Functional activity of upper extremities to improve trunk function after chronic incomplete spinal cord injury

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Abstract

A spinal cord injury (SCI) impairs both motor and sensory functions. Improving trunk function is an important factor to increase quality of life for those living with SCI. However, traditional rehabilitation methods in the United Kingdom (UK) can be complex for individuals living with a chronic SCI due to current challenges in the national health services (NHS), trips to exercise clinics for guidance from physiotherapists. These challenges constrain the time available for exercise. Hence, there is a pressing need for innovative rehabilitation strategies for improving trunk function. Arm cycling is a suitable form of exercise that can be performed independently at home without the need of direct feedback from clinicians. With the current challenges for continuing rehabilitation in the chronic phase of SCI, this thesis investigates the effects of a home-based arm cycling program on trunk function in individuals living with chronic SCI.

In the first chapter, the literature was reviewed to define SCI and the trunk, and to describe the neuromuscular and neurophysiological consequences of SCI in the trunk, as well as current approaches to SCI trunk rehabilitation in the UK. Subsequently, therapeutic interventions targeting the trunk musculature in SCI are described, as well as its assessment methodologies such as electromyography (EMG), kinematics and transcranial magnetic stimulation (TMS). Then, the main question and its objective are outlined.

The second chapter describes a reliability study assessing a novel electromyographic method named high-density surface electromyography (HDEMG) that enables measuring the muscle's spatial characteristics. The reliability of several HDEMG parameters was examined. The results demonstrate that root mean square (RMS), a metric for quantifying muscle

activity, and mean frequency were consistently reliable both within and between sessions during voluntary trunk movements and reaching tasks. The reliability of the barycentre, a measure of the centre of the distribution of muscle activity, varied depending on the task. The technique is found to be appropriate to use in intervention studies.

The third chapter reports an experiment characterising the differences in thoracic trunk muscle function between able-bodied individuals (control group) and individuals with an incomplete SCI (SCI group). All participants performed postural tasks and reaching tasks. During postural tasks, the SCI group demonstrated a more caudal distribution of erector spinae muscle activity compared to the control group. During the reaching tasks, distinct patterns of muscle activity were observed in the control group that was absent in the SCI group, highlighting the injury-related differences between the two groups.

The fourth chapter was an observational study to assess the feasibility and effects of a six-week home-based arm cycling exercise training programme on improving trunk control in individuals with chronic SCI. Before and after the exercise programme, the corticospinal excitability was assessed during rest, as well as the activation of the erector spinae muscles during multidirectional reaching tasks and two postural tasks (rapid shoulder flexion task and external perturbation task). Improvements were observed after the exercise programme, including a slightly higher reaching distance during forward reaching and a higher total trajectory of the trunk and centre of pressure during the perturbation task. Furthermore, a higher corticospinal excitability and higher trunk muscle activity were observed in the post-assessment. The exercise programme was found to be feasible, as demonstrated by a high adherence to the exercise.

The fifth chapter describes the preliminary results of an ongoing randomised control trial (RCT) study in which the effectiveness of arm cycling was compared to conventional physiotherapy exercise to improve trunk function in people with SCI. Participants were randomly allocated to the arm cycling exercise group or conventional physiotherapy exercise group. Both groups performed additional upper-body exercise videos. Descriptive analyses were applied due to the low sample size. The same postural and reaching tasks were performed as in Chapters 3 and 4. A qualitative assessment was carried out to investigate perceptions of the participants on the home-based exercise programme. In the post-assessment, a slightly greater reaching distance and higher trunk- and centre of pressure displacements were found in both groups. The erector spinae activation pattern differed between the two groups, with lower and more cranially located erector spinae activity in the arm cycling group during the reaching tasks. In contrast, the upright sitting group demonstrated a higher and more caudally located erector spinae activity. The results of the qualitative assessment emphasised the role of intrinsic motivation and social support from family as relevant factors to adherence to the study.

The sixth and final chapter is a general discussion of the overall findings and their implications. In addition, recommendations are made for further research in this area.

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Publications

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- Chapter 2
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Conferences

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Abbreviations

μV	microvolt
3-D	Three-dimensional
A/D	Analogue to digital
AD	anterior deltoid
AIS	American spinal injury association impairment scale
ANOVA	analysis of variance
A-P	anterior-posterior
APA	anticipatory postural adjustments
BMI	body mass index
C	control group / cervical
cm	centimetre
CNS	central nervous system
CoP	centre of pressure
CoV	coefficient of variation
COVID	coronavirus disease
CPA	compensatory postural adjustments
dB	Decibel

EMG	electromyography
ES	erector spinae
F	female
HDEMG	high-density surface electromyography
Hz	hertz
ID	identification
ICC	intraclass correlation coefficient
kHz	kilohertz
L	lumbar
LED	light emitting diode
LoI	level of injury
m	metre
M	mean / male
M1	primary motor cortex
MEP	motor evoked potential
M-L	medial-lateral
mm	millimetre

MNF	mean frequency
ms	millisecond
mV	millivolt
MVC	maximum voluntary contraction
n	number
NHS	national health services
PhD	doctor of philosophy
RCT	randomised controlled trial
RMS	root mean square
RPM	revolutions per minute
RSF	rapid shoulder flexion
s	seconds
S	sacral
SD	standard deviation
SEM	standard error of measurement
SCI	spinal cord injury
T	thoracic

TIS	trunk impairment scale
TMS	transcranial magnetic brain stimulation
TSI	time since injury
V	volt
UK	United Kingdom

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1. Introduction

1.1 Spinal cord injury

Spinal cord injury (SCI) is a life-altering event that has detrimental effects on the ones sustaining it and their loved ones. An estimated 2500 new SCI cases are registered in the United Kingdom (UK) on an annual basis, with the majority arising from traumatic incidents such as traffic accidents and falls (McCaughey et al., 2016; Smart, 2019). These effects are not only physiological, influencing overall bodily functions but also psychological and financial. The lifetime costs for individuals with SCI are significant, with estimated mean lifetime costs exceeding one million pounds per individual under the age of 65 (McDaid et al., 2019). In addition to causing psychological distress, SCI can also impact various bodily systems depending on the level and severity of the injury, including cardiovascular and respiratory systems, bladder- and bowel control, and control over the muscles (Hou & Rabchevsky, 2014).

