher lateral force Fy as most of their effort is to push to the lateral direction and less axial rotation Mz because of larger area of constraint.

As can be seen in Table 3.1 several subjects did not succeed in all tasks. Five subjects failed to do 3DOFs protraction task. This doesn't influence the results because the results still have a minimum of 7 subjects. Subject No.8 was discarded from the dataset because of very weak physical level. As the task load is the same for everyone, the weak subject is not expected that should be removed. The underlying findings will be more intuitive and consistent when getting rid of those data.

4.4 Limitations

There are some limitations in this experiment:

- The helmet problem: subject's head can't fit the helmet very well and some slipping inside helmet that causes subject unexpected behaviour, especially moment tasks like flexion and lateral bending. Designing a new helmet that has better constraints, for example adding a chin strap or pad, and is more ergonomic that can fit different shape and size of heads without hurting.
- Subjects' physical variability influences the EMG results. The task load is fixed and the same for everyone. Performing the same task, strong subjects may perform low EMG while weak subjects may perform high EMG level. So the task difficulty is varied per person. An alternative option: the percentage of sub-MVC task can be used.
- In this experiment, subjects performed two types of task: force and moment task. For force load is 30N and moment load is 3Nm which are determined as pilot test results. The study doesn't analyse whether muscle EMG activity level is equivalent for 30N force and 3Nm moment. The differences of control patterns may be caused by the task types or the task loads. It requires further research to normalize the loads.
- Estimation of the exerting force point (x_h, y_h, z_h) needs more accurate calculation (Appendix A). In this study, it is assumed that all subjects exerted force load at the same point. However, it is not true that individuals have a varied or unexpected behaviour and the helmet is not fitted very well. The real exerting force point is quite random which causes the visual feedback isn't intuitive and increases the task difficulty.

4.5 Recommendations

The study analyzes neck muscle control patterns in force and moment task separately which has not been performed before. The 3D visual feedback is applied in neck isometric experiment for the first time. The evaluation of effects indicates it is a good method to separate force and moment task. 3D visual feedback is sufficient for protraction/retraction and flexion/extension tasks but not in the lateral tasks. If all Fx,Fy,Mx,Mz can be added into visual feedback during lateral tasks and subjects are capable to perform those tasks, the performing loads would be more distinguishable and decoupled. Reducing the task load and difficulty level, especially moment tasks can be a good method. However, it also should consider the significant EMG activation level.

When analyzing SCM and SPL muscle control patterns, it is recommended to consider force and moment task respectively in isometric experiment. The results can be different when subjects performing force and moment loads in the forward and lateral direction. It can be used for neck model validation for SCM and SPL.

In this study, the results of EMG tuning curve only have four directions but human head can generate loads around a circle. It is preferable to take the diagonal direction into account. So it will make the EMG tuning curve more completed and detailed.

Before the formal experiment, it is necessary to let subjects do some practice and get familiar with the experiment device and visual feedback. The experiment task is not human natural behaviour and subjects may feel strange and uncomfortable. Subjects can adapt to the tasks by a short training.

Chapter 5 Conclusion

In this isometric experiment, a new intuitive 3D visual feedback was designed to assist subjects in performing force and moment tasks separately. The differences of neck muscle control patterns were analysed between force and moment tasks.

Three conclusions can be inferred from the results of this research:

- 2DOFs tasks showed a consistent load coupling pattern.
- The 3D visual feedback designed was able to separate force and moment tasks and reduce the coupling loads significantly.
- There were significant differences between force and moment tasks in EMG activity results, providing additional information about muscle mechanical function. Sternocleidomastoid and splenius capitis showed different control patterns between force and moment tasks in the forward and lateral direction.

Future work:

In order to obtain a more complete and precise EMG tuning curve, the EMG activity can be measured in diagonal direction or multi-direction with the same experiment setup. It is preferable to test EMG with intramuscular electrodes. Although the 3DOFs visual feedback was sufficient to test force and moment tasks separately in the forward direction, an additional DOF should be added to reduce corresponding coupling load in the lateral direction. It is necessary to design an experiment with 4DOFs visual feedback to test force and moment tasks in the lateral direction. Moreover, the same method can be used to study muscle control patterns and identify the mechanical function for a larger number of superficial and deep neck muscles. More knowledge about mechanical function of neck muscles can be used for clinical diagnosis. Also EMG feedback can be used to indicate graphically which muscles are being active during the isometric testing. Finally, the isometric load data along with EMG activity can be used to validate neck musculoskeletal models.

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Appendices

A Loadcell calibration and coordinate reorientation

The loadcell force and moment can be calculated by the following equation (A-1):

$$\begin{aligned} F_f(load) &= V_{out} / (V_{fexc} * S_f * G_f * 1\times10^{-6}) \\ M_m(load) &= V_{out} / (V_{mexc} * S_m * G_m * 1\times10^{-6}) \end{aligned} \qquad \text{(A-1)}$$

Where Vout is output of loadcell in Vault. Gf and Gm are gain (2000 for Fx, Fy, Mz; 1000 for Mx,My). Vexc is the excitation voltage 2.5V; Sf and Sm are the calibrated gain sensitivity in micro Volts/Vexc-N from loadcell manual.

The subject head forces were the measurement of loadcell that can be read directly but the moments were not. Because the loadcell was located above the helmet, the head coordinate was not coincided with the loadcell coordinate. The head force would influence measurement of moment in the loadcell by multiplying moment arm xh,yh,zh. To get the true head force and moment, a transformation matrix should be calculated. The formula A-2 calculated the loadcell force and moment from head coordinate.

$$\begin{aligned} F_{xL} &= F_{xh} \\ F_{yL} &= F_{yh} \\ F_{zL} &= F_{zh} \\ M_{xL} &= M_{xh} - F_{yh}z_h + F_{zh}y_h \\ M_{yL} &= M_{yh} + F_{xh}z_h - F_{zh}x_h \\ M_{zL} &= M_{zh} - F_{xh}y_h + F_{yh}x_h \end{aligned} \qquad \text{(A-2)}$$

Where Fxh,Fyh,Fzh are head forces, Mxh,Myh,Mzh are head moments; FxL,FyL,FzL are loadcell forces, MxL,MyL,MzL are loadcell moments; xh,yh,zh are the coordinate of head with respect to the loadcell coordinate.

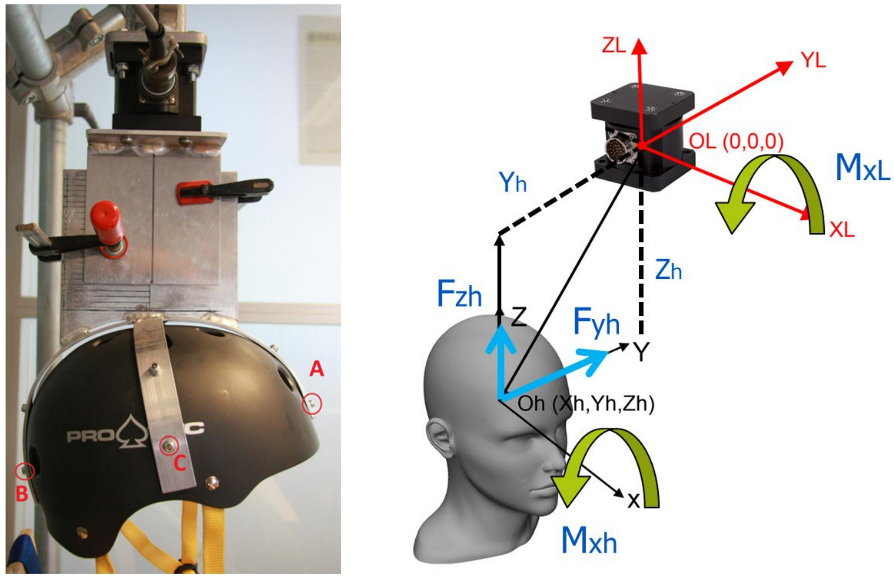

Figure A.1 The helmet and loadcell are connected by the board (left). Three points A, B, C defined on the helmet are used to calibrate for each task (nails of helmet). Schematic plot of human head and loadcell (right).

The transformation matrix (A-3) is from head coordinate to loadcell coordinate:

$$\begin{bmatrix} F_{xL} \\ F_{yL} \\ F_{zL} \\ M_{xL} \\ M_{yL} \\ M_{zL} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & -z_h & y_h & 1 & 0 & 0 \\ z_h & 0 & -x_h & 0 & 1 & 0 \\ -y_h & x_h & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} F_{xh} \\ F_{yh} \\ F_{zh} \\ M_{xh} \\ M_{yh} \\ M_{zh} \end{bmatrix} \tag{A-3}$$

Make an inverse and the transformation matrix (A-4) is from loadcell coordinate to head coordinate.

$$\begin{bmatrix} F_{xh} \\ F_{yh} \\ F_{zh} \\ M_{xh} \\ M_{yh} \\ M_{zh} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & z_h & -y_h & 1 & 0 & 0 \\ -z_h & 0 & x_h & 0 & 1 & 0 \\ y_h & -x_h & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} F_{xL} \\ F_{yL} \\ F_{zL} \\ M_{xL} \\ M_{yL} \\ M_{zL} \end{bmatrix} \tag{A-4}$$

Write into the equation form:

$$
\begin{aligned}
F_{xh} &= F_{xL} \\
F_{yh} &= F_{yL} \\
F_{zh} &= F_{zL} \\
M_{xh} &= z_h F_{yL} - y_h F_{zL} + M_{xL} \\
M_{yh} &= -z_h F_{xL} + x_h F_{zL} + M_{yL} \\
M_{zh} &= y_h F_{xL} - x_h F_{yL} + M_{zL}
\end{aligned}
\tag{A-5}
$$

The head coordinate (xh,yh,zh) with respect to loadcell coordinate is defined on the helmet. Ideally, it should be defined on the anatomical landmark of subject head. The coordinate would be varied as different size of head and should be measured individually every time. To simplify the experiment procedure and shorten experiment time, The head coordinate (xh,yh,zh) is fixed on the helmet. The head coordinate is varied as the task type. For each experiment task, the subjects head would perform force at different positions inside helmet. For example, subjects push forward that perform protraction force task, push backward which are retraction force task, and push laterally which are lateral traction force tasks. So the determination of head coordinate should be considered separately. Also it would be varied with different individuals. It can be assumed that all subjects exerted forces at the same landmarks A, B, C point of the helmet (Figure A.1). The head and loadcell are connected by the board which can be seen as the rigid body. The head moments generated around anatomical axes are exactly the same as moments around the axes through A, B, C point of helmet. The point A is used in the forward task like protraction force and flexion moment tasks; the point B is used in the backward task like retraction force and extension moment tasks; the point C is used in the lateral task like lateral traction force and lateral moment tasks. The force in z direction is not considered because it is not generated by the neck but the sitting posture.