The spinal cord is responsible for relaying sensory and motor information from the brain (Ahuja et al., 2017). The spinal column can be divided into four main segments: cervical (C1 – C7), thoracic (T1 – T12), lumbar (L1 – L5), and the sacral segment extending from S1 to S5 (Burns et al., 2012). Myelinated tracts that pass through small openings in the spinal cord are responsible for conveying sensory information and motor information (Ahuja et al., 2017). Neurological damage to these tracts can result in a loss of motor and sensory function below the point where the tract is damaged (Figure 1.1). In addition to the level of injury, SCI can also be classified based on its severity. The International Standards for Neurological Classification of Spinal Cord Injury introduced the American Spinal Injury Association

Impairment Scale (AIS) to evaluate the extend of the injury (Rupp et al., 2021). The assessment involves testing both motor and sensory functions to determine a grade, which ranges from A to E. Injuries classified as AIS A and B are considered motor complete, meaning there is no spared motor function below the level of injury, while AIS C and D injuries involve some preserved motor function beneath the point of injury (Rupp et al., 2021).

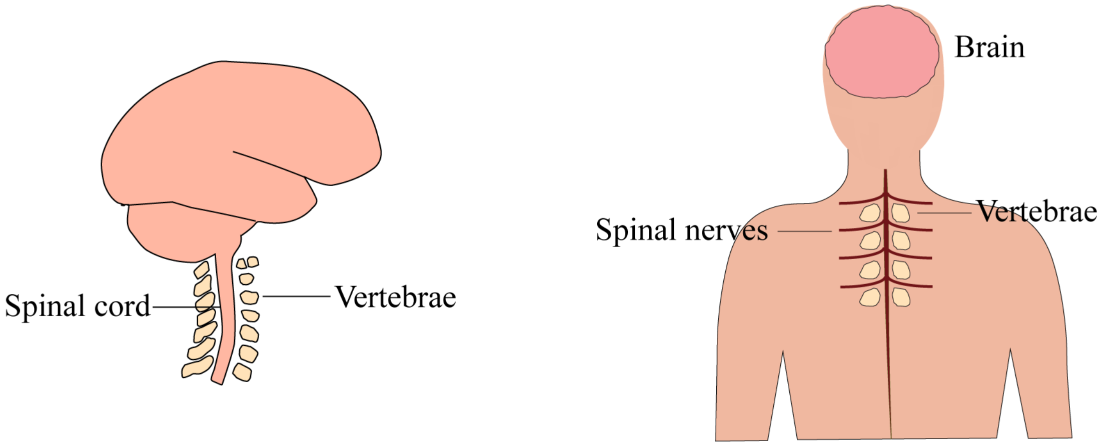

Figure 1.1. **Schematic representation of the spinal tracts and vertebrae.** The corticospinal tracts relay sensory and motor signals coming from the brain to the muscles. Spinal nerves are connected to the corticospinal tracts to send these signals to specific parts of the body. However, these signals are compromised below the level of injury.

1.2 Trunk control

One of the bodily peripheral effects of SCI is a loss of trunk control: a function necessary for a range of movements. The trunk is a complex system comprising the body's musculature and the corresponding cervical and thoracic nerve roots from the spinal cord that extend through the trunk to stabilise the spine and to maintain balance and posture (Bergmark, 1989; Gauthier et al., 2013). The trunk can be further subdivided into a thoracic portion, or upper torso, an abdominal portion, and a pelvic portion, or lower torso, with muscles such as multifidus and erector spinae covering several portions in a cranio-caudal direction, while muscles such as the external oblique muscles are located in a single region of the trunk (Perotto, 2011).

The trunk is able to make complex movements, and the engagement of various trunk muscles are involved depending on the specific task. For example, maintaining an upright sitting position involves the interplay of the erector spinae, internal and external obliques, and the rectus abdominis muscles (Freddolini et al., 2014). Lateral flexion, on the other hand, involves coordinated input from the multifidus, erector spinae and external obliques (Haas et al., 2022). For trunk flexion-extension movements, contributions of several abdominal muscles are needed, including the rectus abdominis, internal and external obliques, and the erector spinae (Oddsson & Thorstensson, 1990). It is worth noting that the erector spinae is a frequently assessed muscle due to its relevance in maintaining upright posture and in assisting movements of the upper extremities (Andersson & Winters, 1990; Floyd & Silver, 1955; O'Sullivan et al., 2006; Zedka & Prochazka, 1997).

1.3 Changes in trunk control after SCI

Individuals who have sustained a cervical or thoracic SCI may experience challenges with controlling the trunk muscles due to damage to spinal pathways, which significantly hampers their ability to perform daily tasks like reaching, dressing, and sports participation (Altmann et al., 2017; Chen et al., 2003; Field-Fote & Ray, 2010; Seelen et al., 1998).

1.3.1 Kinematics

A reduced trunk control also has an impact on their ability to maintain postural stability, impacting static and dynamic balance. The postural stability can be assessed with measures of a force plate or reflective markers placed on the body, such as the sway, displacement, and velocity (Grooten et al., 2018; Kejonen et al., 2003; Kerr & Eng, 2002; Prieto et al., 1996; Vette et al., 2010). Several studies compared able-bodied individuals with individuals with a cervical or thoracic SCI (Milosevic, Gagnon, et al., 2017; Milosevic et al., 2015). Both groups were instructed to sit quietly and independently on a force plate without back support while the sway of the centre of pressure was assessed. The results showed that individuals with SCI demonstrated more postural sway, indicating that the SCI group had reduced seated postural stability compared to the able-bodied individuals (Milosevic, Gagnon, et al., 2017; Milosevic et al., 2015). The differences in postural sway between the two groups were observed in both the anterior-posterior direction and medial-lateral direction (Milosevic, Gagnon, et al., 2017). Functional performance seems also to be dependent of the level of injury. Chen et al. (2003) demonstrated that individuals with a low thoracic SCI exhibited a better dynamic sitting balance compared to individuals with a high thoracic SCI. Dynamic sitting balance was measured during a multidirectional leaning task using a force plate. Weight-shift displacements, calculated as the distance in centimetres between the starting position and the farthest reaching point during reaching tasks, revealed that the low thoracic SCI group had greater displacements than the high thoracic SCI group. The authors proposed that the involvement of muscles below the level of injury may contribute to the increased reaching ability observed in the low thoracic group (Chen et al., 2003).

1.3.2 Electromyography

The changes in trunk control have also been investigated with electromyography (EMG) to identify changes in neuromuscular function after SCI. Bipolar surface EMG is a method to assess muscle activity by placing electrodes over the skin from which several properties can be derived, such as root-mean-square (RMS) amplitudes and muscle activation patterns (Balbinot et al., 2021; Campanini et al., 2022). Li et al. (2012) conducted a clinical AIS assessment and a functional neurophysiological assessment in individuals with cervical and thoracic injuries, both motor complete and motor incomplete. Muscle activity from relevant muscles were recorded during the neurophysiological assessment, including, but not limited to, the biceps and triceps brachii, erector spinae, vastus lateralis, rectus femoris, tibialis anterior, soleus, and extensor carpi radialis. The study’s finding was that a higher general AIS motor score was associated with a larger general RMS amplitude (Li et al., 2012). Furthermore, changes in erector spinae EMG amplitudes were observed during the neurophysiological assessment, a muscle not evaluated during the clinical AIS assessment. Interestingly, EMG activity was also observed in trunk muscles below the level of injury in individuals with AIS A, which is classified as motor complete according to the clinical AIS assessment. The authors proposed that incorporating EMG allows for the detection of subclinical improvements in trunk muscle function, given that the clinical AIS evaluation does not include assessment of trunk motor function (Li et al., 2012; Rupp et al., 2021).

Potten et al. (1999) investigated dynamic balance during a forward reaching task in individuals with a thoracic SCI and able-bodied controls using a force platform and EMG. Muscle activity was recorded from several trunk muscles, including the thoracic and lumbar erector spinae, latissimus dorsi, trapezius muscles, and the obliques. Thirty individuals were assessed, divided into three groups: ten individuals with a complete high thoracic SCI, ten individuals with a complete low thoracic SCI, and ten able-bodied controls (Potten et al., 1999). All participants were tasked to reach in the forward direction, while their muscle activity and centre of pressure displacements were measured. The first result was that the able-bodied controls exhibited a greater centre of pressure displacement compared to the SCI groups (Potten et al., 1999). Notably, no differences were found between the two SCI groups, contrasting the findings of Chen et al. (2003). This discrepancy might be attributed to factors such as a smaller sample size and variations in trunk length and level of injury, both of which are predictors of dynamic balance ability (Chen et al., 2003). The second result of Potten et al. (1999) was that distinct muscle activity patterns were observed between groups. During the reaching phase, both SCI groups demonstrated a greater EMG activity in the higher-thoracic erector spinae than the able-bodied individuals. Conversely, the able-bodied individuals demonstrated greater EMG activity in the lumbar erector spinae. In essence, it appears that the SCI groups rely more on the higher portion of the erector spinae, suggesting potential compensatory mechanisms such as tilting the pelvis backwards, to stabilise posture during forward reaching due to a diminished control over the muscles below the injury (Potten et al., 1999). Furthermore, the able-bodied individuals demonstrated phase-dependent activity in the latissimus dorsi and trapezius muscles during forward reaching, while both SCI groups demonstrated continuous activity in these muscles, possibly reflecting additional compensatory mechanisms to maintain sitting balance (Potten et al., 1999).

There are also differences in neuromuscular control between individuals with SCI and able-bodied individuals during external perturbations. Bjerkefors et al. (2009) measured trunk muscle activity from the erector spinae, trapezius, latissimus dorsi, and pectoralis major in a person with a complete thoracic SCI and an able-bodied individual during external perturbations. These perturbations were induced by displacing a belt connected to the seated participant, i.e., briefly pulling the participant. The descriptive findings revealed that the individual with SCI exhibited lower trunk muscle activity in comparison with the able-bodied participant, which is different from muscle activity obtained during dynamic movements, such as forward reaching described earlier (Potten et al., 1999). In addition, the muscle activity pattern differed: the SCI individual activated muscles that are not considered as postural muscles for postural stability, which might be a compensatory mechanism of postural control in response to the external perturbations (Bjerkefors et al., 2009).