In the experiment, the experiment setup was calibrated to estimate the coordinate of exerting force point A, B, C. The moment arm zh* was estimated by exerting a horizontal force by the spring at three points A,B,C of the helmet (three nails of helmet) respectively to see if the visual target was moving horizontally (Figure A.1). zh* was measured several times and an estimated one was obtained (Table A.1). For xh and yh, they were set as 0 because they were related to the vertical force Fz coupled into moment Mx and moment My. To calculate axial rotation moment Mz, yh and Fy were very small in protraction/flexion task which the term $y_h F_{xL} - x_h F_{yL}$ was almost 0; similarly in lateral force/moment task xh and Fx were very small which the term $y_h F_{xL} - x_h F_{yL}$ was almost 0. Setting coordinates xh and yh were 0 didn't influence the calculation results.

Three assumptions are used in this method:

- Subject heads with helmet connected to loadcell can be seen as a rigid body.
- Subjects are exerting head forces on the same point defined on the helmet.
- The vertical force Fz is not considered.

Table A.1 The estimation of Zh* per each task by calibration at the exerting force points A, B, C.

Exerting force point	Tasks	Zh*[m]
A	Protraction/flexion	-0.21
B	Retraction/extension	-0.273
C	Lateral traction/lateral bending	-0.228

The vertical distance Zh is calculated from the coordinate of loadcell to the three nails (A, B, C) of helmet using the equation (A-6).

$$z_h = z_h^* - L_b - z_o \tag{A-6}$$

Where Zh* is the standard distance that two connector boards are completely overlap (Table A.1); Lb is the length of two connector boards are not overlap due to the subject sitting height. It is measured for each subject prior to experiment. Zo is the distance of the center of the top of loadcell relative to its coordinate which is 3.24697cm from loadcell calibration manual.

Finally, the simplified equation is obtained as below:

$$\begin{aligned} F_{xh} &= F_{xL} \\ F_{yh} &= F_{yL} \\ M_{xh} &= z_h F_{yL} + M_{xL} \\ M_{yh} &= -z_h F_{xL} + M_{yL} \\ M_{zh} &= M_{zL} \end{aligned} \tag{A-7}$$

Transform the head forces and moments to the coordinate of D-flow displayed in the monitor.

$$\begin{aligned} F_{xd} &= F_{xh} \\ F_{zd} &= -F_{yh} \\ M_{xd} &= M_{xh} \\ M_{yd} &= M_{zh} \\ M_{zd} &= -M_{yh} \end{aligned} \tag{A-8}$$

B Experiment procedure checklist

The whole experiment is performed as the following procedure:

Experimental Procedure No.	Task		Check to finish	
1	Introduce the experiment goals and head movement. Demo the task with VFB (use hands).			
2	Fill the subject information and consent form.			
3	Choose a suitable helmet and sit in the chair; tune the distance of load cell.			
4	Put EMG on the neck, set EMG Recording 60s.			
5	Sit down, belt tighten. Measure distance Lb.			
6	Free to try different tasks with VFB, explain and practice, after the "Start" word disappears to start the task. Make a calibration. Disable trigger.			
7	Fill the subject No. in the "record module".			
8	When all tasks finish and fill the form.			
MVC Tasks				
1	Left shoulder lift		1	
2	Right shoulder lift		2	
3	Retraction		3	6
4	Left Twist		4	7
5	Right Twist		5	8
Experiment tasks				
Test 1	Task	Visual feedback	Rep 1	Rep 2
1	Protraction	Fx,Fy	1	2
2	Retraction	Fx,Fy	3	4
3	Flexion	My,Fy	5	6
4	Extension	My,Fy	7	8
5	Left Lateral traction	Fy,Fx	9	10
6	Right Lateral traction	Fy,Fx	11	12
7	Left Lateral Bending	Mx,Fx	13	14
8	Right Lateral Bending	Mx,Fx	15	16
Test 2				
9	Protraction	Fx,My,Fy	17	18
10	Retraction	Fx,My,Fy	19	20
11	Flexion	My,Fx,Fy	21	22
12	Extension	My,Fx,Fy	23	24
13	Left Lateral traction	Fy,Fx,Mx	25	26
14	Right Lateral traction	Fy,Fx,Mx	27	28
15	Left Lateral Bending	Mx,Fx,Fy	29	30
16	Right Lateral Bending	Mx,Fx,Fy	31	32
17	Left Lateral traction	Fy,Fx,Mz	33	34
18	Right Lateral traction	Fy,Fx,Mz	35	36

C Force and moment task with 2DOFs visual feedback on loads

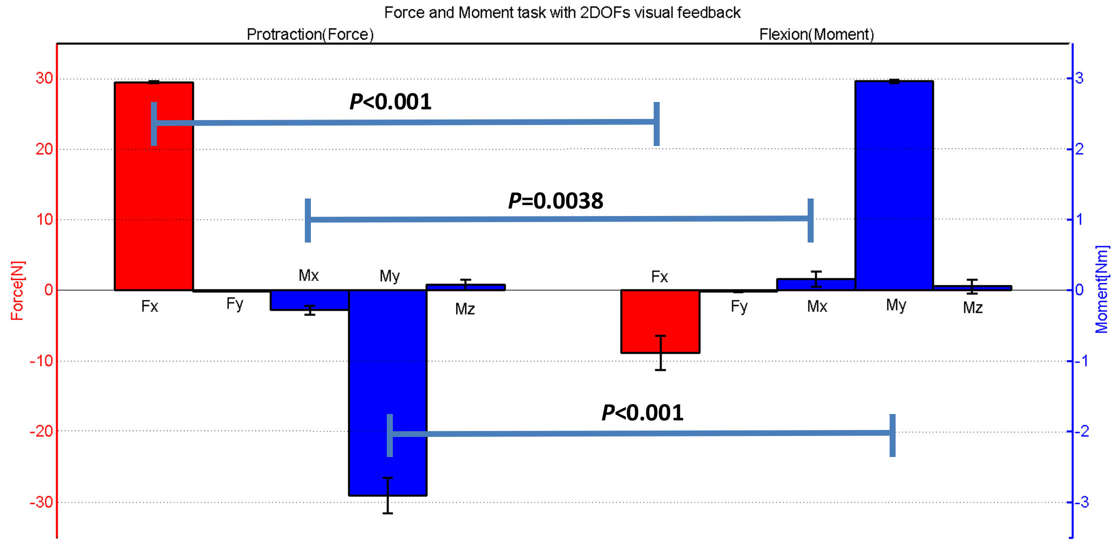

Figure C.1 In the forward direction, the force task: protraction (left) and moment task: flexion (right) with 2DOFs visual feedback. The red bars indicate mean values of force; the blue bars indicate mean values of moment. The standard error of the mean boundary is depicted by the vertical bar. Task loads Fx and My are significantly different (p<0.001). Besides, Mx is also significantly different (p=0.0038).

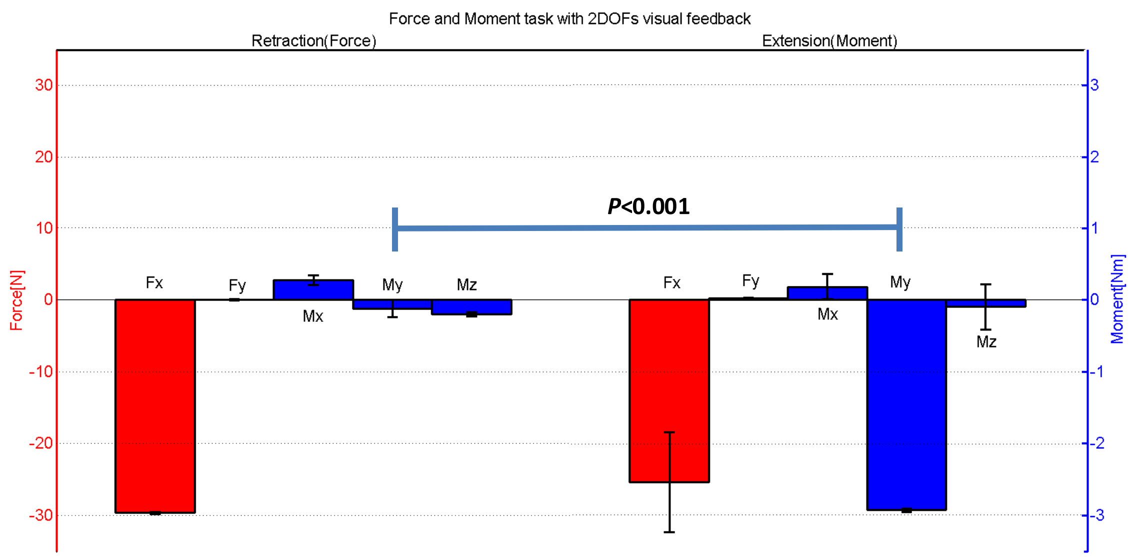

Figure C.2 In the backward direction, the force task: retraction (left) and moment task: extension (right) with 2DOFs visual feedback. The red bars indicate mean values of force; the blue bars indicate mean values of moment. The standard error of the mean boundary is depicted by the vertical bar. Task loads My are significantly different (p<0.001).