In summary, changes in trunk muscle function following a SCI affects both static and dynamic balance, as well as postural control, which can be captured with EMG recordings and kinematics. The altered muscle activation patterns are task-dependent, with a greater involvement of the high-thoracic erector spinae during reaching tasks compared to able-individuals, and lower trunk muscle activity during perturbations compared to able-bodied individuals. In addition, individuals with SCI activate non-postural muscles during both tasks, possibly reflecting compensatory mechanisms to maintain posture.

1.3.3 Electrophysiology

In addition to the muscular changes in SCI, there are also indications of alterations in the corticospinal tracts, the neural pathways responsible for transmitting information between the cortex and the trunk muscles (Balbinot et al., 2022; Ellaway et al., 2007). The excitability of this pathway can be evaluated with transcranial magnetic stimulation (TMS), a technique that induces a magnetic current to stimulate a specific area of the brain, such as the primary motor cortex (M1). The responsiveness of the corticospinal pathways after TMS stimulation can be monitored using EMG by placing electrodes on the skin overlaying the muscle(s) of interest (Figure 1.2). Following TMS stimulation, the EMG signals demonstrate a characteristic peak and trough, called a motor evoked potential (MEP) and provide a way to examine the corticospinal excitability (Balbinot et al., 2022).

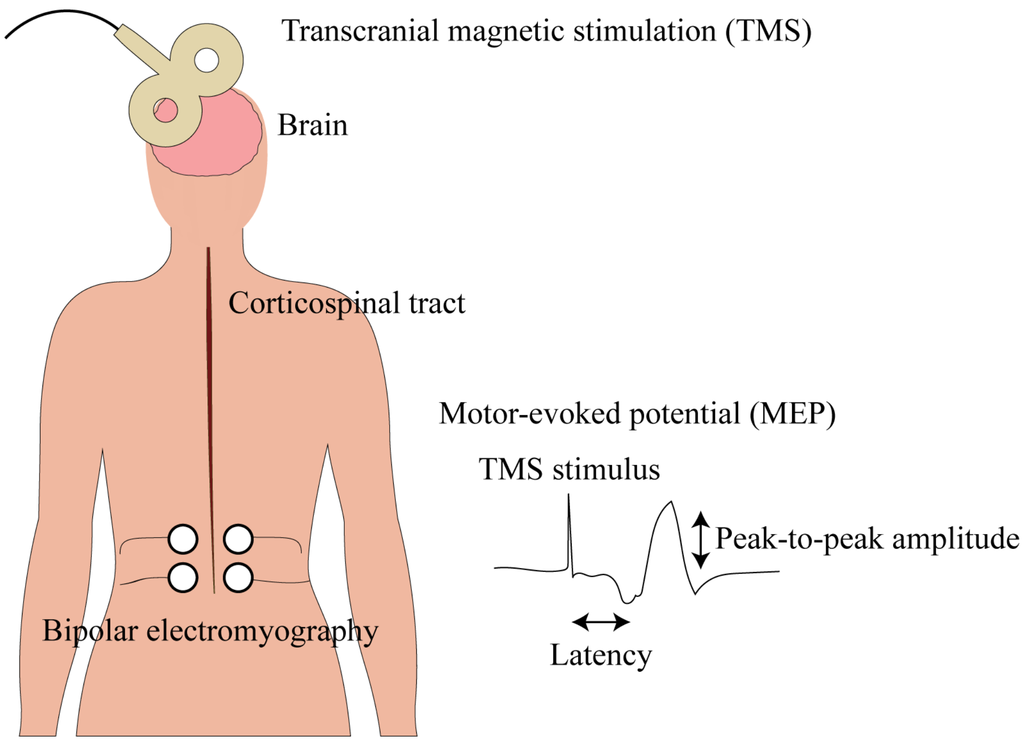

Figure 1.2. A setup using transcranial magnetic stimulation. A coil is placed over the head to stimulate an area of the primary motor cortex (M1) that activates the trunk muscles. The brain's output travels over the corticospinal tracts to the erector spinae and can be captured with EMG. The output, called a motor-evoked potential (MEP), typically demonstrates a trough followed by a peak and its magnitude is called a peak-to-peak amplitude.

Use of TMS-EMG methodologies with individuals who have a SCI show that they exhibit both reduced and delayed peak-to-peak MEP amplitudes in comparison to able-bodied controls, indicating damage in the descending corticospinal tracts responsible for transmitting the TMS-induced motor responses (Alexeeva et al., 1998; Curt & Ellaway, 2012; Smith et al., 2000). In addition, MEPs seem to be related to functional outcome. Curt et al. (1998) assessed the AIS motor and sensory scores in individuals with an acute SCI and individuals with a chronic SCI. The acute SCI group was assessed on two occasions: an initial examination and a six-month follow-up. MEPs were recorded from the tibialis anterior and quadriceps femoris. It was found that both the MEP and AIS scores were predictive of functional motor recovery (Curt et al., 1998). These findings, supported by other studies, present an innovative and promising approach to predict muscle function recovery (Levy et al., 1987; Petersen et al., 2012).

The relation between MEPs and the trunk muscles in SCI has been sparsely investigated. One study found that SCI individuals who exhibited increased MEPs during contralateral arm muscle contractions, a phenomenon known as crossed corticospinal facilitation, had better trunk control compared to SCI individuals who did not show increased MEPs during contralateral arm muscle contractions (Chiou & Strutton, 2020). Another study involving stroke survivors assessed the relation between the trunk control test, a clinical scale assessing trunk function, and MEPs (Fujiwara et al., 2001). MEPs were recorded from the external oblique muscles and the erector spinae in twenty stroke survivors. A relation was identified between trunk function recovery and the MEP amplitudes from the trunk muscles (Fujiwara et al., 2001). In summary, the neuromuscular and neurophysiological changes following SCI are apparent, and present opportunities for targeted rehabilitation to improve trunk function.