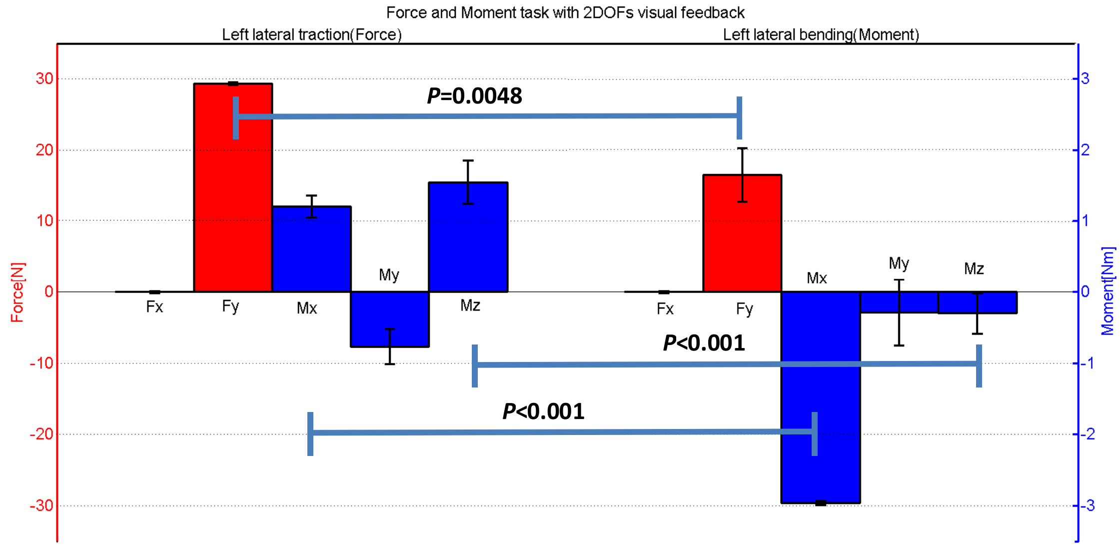

Figure C.3 In the leftward direction, the force task: the lateral traction (left) and moment task: the lateral bending (right) with 2DOFs visual feedback. The red bars indicate mean value of force; the blue bars indicate mean value of moment. The standard error of the mean boundary is depicted by the vertical bar. Fy, Mx and Mz are significantly different (Fy: p=0.0048, Mx: p<0.001, Mz: p<0.001).

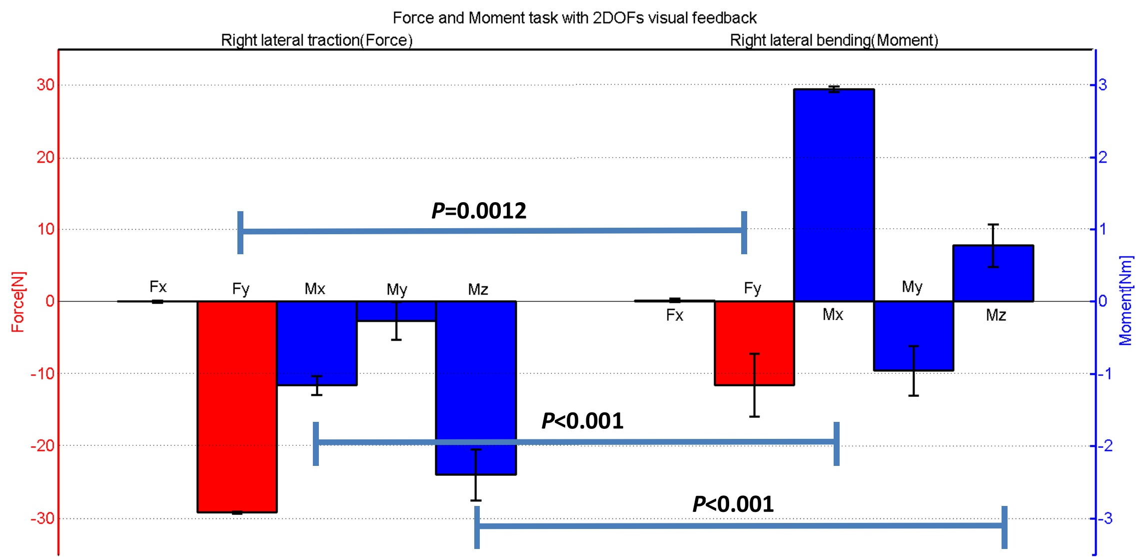

Figure C.4 In the rightward direction, the force task: the lateral traction (left) and moment task: the lateral bending (right) with 2DOFs visual feedback. The red bars indicate mean value of force; the blue bars indicate mean value of moment. The standard error of the mean boundary is depicted by the vertical bar. Fy, Mx and Mz are significantly different (Fy: p=0.0012, Mx: p<0.001, Mz: p<0.001).

D Effects of visual feedback on EMG

Effects of 2DOFs and 3DOFs visual feedback were compared for each muscle in force and moment task respectively. The normalized EMG mean and standard error (colour shaded area) over 11 subjects in force and moment tasks are shown. The plot consists of left and right side muscle and the results with 2DOFs and 3DOFs visual feedback are put together. Blue lines represent force task with 2DOFs visual feedback; Green lines represent moment task 2DOFs visual feedback; Red lines represent moment task with 3DOFs visual feedback; Cyan lines represent force task with 3DOFs visual feedback added Mx to leftward and rightward; Magenta lines represent force task with 3DOFs visual feedback added Mz to leftward and rightward.

- Sternocleidomastoid

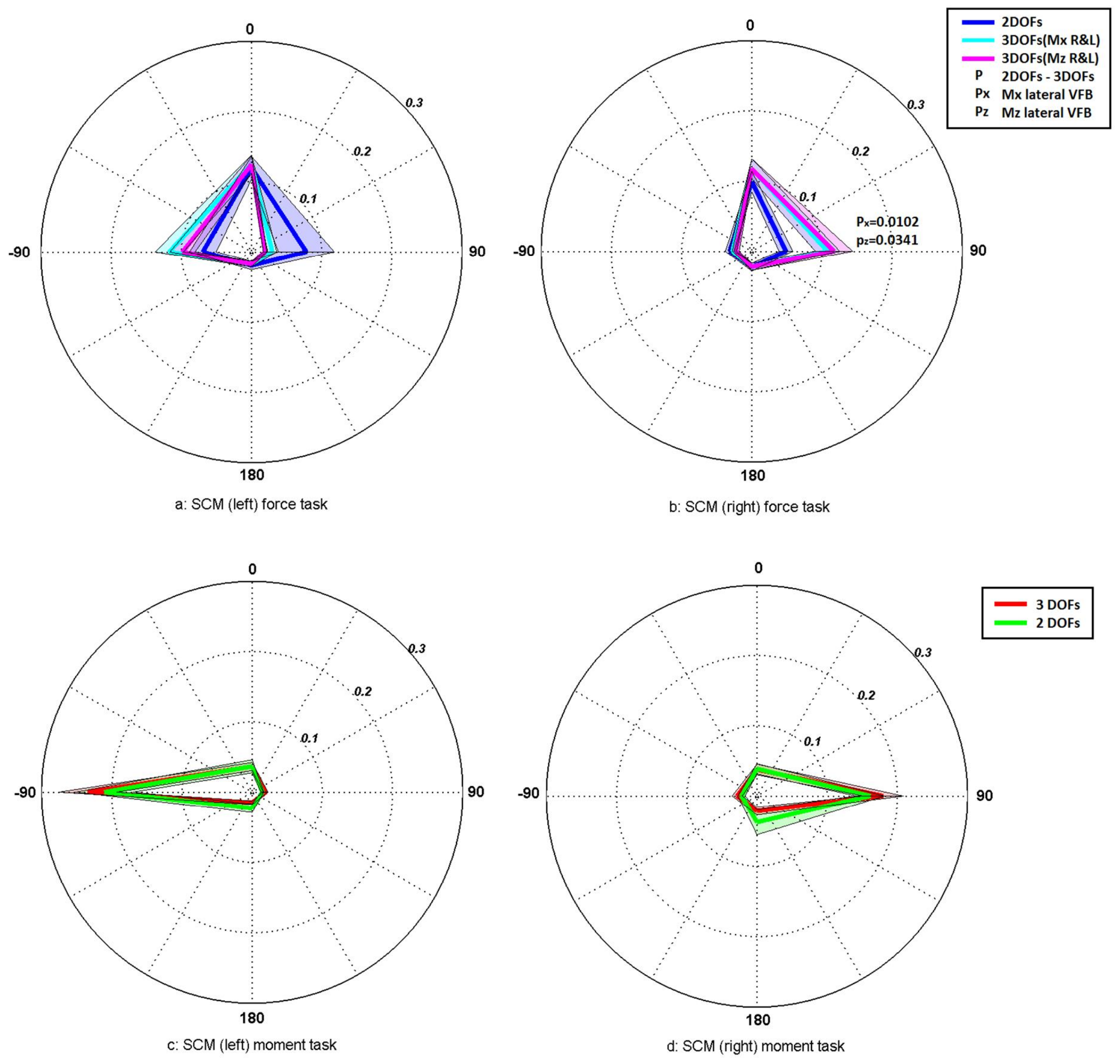

Figure D.1 a,b: Sternocleidomastoid (SCM) force task with 2DOFs and 3DOFs visual feedback. Two 3DOFs force tasks are shown, with My in pro/retraction tasks and with additional Mx or Mz visual feedback in lateral force tasks. The thick line indicates the mean normalized EMG and the standard error is depicted by the shaded areas. Right SCM in 3DOFs force task has a higher activation than with 2DOFs task in rightward direction (p_x =0.0102, p_z =0.0341).

c,d: Sternocleidomastoid (SCM) moment task with 2DOFs and 3DOFs visual feedback. No significant difference between 2DOFs and 3DOFs task is shown for each direction.

- Splenius capitis

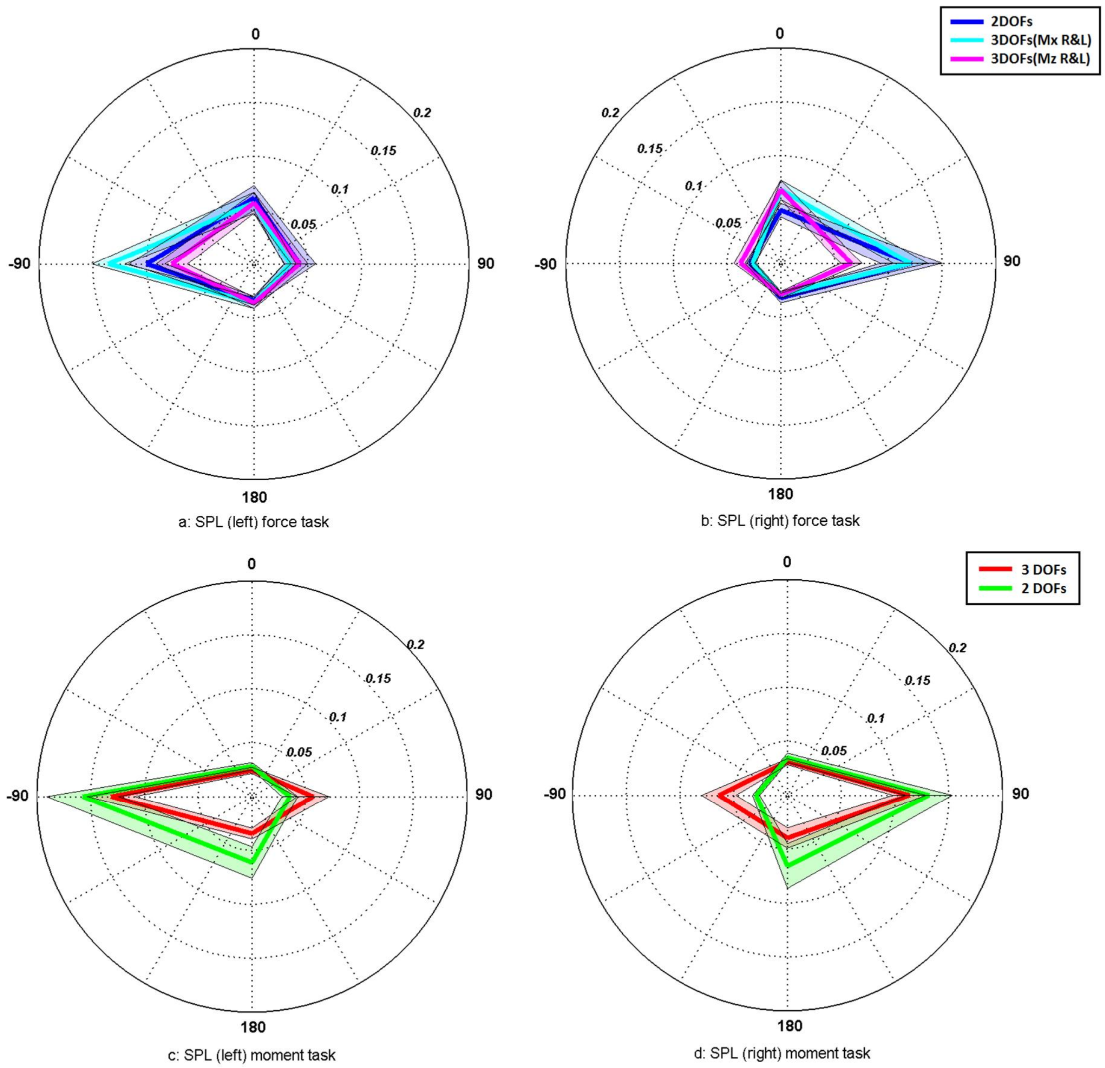

Figure D.2 a,b: Splenius capitis (SPL) force task with 2DOFs and 3DOFs visual feedback. Two 3DOFs force tasks are shown, with My in pro/retraction tasks and with additional Mx or Mz visual feedback in lateral force tasks. The thick line indicates the mean normalized EMG and the standard error is depicted by the shaded areas. No significant difference between 2DOFs and 3DOFs task is shown for each direction.

c,d: Splenius capitis (SPL) moment task with 2DOFs and 3DOFs visual feedback. No significant difference between 2DOFs and 3DOFs task is shown for each direction.

- Semispinalis capitis

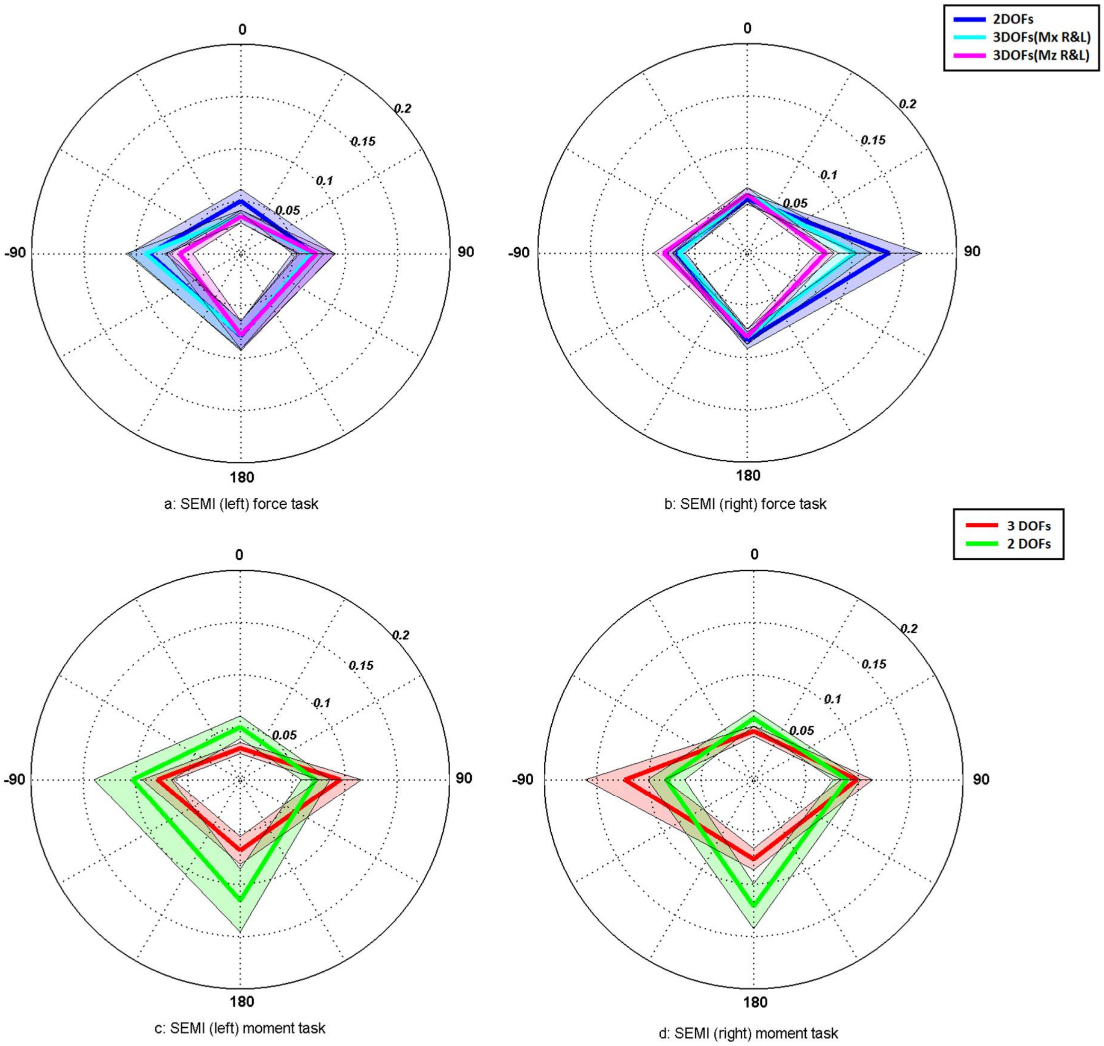

Figure D.3 a,b: Semispinalis capitis (SEMI) force task with 2DOFs and 3DOFs visual feedback. Two 3DOFs force tasks are shown, with My in pro/retraction tasks and with additional Mx or Mz visual feedback in lateral force tasks. The thick line indicates the mean normalized EMG and the standard error is depicted by the shaded areas. No significant difference between 2DOFs and 3DOFs task is shown for each direction.

c,d: Semispinalis capitis (SEMI) moment task with 2DOFs and 3DOFs visual feedback. No significant difference between 2DOFs and 3DOFs task is shown for each direction.