1.4 SCI rehabilitation

In the UK, people experiencing an acute traumatic SCI are initially transferred to either a trauma centre or specialised spinal cord injury centre for immediate care. If initially transported to a trauma centre, patients may later be transferred to a specialised spinal cord injury centre for further treatment after stabilisation. In England, there are eight of such specialised spinal cord injury centres (National Health Services, 2019; NHS Clinical Advisory Groups, 2011). After emergency care and a recovery period, multidisciplinary specialised rehabilitation starts. The rehabilitation aims to maximise functional capacity and involves the collaborative input of ward nurses, physiotherapists, occupational therapist, and psychologists (National Health Services, 2019). Upon completion of the rehabilitation period, the patient is prepared for a return to home and continues to receive ongoing physiotherapy in community settings.

However, several factors are currently stressing the national health services (NHS), resulting in shorter length of stay in the spinal cord injury centres, pressures on post-discharge follow-up, shortage in clinical workforce, and longer waiting lists for physiotherapy (Soopramanien et al., 2020; Yang et al., 2021). Moreover, visits to the physiotherapists are infrequent and further complicated by travel and the requirement of direct feedback from the physiotherapist on correct exercise execution. Indeed, even though the vast majority of SCI individuals recognise the importance of exercise for their functional recovery, more than half of them reported a lack of access to exercise facilities (Anderson, 2004). In addition, individuals living with SCI emphasize improving trunk control over other factors like sensation and chronic pain to improve their overall quality of life (Anderson, 2004). This leaves limited opportunity for trunk rehabilitation in the chronic phase of SCI upon arrival at home and a new approach to rehabilitation is needed to improve trunk function in the chronic stage of SCI.

1.5 Therapeutic interventions for improving trunk function

The main neuromuscular consequence on SCI is a loss of control over the muscles below the area of the injury. Conventional physiotherapy aims at improving trunk function by way of exercise, which include task-specific, upper-body, and whole-body exercise programmes.

1.5.1 Task-specific exercise

For instance, a six-week upright sitting exercise programme improved unsupported sitting in individuals with SCI (Boswell-Ruys et al., 2010). Conventional exercises were performed, including reaching and grasping exercises, and boxing. The upper body sway test and the maximal balance range test were the primary outcomes of interest. Participants improved in the outcome variables following the upright sitting exercise programme (Boswell-Ruys et al., 2010). Similarly, Betker et al. (2007) reported trunk improvements in two individuals with complete paraplegia following 12 exercise sessions consisting of game-based dynamic seated balance training, although the outcome measure, dynamic balance, was defined as whether individuals fell during the assessment while no quantifiable results have been reported (Betker et al., 2007). Kim et al. (2010) demonstrated improved reaching distance in the modified functional reach test and smaller sway area during a static balance task following four weeks of balance training on an unstable surface (Kim et al., 2010).

1.5.2 Upper-body and whole-body exercise

In addition to task-specific exercise, upper-body exercise and whole-body programmes also have been shown to be effective in improving trunk function, although with mixed results. For example, an eight-week community exercise programme consisting of a circuit training setting involving resistance- and cardio exercises for SCI improved reaching and quality of life, assessed with modified functional reach test and Life Satisfaction Questionnaire 9, respectively (Sliwinski et al., 2020). Bergmann et al. (2019) demonstrated improvements in dynamic sitting balance following a home-based six-week therapeutic exercise programme combined with functional electrical stimulation on the erector spinae and rectus abdominis. While the study reported that eight exercises were performed as part of the exercise programme, aimed at improving seated balance and posture, it did not specify which specific exercises were performed (Bergmann et al., 2019). Williams et al. (2020) reported improved static sitting balance with the eyes closed following a five-week arm cycling exercise programme in motor complete and incomplete SCI, albeit the static sitting balance with eyes open did not improve (Williams et al., 2020). Performing wheelchair Tai Chi for six weeks also improved static sitting balance (Qi et al., 2018). In addition to the improved static sitting balance, improvements were also found in the social, psychological, physical and environmental component of the World Health Organization's Quality of Life Instrument, suggesting a higher quality of life (Qi et al., 2018; Whoqol Group., 1995). Kayak training has been shown to improve static stability by having smaller displacements following external perturbations in individuals with a complete and incomplete injury (Bjerkefors et al., 2007; Grigorenko et al., 2004). However, wheelchair curling for four weeks does not increase reaching distance statistically, although subjective improvements in trunk control were reported. The subjective improvements in trunk control were assessed with an open question. However, it was not described how the data of the open question was analysed (Herzog et al., 2018).

Although many studies have demonstrated the effectiveness of exercise programmes on trunk function in chronic SCI, few have investigated the neuromuscular changes following an exercise programme. Including measures such as EMG could shed light on underlying mechanisms of the improvements. EMG has been increasingly used as an outcome measurement in treadmill exercise neurorehabilitation settings following SCI, but not many studies have specifically assessed changes in trunk muscle function (Alexander et al., 2009; Balbinot et al., 2022; Korupolu et al., 2019). One recent study assessed the effects of an eight-week pendulum and supported stand-sit exercise programme (two sessions per week) on trunk muscle function in individuals with a thoracic incomplete SCI (Frison et al., 2019). EMG activity was recorded from the internal and external obliques, rectus abdominis, and longissimus muscles during isometric trunk flexion and extension (Frison et al., 2019). Following the exercise programme, higher flexion and extension torques, as well as higher muscle activity in the rectus abdominis were reported.

In addition to the muscular changes, the changes in corticospinal excitability have also been investigated in SCI following exercise programmes, although scarcely. The changes in corticospinal excitability can be assessed by applying TMS over the primary motor cortex before and after an exercise intervention. Using the same TMS stimulus intensity after completion of the exercise intervention, an increase in its amplitude suggests an enhanced transmission of signals from the brain to the muscle of interest, demonstrating an greater responsiveness of the corticospinal pathways, i.e., increased corticospinal excitability (Field-Fote, 2009; Jo et al., 2020). In a study involving individuals with incomplete SCI reported increased MEPs in the leg muscles following a three-to-five-month treadmill exercise programme (Thomas & Gorassini, 2005). Jo & Perez (2020) reported effects of SCI groups performing either upper-limb exercises (arm cycling, gross and fine grasping) or lower-limb exercises (overground- and treadmill walking, and stair climbing), both combined with corticospinal-motor neuronal stimulation. Improvements were found in fine and gross motor skills, and walking. In addition, higher MEP amplitudes were observed following the exercise programme. Notably, no effects were found in the exercise-only group (Jo & Perez, 2020). Repetitive TMS stimulation can also increase the corticospinal excitability in individuals with SCI. Paradigms such as intermittent theta burst stimulation and Hebbian stimulation, the latter combined with exercise, have led to increased MEP amplitudes in individuals with SCI (Jo et al., 2023; Mittal et al., 2022).

1.6 Arm cycling: exercise with potential

Arm cycling exercise is a common exercise modality and considered suitable for individuals with SCI to improve cardiorespiratory outcomes (Chiou et al., 2022; Jacobs & Nash, 2004). In addition, arm cycling activates the trunk muscles during the exercise (Williams et al., 2020) and temporarily increases MEP amplitudes following 30 minutes of arm cycling (Chiou et al., 2020).

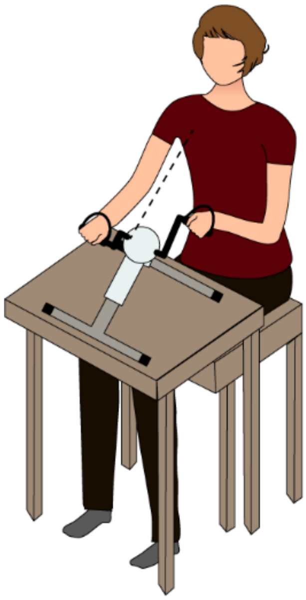

Figure 1.3. Arm cycling setup. The participant is seated on a flat, steady surface with sufficient distance from the arm bike so that the elbows are almost fully extended when the pedal is furthers away from the participant’s body. The arm bike is placed on a high enough surface, where the pedal axis matches the height of the shoulders. The trunk muscles are engaged whilst cycling in this position.

The underlying mechanisms that lead to increased MEP amplitudes are thought to reflect crossed corticospinal facilitation, which is the phenomenon wherein activating a certain muscle, such as the arm, can increase the MEP amplitudes in the contralateral muscle (Davey et al., 2002). This does not have to be the same muscle, as it has been found that activating the arm muscles can increase MEP size in the contralateral erector spinae (Chiou et al., 2018). It has been shown that the crossed corticospinal facilitation is preserved in some SCI individuals, and that the amount of facilitation is related to neurophysiological outcomes during postural and functional tasks (Chiou & Strutton, 2020). Assessing MEP amplitudes, or the corticospinal excitability, is an approach to investigate the neuroplasticity in the brain (Bashir et al., 2010; Pascual-Leone et al., 1998).

Arm cycling can be performed unsupervised and on a daily basis from home (Nightingale et al., 2018) and has the potential to circumvent existing NHS barriers, including stressors on follow-up after discharge, shortages of clinical staff, delays for accessing physiotherapy services, and a lack of access to exercise facilities. Performing the exercise from home removes the need for commuting, and the relatively simple exercise also reduces the need for considerable input from clinicians. Removing these pressures allows more time dedicated to the exercise. Hence, arm cycling exercise holds promise for improving trunk function in people with chronic SCI.

1.7 High-density surface electromyography

Use of conventional EMG is widespread to measure myoelectric activity in healthy and clinical populations, and the recordings unravel relevant spatial and temporal information (Campanini et al., 2022). However, the method has limitations. For example, the small electrodes have spatial constrains and measure muscle activity from a small region of the muscle (Drost et al., 2006). High-density surface electromyography is a technique that builds on traditional EMG by adding move channels to the electrode, creating a matrix of electrodes that can measure a larger portion of muscle activity compared to conventional EMG (Zwarts & Stegeman, 2003) (Fig. 1.4). This approach has the potential to unravel additional electromyographic properties in comparison to conventional EMG, such as the characteristics of motor units, muscle fibre conduction velocity, fatigue, and spatial properties of muscle activity (Drost et al., 2006). The technique has been applied in healthy individuals, but also in clinical populations such as low back pain and uncovered different patterns of erector spinae activity compared to healthy individuals (Balbinot et al., 2021). HDEMG provides reliable measures between sessions in assessing motor unit properties from lower limb muscles during an isometric knee extension task, HDEMG latency and amplitudes from lower limb muscles during perturbations in stroke survivors and healthy control participants, and the distribution of trunk muscle activity during an isometric fatiguing task (Gallina et al., 2016; Martinez-Valdes et al., 2016). With the superior spatial characteristic, the technique will be used throughout the studies in this thesis in both able-bodied individuals and people with SCI. Its reliability with electrodes placed on the erector spinae during functional tasks is investigated and reported in the first chapter.