- Trapezius

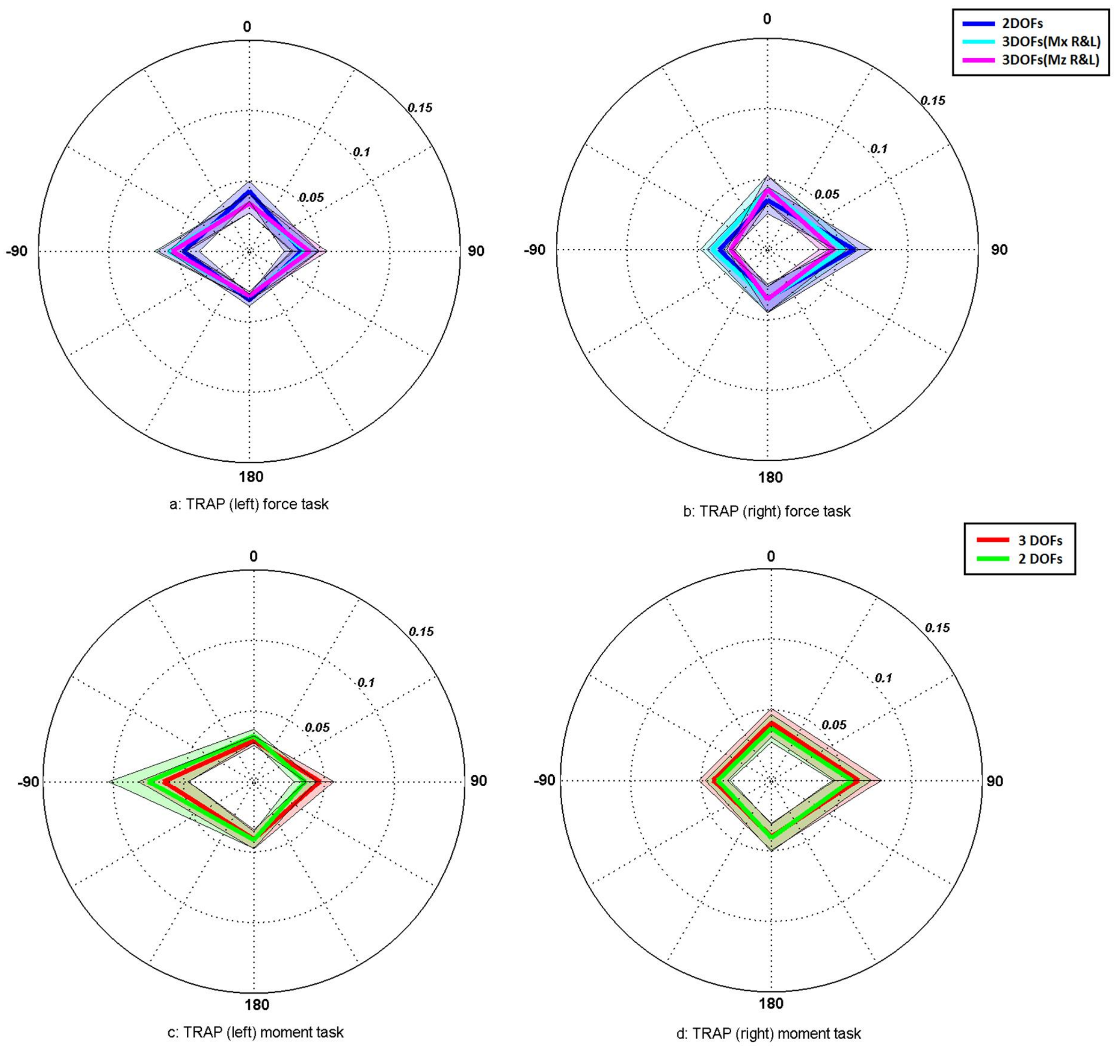

Figure D.4 a,b: Trapezius (TRAP) force task with 2DOFs and 3DOFs visual feedback. Two 3DOFs force tasks are shown, with My in pro/retraction tasks and with additional Mx or Mz visual feedback in lateral force tasks. The thick line indicates the mean normalized EMG and the standard error is depicted by the shaded areas. No significant difference between 2DOFs and 3DOFs task is shown for each direction.

c,d: Trapezius (TRAP) moment task with 2DOFs and 3DOFs visual feedback. No significant difference between 2DOFs and 3DOFs task is shown for each direction.

E Muscle group EMG activation level

Four pairs of muscles: sternocleidomastoid (SCM), splenius capitis (SPL), semispinalis capitis (SEMI), trapezius (TRAP) showed a varied EMG activation level in force and moment tasks with 2DOFs and 3DOFs visual feedback. The EMG activities of 8 muscles are put in one plot per each task. The difference of the moment task and force task is compared. The bar indicates the mean normalized EMG and the standard error is depicted by the vertical bar.

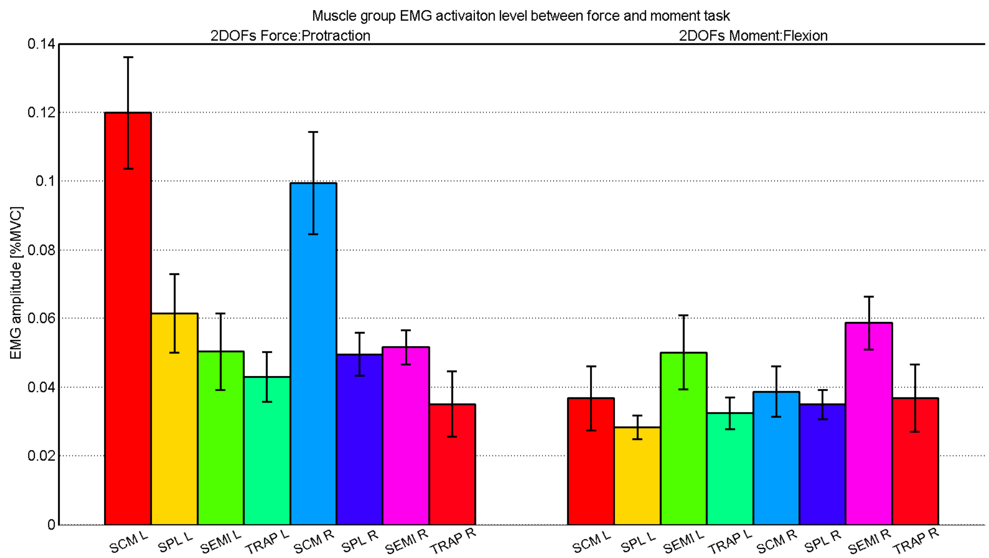

Figure E.1 Protraction force task and flexion moment task with 2DOFs visual feedback

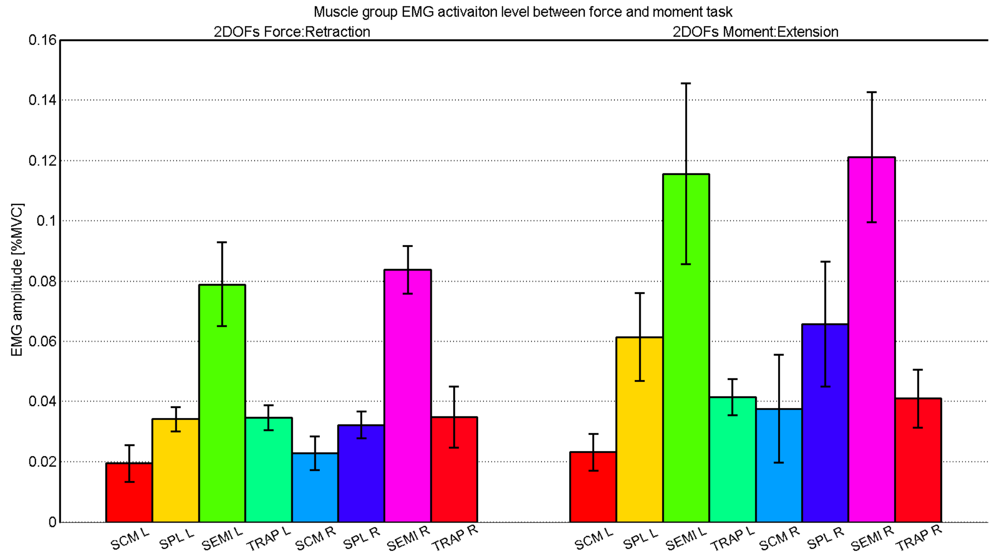

Figure E.2 Retraction force task and extension moment task with 2DOFs visual feedback

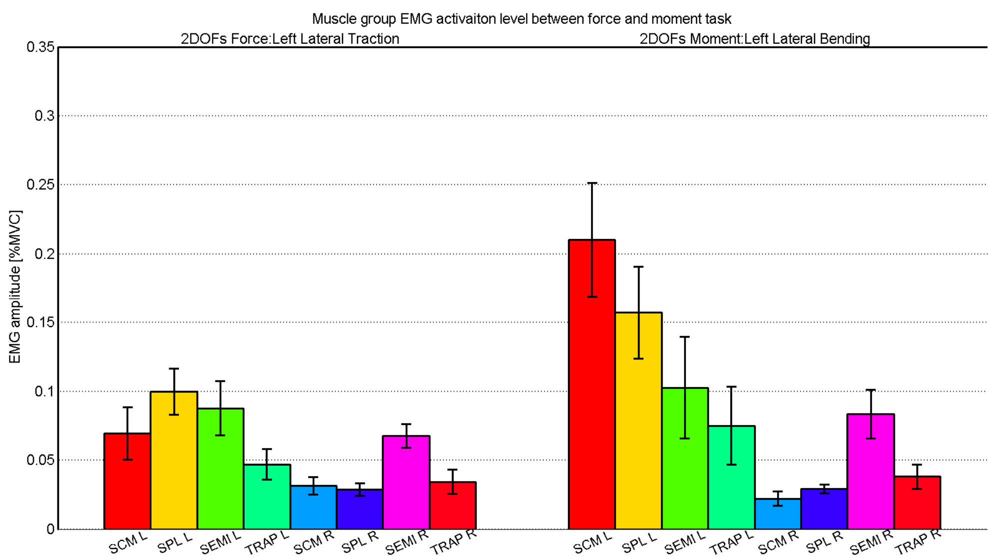

Figure E.3 Left lateral traction force task and left lateral moment task with 2DOFs visual feedback

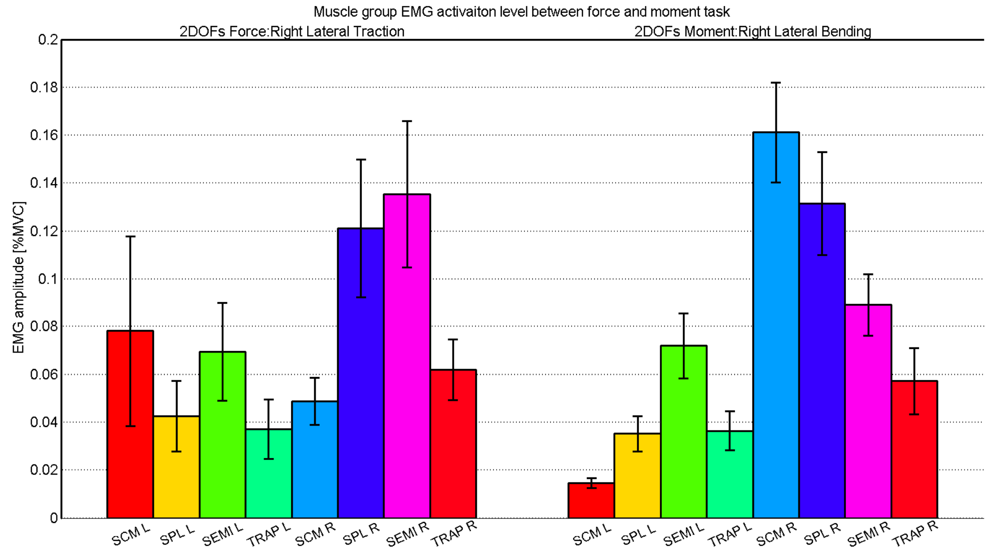

Figure E.4 Right lateral traction force task and right lateral moment task with 2DOFs visual feedback