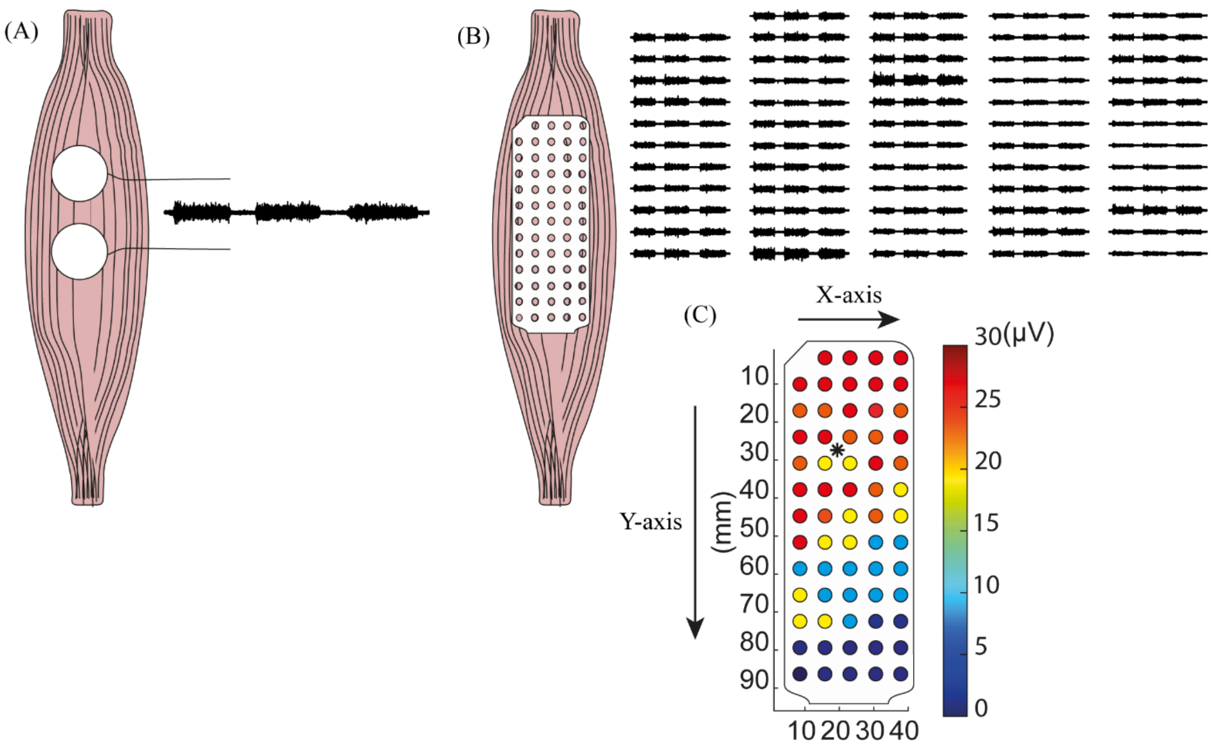

Figure 1.4. High-density surface electromyography. (A) Conventional bipolar surface electromyography can record activity from a local region of the muscle using two electrodes (bipolar) that are placed over the skin overlaying the muscle of interest. (B) High-density surface electromyography can record activity from a larger portion of the muscle using multiple channels that can record muscle activity. In this instance there are 64 channels that form a rectangular matrix. (C) An example of the electromyographic output shown in a map, with the activity of individual channels quantified as RMS amplitude (microvolt). The black asterisk in the channel matrix is the centroid, representing the central point of muscle activity considering all activity within the matrix. Its position can be located by calculating the distance along both the vertical (y-axis) and horizontal (x-axis) axes of the electrode matrix. The distance is calculated in millimetres. µV: microvolt, mm: millimetre.

1.8 Summary and research question

Electromyographic and neural changes in trunk function are apparent after SCI. Ongoing trunk rehabilitation is challenging once SCI individuals return home after hospital treatment due to current NHS challenges and the current approach to trunk rehabilitation. Arm cycling appears to be a suitable upper-body exercise that can be performed from home, removing the need to commute and to receive extensive feedback from clinical professionals. The effects of arm cycling on trunk function in people with chronic SCI is currently not known and it is of importance to investigate given the reduced posture and balance in persons with SCI. Therefore, the aim of this thesis is to investigate whether home-based arm cycling can improve trunk function in people with chronic SCI. To answer this research question, specific objectives are described below:

1. The first objective is to assess whether HDEMG provides reliable readouts from several parameters of the erector spinae muscles. To investigate this, a reliability study will be carried out with participants coming to the lab on two separate occasions to perform functional and postural tasks. The results will indicate whether the method is suitable to use for longitudinal studies to measure the possible changes in parameters of the erector spinae.
2. The second objective, after establishing the reliability of the HDEMG parameters, is to examine the neurophysiological differences between able-bodied individuals and people with chronic SCI during frequently used functional and postural tasks. The results will reveal the differences in trunk muscle characteristics between the two

groups. In addition, the results of the able-bodied group will provide a baseline for post-intervention function of the erector spinae muscles involving people with SCI.