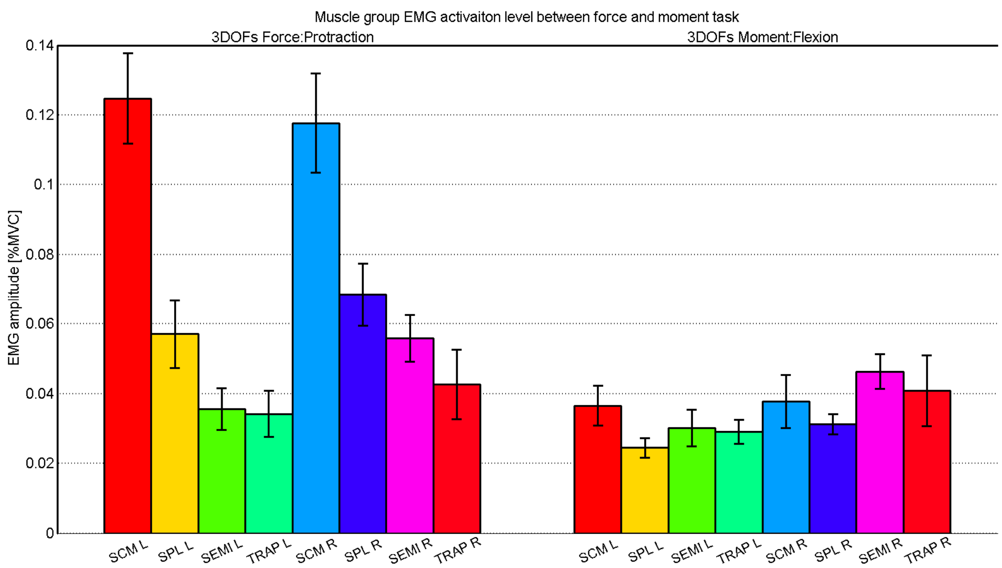

Figure E.5 Protraction force task and flexion moment task with 3DOFs visual feedback

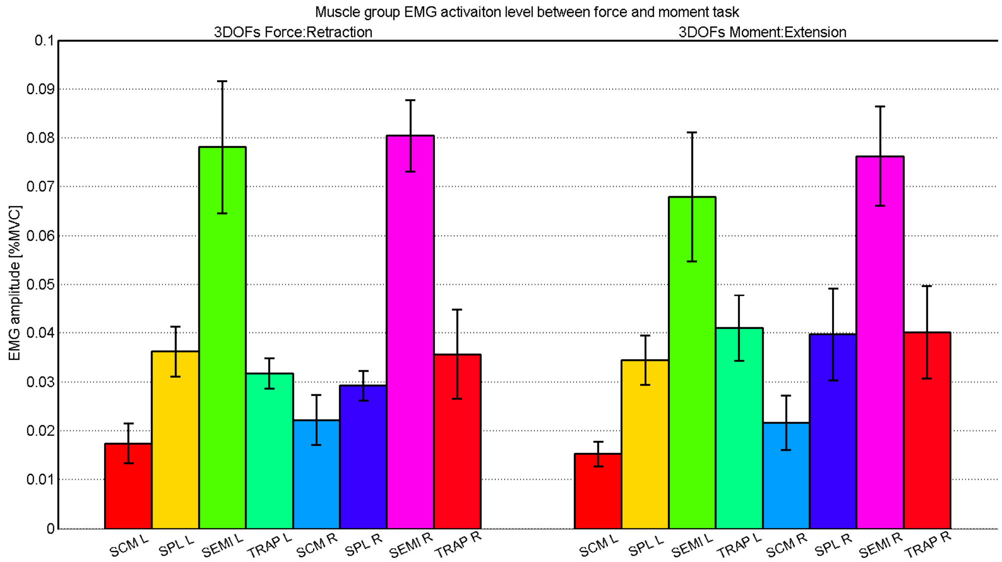

Figure E.6 Retraction force task and extension moment task with 3DOFs visual feedback

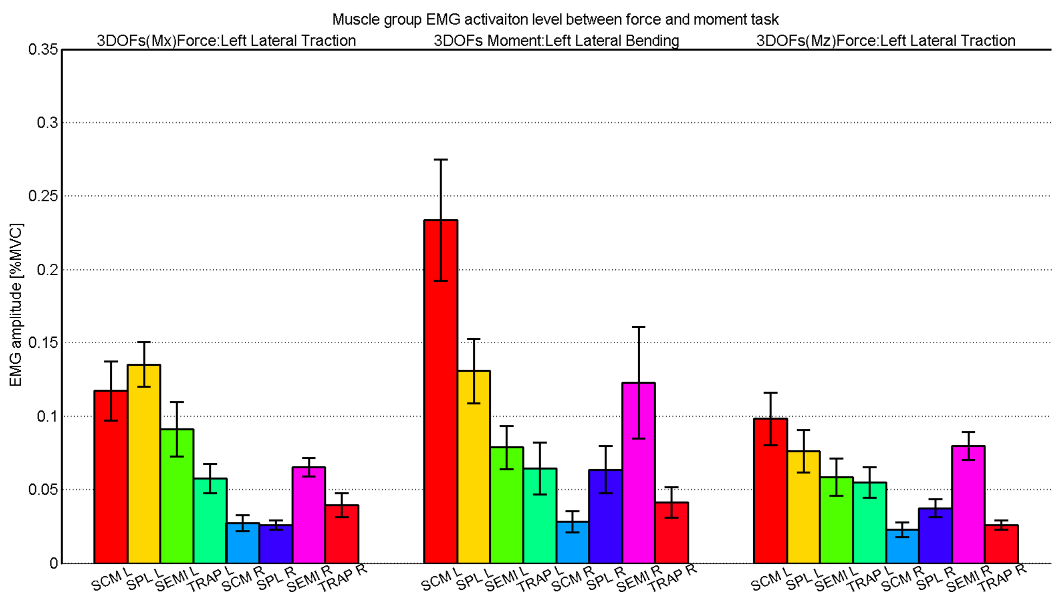

Figure E.7 Left lateral traction force task and left lateral moment task with 3DOFs visual feedback. Two 3DOFs force tasks are shown with additional Mx or Mz visual feedback.

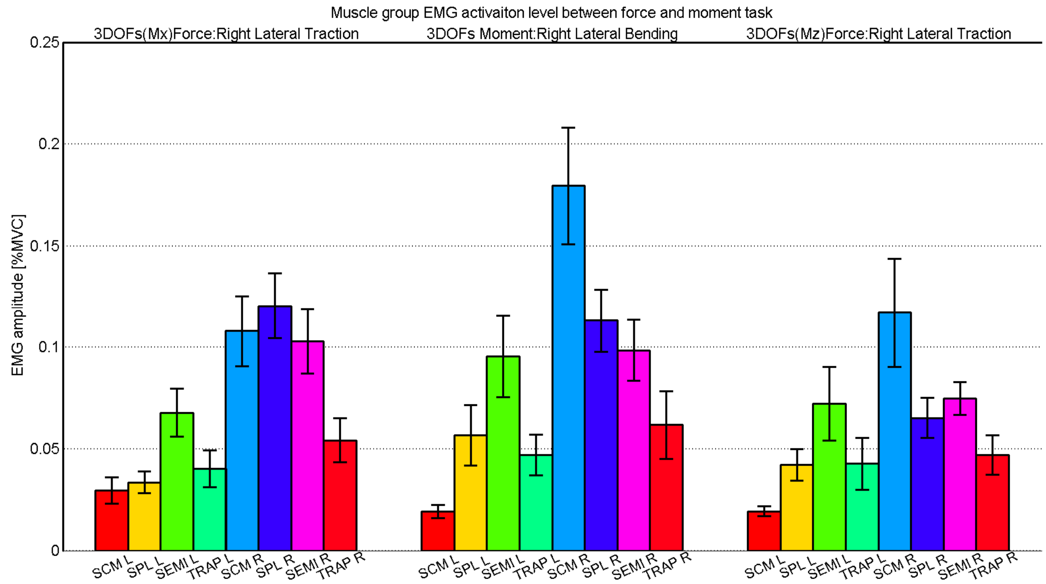

Figure E.8 Right lateral traction force task and right lateral moment task with 3DOFs visual feedback. Two 3DOFs force tasks are shown with additional Mx or Mz visual feedback.

F Student's *t*-test results

- Effects of visual feedback on loads: check the significant difference on five loads (Fx,Fy,Mx,My,Mz) between 2DOFs and 3DOFs visual feedback per each task. The significant level P<0.05 is marked as blue shaded area.

Task	*t*-test results	Fx	Fy	Mx	My	Mz
Protraction	t(df), df=16	-1.3435	-0.2317	-0.8118	-8.5442	-1.8185
	P value	0.1979	0.8197	0.4288	<0.001	0.0878
	95% CI	-0.8430, 0.1890	-0.3790, 0.3043	-0.3597, 0.1605	-3.5603, -2.1448	-0.5064, 0.0388
Retraction	t(df), df=20	0.0328	0.2037	0.2843	-0.8819	-1.5873
	P value	0.9067	0.7928	0.7981	0.8947	0.0975
	95% CI	-0.4706, 0.4856	-0.3011, 0.3663	-0.2111, 0.2777	-0.4001, 0.1623	-0.1951, 0.0265
Flexion	t(df), df=16	-3.0828	-1.2084	-0.3054	-0.5128	0.0147
	P value	0.0071	0.2445	0.7640	0.6151	0.9884
	95% CI	-15.6653, -2.8994	-0.5192, 0.1422	-0.4138, 0.3096	-0.1286, 0.0785	-0.3090, 0.3133
Extension	t(df), df=20	-3.4022	1.3841	0.2874	-0.2369	0.2320
	P value	0.0028	0.1816	0.7768	0.8152	0.8189
	95% CI	-40.0532, -9.6062	-0.1004, 0.4962	-0.5256, 0.6936	-0.1161, 0.0924	-0.6498, 0.8125
Left lateral bending	t(df), df=17	0.1609	3.8844	-0.2157	-0.5007	2.3734
	P value	0.8741	0.0012	0.8318	0.6230	0.0297
	95% CI	-0.4508, 0.5252	7.4592, 25.1954	-0.1232, 0.1003	-1.9597, 1.2080	0.1828, 3.1099
Right lateral bending	t(df), df=19	0.9467	-2.4451	0.0364	-0.3219	-1.5986
	P value	0.3557	0.0244	0.9713	0.7511	0.1264
	95% CI	-0.3818, 1.0123	-20.9515, -1.6255	-0.1035, 0.1072	-1.4367, 1.0537	-2.2372, 0.2996
left lateral traction (Mx)	t(df), df=20	-0.4088	-0.6689	7.1094	-1.1815	0.7080
	P value	0.6871	0.5112	<0.001	0.2513	0.4871
	95% CI	-0.5830, 0.3920	-0.7507, 0.3862	0.8491, 1.5543	-1.1829, 0.3274	-0.6499, 1.3177
left lateral traction (Mz)	t(df), df=20	0.8415	-0.4827	-1.6407	-1.4347	4.8688
	P value	0.4100	0.6345	0.1165	0.1668	<0.001
	95% CI	-0.2523, 0.5935	-0.5558, 0.3469	-2.6517,0.3168	-2.1994, 0.4069	0.8945, 2.2355
Right lateral traction (Mx)	t(df), df=20	1.4311	2.1967	-8.2089	0.2123	-2.2656
	P value	0.1678	0.0400	<0.001	0.8340	0.0347
	95% CI	-0.1697, 0.9116	0.0240, 0.9271	-1.4758,-0.8778	-0.6622, 0.8123	-2.4228,-0.1000
Right lateral traction (Mz)	t(df), df=20	1.5557	1.1640	0.6877	-0.7935	-6.3858
	P value	0.1355	0.2581	0.4995	0.4368	<0.001
	95% CI	-0.1717, 1.1789	-0.2226, 0.7846	-0.6259, 1.2415	-1.2843, 0.5765	-3.1577,-1.6027

df- Degrees of freedom of the test. 95% CI, 95% confidence interval on the difference of population means.

- Effects of force versus moment tasks on loads: check the significant difference on five loads (Fx,Fy,Mx,My,Mz) between force and moment task towards the same direction with the same visual feedback.

Task	*t*-test results	Fx	Fy	Mx	My	Mz
Protraction Flexion 2DOFs	t(df), df=19	15.0638	0.5019	-3.2912	-21.1157	0.1524
	P value	<0.001	0.6215	0.0038	<0.001	0.8805
	95% CI	33.0518, 43.7186	-0.1899, 0.3096	-0.7292, -0.1623	-6.4477, -5.2848	-0.2645, 0.3060
Protraction Flexion 3DOFs	t(df), df=13	129.2974	-0.4397	-2.4571	-61.8411	1.9813
	P value	<0.001	0.6674	0.0288	<0.001	0.0691
	95% CI	28.9381, 29.9216	-0.5397, 0.3571	-0.7484, -0.0481	-3.1449, -2.9326	-0.0232, 0.5367
Retraction Extension 2DOFs	t(df), df=20	-0.5873	-0.9328	0.4751	21.0634	-0.3243
	P value	0.5636	0.3621	0.6399	<0.001	0.7491
	95% CI	-19.504,10.9342	-0.5292, 0.2022	-0.3253, 0.5172	2.5309, 3.0873	-0.7978, 0.5831
Retraction Extension 3DOFs	t(df), df=20	-100.8711	0.0147	0.6070	54.2781	0.4589
	P value	<0.001	0.9884	0.5507	<0.001	0.6512
	95% CI	-29.7243, -28.5199	-0.2563, 0.2599	-0.3573, 0.6505	2.8041, 3.0283	-0.2066, 0.3232
Left lateral traction Left lateral bending 2DOFs	t(df), df=18	-0.0531	3.2109	22.4397	-0.8442	3.9778
	P value	0.9583	0.0048	<0.001	0.4096	<0.001
	95% CI	-0.4439, 0.4221	4.4352, 21.2251	3.7811, 4.5623	-1.6661, 0.7110	0.8742, 2.8313
Left lateral traction (Mx) Left lateral bending 3DOFs	t(df), df=19	0.4755	102.0643	54.8601	-0.7594	4.7664
	P value	0.6399	<0.001	<0.001	0.4570	<0.001
	95% CI	-0.4144, 0.6580	28.7381, 29.9414	2.8457, 3.0714	-1.5991, 0.7477	1.7753, 4.5551
Left lateral traction(Mz) Left lateral Bending 3DOFs	t(df), df=19	-0.6411	127.9524	7.3120	0.0552	3.4776
	P value	0.5291	<0.001	<0.001	0.9565	0.0025
	95% CI	-0.6155, 0.3269	28.7833, 29.7406	3.8027, 6.8528	-1.5795, 1.6651	0.7701, 3.0982
Right lateral traction Right lateral bending 2DOFs	t(df), df=19	-0.5165	-3.8164	-27.6222	1.4857	-6.3913
	P value	0.6115	0.0012	<0.001	0.1538	<0.001
	95% CI	-0.8265, 0.4993	-27.2790,-7.9554	-4.4193, -3.7968	-0.2810, 1.6559	-4.2188, -2.1373
Right lateral traction (Mx) Right lateral bending 3DOFs	t(df), df=20	-0.7913	-129.2188	-55.0574	0.8395	-4.4601
	P value	0.4381	<0.001	<0.001	0.4111	<0.001
	95% CI	-0.7971, 0.3587	-29.8556,-28.907	-3.0404, -2.8184	-0.6251, 1.4669	-4.2350,-1.5360
Right lateral traction (Mz) Right lateral bending 3DOFs	t(df), df=20	-1.0406	-116.1718	-10.3285	1.4898	-3.5511
	P value	0.3105	<0.001	<0.001	0.1519	0.0020
	95% CI	-1.0574, 0.3536	-29.7108,-28.6627	-5.3055, -3.5226	-0.3401, 2.0399	-2.8044, -0.7289

df- Degrees of freedom of the test. 95% CI, 95% confidence interval on the difference of population means.

- Effects of force versus moment tasks on EMG: check the significant difference on four pairs of muscles between force and moment task towards the same direction with the same visual feedback.

Muscles	t-test results	Forward	Backward	Leftward	Rightward
Right SCM 2DOFs	t(df)	3.3602 (df=19)	-0.7529 (df=20)	1.0178 (df=18)	-4.6189 (df=19)
	P value	0.0033	0.4603	0.3222	<0.001
	95% CI	0.0229, 0.0985	-0.0557, 0.0262	-0.0100, 0.0287	-0.1634, -0.0615
left SCM 2DOFs	t(df)	4.0790 (df=19)	-0.4186 (df=20)	-2.8953 (df=18)	1.4456 (df=19)
	P value	<0.001	0.6800	0.0096	0.1646
	95% CI	0.0405, 0.1258	-0.0224, 0.0149	-0.2431, -0.0387	-0.0284, 0.1555
Right SPL 2DOFs	t(df)	1.7824 (df=19)	-1.5065 (df=20)	-0.0858 (df=18)	-0.2664 (df=19)
	P value	0.0907	0.1476	0.9326	0.7928
	95% CI	-0.0025, 0.0317	-0.0800, 0.0129	-0.0138, 0.0127	-0.0921, 0.0713
left SPL 2DOFs	t(df)	2.5256 (df=19)	-1.7121 (df=20)	-1.4244 (df=18)	0.4034 (df=19)
	P value	0.0206	0.1024	0.1714	0.6912
	95% CI	0.0057, 0.0607	-0.0603, 0.0059	-0.1424, 0.0273	-0.0305, 0.0451
Right SEMI 2DOFs	t(df)	-0.7231 (df=19)	-1.5524 (df=20)	-0.7547 (df=18)	1.2806 (df=19)
	P value	0.4785	0.1362	0.4602	0.2157
	95% CI	-0.0275, 0.0134	-0.0875, 0.0128	-0.0599, 0.0282	-0.0295, 0.1224
left SEMI 2DOFs	t(df)	0.0128 (df=19)	-1.0556 (df=20)	-0.3340 (df=18)	-0.0943 (df=19)
	P value	0.9899	0.3037	0.7422	0.9259
	95% CI	-0.0348, 0.0352	-0.1091, 0.0358	-0.1099, 0.0798	-0.0584, 0.0533
Right TRAP 2DOFs	t(df)	-0.1215 (df=19)	-0.4144 (df=20)	-0.2784 (df=18)	0.2282 (df=19)
	P value	0.9046	0.6830	0.7839	0.8220
	95% CI	-0.0326, 0.0290	-0.0366, 0.0245	-0.0330, 0.0253	-0.0376, 0.0468
left TRAP 2DOFs	t(df)	1.1261 (df=19)	-0.8917 (df=20)	-0.8687 (df=18)	0.0510 (df=19)
	P value	0.2741	0.3831	0.3964	0.9598
	95% CI	-0.0091, 0.0302	-0.0227, 0.0091	-0.0964, 0.0400	-0.0330, 0.0346

df- Degrees of freedom of the test. 95% CI, 95% confidence interval on the difference of population means.

Muscles	t-test results	Forward	Backward	Leftward (FB:Mx)	Leftward (FB:Mz)	Rightward (FB:Mx)	Rightward (FB:Mz)
Right SCM 3DOFs	t(df)	3.8786 (df=13)	0.0678 (df=20)	-0.0881 (df=19)	-0.5347(df=17)	-2.0387 (df=20)	-1.4834 (df=19)
	P value	0.0019	0.9466	0.9307	0.5998	0.0549	0.1544
	95% CI	0.0354,0.1245	-0.0160,0.0171	-0.0210,0.0193	-0.0264,0.0157	-0.1446,0.0017	-0.1505,0.0257
Left SCM 3DOFs	t(df)	4.8725 (df=13)	0.4264 (df=20)	-2.3860 (df=19)	-2.5978 (df=17)	1.3699 (df=20)	0.0407 (df=19)
	P value	<0.001	0.6744	0.0276	0.0188	0.1859	0.9680
	95% CI	0.0491, 0.1273	-0.0084,0.0127	-0.2182,-0.0143	-0.2452,-0.0254	-0.0054,0.0262	-0.0092, 0.0095
Right SPL 3DOFs	t(df)	3.1230 (df=13)	-1.0120 (df=20)	-2.1980 (df=19)	-1.3300(df=17)	0.3145 (df=20)	-2.4172 (df=19)
	P value	0.0081	0.3236	0.0405	0.2011	0.7564	0.0259
	95% CI	0.0115, 0.0631	-0.0323, 0.0112	-0.0735, -0.0018	-0.0681, 0.0154	-0.0411,0.0557	-0.0894,-0.0064
Left SPL 3DOFs	t(df)	2.5527 (df=13)	0.2324 (df=20)	0.1526 (df=19)	-1.8035(df=17)	-1.4049 (df=20)	-0.7939 (df=19)
	P value	0.0241	0.8186	0.8803	0.0891	0.1754	0.4371
	95% CI	0.0050, 0.0602	-0.0140, 0.0175	-0.0554, 0.0641	-0.1183, 0.0093	-0.0577, 0.0113	-0.0528, 0.0237
Right SEMI 3DOFs	t(df)	0.8895 (df=13)	0.3192 (df=20)	-1.4206 (df=19)	-0.9459 (df=17)	0.1876 (df=20)	-1.2671 (df=19)
	P value	0.3899	0.7529	0.1716	0.3574	0.8531	0.2204
	95% CI	-0.0137, 0.0328	-0.0232, 0.0315	-0.1424, 0.0273	-0.1394, 0.0531	-0.0436, 0.0522	-0.0627, 0.0154
Left SEMI 3DOFs	t(df)	0.5175 (df=13)	0.5157 (df=20)	0.4818 (df=19)	-0.9105(df=17)	-1.1320 (df=20)	-0.7947 (df=19)
	P value	0.6135	0.6117	0.6355	0.3753	0.2710	0.4366
	95% CI	-0.0171, 0.0278	-0.0311, 0.0515	-0.0412, 0.0659	-0.0671, 0.0267	-0.0787, 0.0233	-0.0846, 0.0380
Right TRAP 3DOFs	t(df)	0.1008 (df=13)	-0.3282 (df=20)	-0.1366 (df=19)	-1.2275(df=17)	-0.3630 (df=20)	-0.7040 (df=19)
	P value	0.9212	0.7462	0.8928	0.2364	0.7204	0.4900
	95% CI	-0.0382, 0.0419	-0.0334, 0.0243	-0.0520, 0.0384	-0.0417, 0.0110	-0.0507, 0.0357	-0.0587, 0.0291
Left TRAP 3DOFs	t(df)	0.5369 (df=13)	-1.1920 (df=20)	-0.3163 (df=19)	-0.9105 (df=17)	-0.4783 (df=20)	-0.2493 (df=19)
	P value	0.6004	0.2472	0.7552	0.6928	0.6376	0.8058
	95% CI	-0.0154, 0.0256	-0.0255, 0.0069	-0.0314, 0.0276	-0.0593, 0.0403	-0.0361, 0.0226	-0.0404, 0.0318

df- Degrees of freedom of the test. 95% CI, 95% confidence interval on the difference of population means.

- Effects of visual feedback on EMG: check the significant difference on four pairs of muscles between 2DOFs and 3DOFs visual feedback per each direction.

Muscles	*t*-test results	Forward	Backward	Leftward (VFB:Mx)	Leftward (VFB:Mz)	Rightward (VFB:Mx)	Rightward (VFB:Mz)
Right SCM Force task	t(df)	-0.7349 (df=16)	0.0827 (df=20)	0.4744 (df=20)	0.9617 (df=18)	-2.8351 (df=20)	-2.2828 (df=19)
	P value	0.4730	0.9349	0.6404	0.3489	0.0102	0.0341
	95% CI	-0.0709, 0.0344	-0.0161, 0.0174	-0.0141, 0.0223	-0.0102, 0.0275	-0.1029, -0.0157	-0.1310,-0.0057
Left SCM Force task	t(df)	-0.1877 (df=16)	0.2621 (df=20)	-1.6494 (df=20)	-0.9944 (df=18)	1.1482 (df=20)	1.3364 (df=19)
	P value	0.8535	0.7959	0.1147	0.3332	0.2644	0.1972
	95% CI	-0.0591, 0.0495	-0.0139, 0.0179	-0.1088, 0.0127	-0.0901, 0.0322	-0.0396, 0.1367	-0.0333, 0.1507
Right SPL Force task	t(df)	-1.4988 (df=16)	0.5330 (df=20)	0.4254 (df=20)	-1.0756 (df=18)	0.0181 (df=20)	1.6704 (df=19)
	P value	0.1534	0.5999	0.6751	0.2963	0.9858	0.1112
	95% CI	-0.0457, 0.0078	-0.0088, 0.0148	-0.0096, 0.0145	-0.0262, 0.0084	-0.0715, 0.0727	-0.0141, 0.1258
Left SPL Force task	t(df)	0.2429 (df=16)	-0.2995 (df=20)	-1.4920 (df=20)	0.9388 (df=18)	0.5428 (df=20)	0.0133 (df=19)
	P value	0.8112	0.7676	0.1513	0.3602	0.5933	0.9895
	95% CI	-0.0345, 0.0434	-0.0164, 0.0123	-0.0853, 0.0142	-0.0289, 0.0756	-0.0255, 0.0434	-0.0380, 0.0385
Right SEMI Force task	t(df)	-0.4386 (df=16)	0.2960 (df=20)	0.0884 (df=20)	-0.8578 (df=18)	0.9039 (df=20)	1.7457 (df=19)
	P value	0.6668	0.7703	0.8391	0.4023	0.3768	0.0970
	95% CI	-0.0249, 0.0163	-0.0203, 0.0271	-0.0210, 0.0256	-0.0418, 0.0176	-0.0427, 0.1079	-0.0120, 0.1332
Left SEMI Force task	t(df)	0.9149 (df=16)	0.0439 (df=20)	-0.0950 (df=20)	1.0974 (df=18)	0.0636 (df=20)	-0.0956 (df=19)
	P value	0.3738	0.9654	0.9011	0.2869	0.9499	0.9248
	95% CI	-0.0195, 0.0491	-0.0417, 0.0435	-0.0624, 0.0553	-0.0265, 0.0846	-0.0499, 0.0531	-0.0646, 0.0590
Right TRAP Force task	t(df)	-0.4621 (df=16)	-0.0505 (df=20)	-0.4071 (df=20)	0.7607 (df=18)	0.4343 (df=20)	0.8524 (df=19)
	P value	0.6502	0.9603	0.6883	0.4567	0.6687	0.4046
	95% CI	-0.0426, 0.0273	-0.0306, 0.0291	-0.0316, 0.0213	-0.0145, 0.0310	-0.0288, 0.0440	-0.0216, 0.0513
Left TRAP Force task	t(df)	0.7405 (df=16)	0.5428 (df=20)	-0.6803 (df=20)	-0.4732 (df=18)	-0.1911 (df=20)	-0.2883 (df=19)
	P value	0.4697	0.5933	0.5041	0.6417	0.8504	0.7762
	95% CI	-0.0164, 0.0341	-0.0084, 0.0143	-0.0433, 0.0220	-0.0434, 0.0275	-0.0367, 0.0305	-0.0455, 0.0345

df- Degrees of freedom of the test. 95% CI, 95% confidence interval on the difference of population means.

Muscles	*t*-test results	Forward	Backward	Leftward	Rightward
Right SCM moment task	t(df)	0.0783 (df=16)	0.8153 (df=20)	-0.5953 (df=17)	-0.4771 (df=19)
	P value	0.9386	0.4245	0.5595	0.6387
	95% CI	-0.0252, 0.0272	-0.0249, 0.0568	-0.0276, 0.0155	-0.0985, 0.0619
Left SCM moment task	t(df)	0.0188 (df=16)	1.1511 (df=20)	-0.3529 (df=17)	-1.0941 (df=19)
	P value	0.9853	0.2633	0.7285	0.2876
	95% CI	-0.0278, 0.0283	-0.0064, 0.0222	-0.1633, 0.1165	-0.0133, 0.0042
Right SPL moment task	t(df)	0.6140 (df=16)	1.0869 (df=20)	-1.8228 (df=17)	0.6484 (df=19)
	P value	0.5478	0.2900	0.0860	0.5245
	95% CI	-0.0092, 0.0167	-0.0239, 0.0759	-0.0748, 0.0055	-0.0408, 0.0775
Left SPL moment task	t(df)	0.7387 (df=16)	1.6615 (df=20)	0.5839 (df=17)	-1.1917 (df=19)
	P value	0.4708	0.1122	0.5670	0.2480
	95% CI	-0.0072, 0.0150	-0.0069, 0.0607	-0.0689, 0.1216	-0.0594, 0.0163
Right SEMI moment task	t(df)	1.1215 (df=16)	1.8005 (df=20)	-0.8144 (df=17)	-0.4446 (df=19)
	P value	0.2786	0.0869	0.4267	0.6617
	95% CI	-0.0110, 0.0358	-0.0071, 0.0969	-0.1417, 0.0628	-0.0545, 0.0354
Left SEMI moment task	t(df)	1.3666 (df=16)	1.3901 (df=20)	0.5367 (df=17)	-0.8926 (df=19)
	P value	0.1906	0.1798	0.5985	0.3832
	95% CI	-0.0110, 0.0509	-0.0239, 0.1194	-0.0699, 0.1177	-0.0789, 0.0317
Right TRAP moment task	t(df)	-0.2388 (df=16)	0.0574 (df=20)	-0.2085 (df=17)	-0.1946 (df=19)
	P value	0.8143	0.9548	0.8373	0.8477
	95% CI	-0.0391, 0.0312	-0.0288, 0.0304	-0.0358, 0.0294	-0.0534, 0.0443
Left TRAP moment task	t(df)	0.4842 (df=16)	0.0522 (df=20)	0.2862 (df=17)	-0.7649 (df=19)
	P value	0.6348	0.9589	0.7782	0.4537
	95% CI	-0.0113, 0.0181	-0.0192, 0.0202	-0.0685, 0.0899	-0.0397, 0.0185

df- Degrees of freedom of the test. 95% CI, 95% confidence interval on the difference of population means.