3. The third objective is to assess the feasibility of a six-week home-based arm cycling exercise programme. In addition, the effects of the exercise programme on the neurophysiology of the trunk muscles in individuals with chronic SCI will be investigated. The results showed that a home-based exercise programme of six weeks is feasible for individual with chronic SCI. Furthermore, the exercise programme improved trunk function and increased corticospinal excitability.
4. The fourth objective is to perform a randomised controlled trial study to investigate the effects of eight weeks of arm cycling exercise combined with upper-body exercise and to compare the effects to conventional physiotherapy exercise in people with chronic SCI. The results demonstrated that performing eight weeks of home-based arm cycling exercise combined with upper-body exercise leads to further improvements in trunk function compared to six weeks. The results also revealed that both arm cycling and conventional physiotherapy exercise lead to improved trunk function.

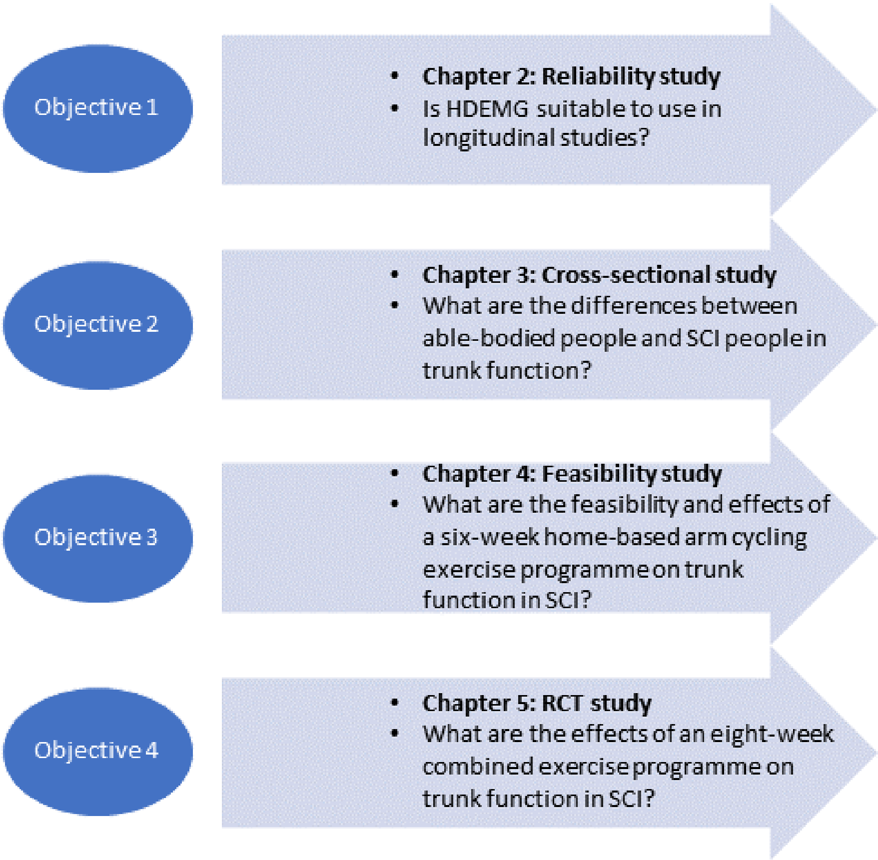

Figure 1.5. Flowchart of the objectives of the thesis. Each chapter addresses one of the objectives described above to ultimately address the main research question whether home-based arm cycling can improve trunk function in persons with chronic SCI.

2. Reliability of high-density surface electromyography in assessing characteristics for the thoracic erector spinae during static and dynamic tasks

Rationale

HDEMG will first be utilised in a reliability study to assess whether the method is suitable to use in longitudinal studies, e.g., to provide reliable readouts.

Van Helden, J. F. L., Martinez-Valdes, E., Strutton, P. H., Falla, D., & Chiou, S. Y. (2022). Reliability of high-density surface electromyography for assessing characteristics of the thoracic erector spinae during static and dynamic tasks. *Journal of Electromyography and Kinesiology*, *67*, 102703. https://doi.org/10.1016/j.jelekin.2022.102703

3. Changes in thoracic erector spinae regional activation during postural adjustments and functional reaching tasks after spinal cord injury

Rationale

With the reliability established of HDMEG parameters of the thoracic erector spinae during functional tasks and dynamic tasks, this chapter investigated the neurophysiological differences between able-bodied individuals and people with chronic SCI.

van Helden, J. F. L., Cabral, H. V., Alexander, E., Strutton, P. H., Martinez-Valdes, E., Falla, D., Chowdhury, J. R. & Chiou, S. Y. (submitted). Changes in thoracic erector spinae regional activation during postural adjustments and functional reaching tasks after spinal cord injury.

4. Home-based arm cycling exercise improves trunk control in persons with incomplete spinal cord injury: an observational study.

Rationale

In the previous chapter, differences in the erector spinae were identified between able-bodied people and individuals with SCI. The findings provide insight into the differences and how the erector spinae activity is distributed in non-injured people. The next chapter is an observational study to investigate the feasibility and effects of a six-week home-based arm cycling exercise programme on trunk function in people with chronic incomplete SCI.

van Helden, J. F. L., Alexander, E., Cabral, H. V., Strutton, P. H., Martinez-Valdes, E., Falla, D., Chowdhury, J. R. & Chiou, S. Y. (2023). Home-based arm cycling exercise improves trunk control in persons with incomplete spinal cord injury: an observational study. *Scientific Reports, 13,* 22129, 1-13. https://doi.org/10.1038/s41598-023-49053-w

5. Effects of a home-based core exercise training programme on trunk control in individuals with chronic spinal cord injury: an RCT study

Rationale

The previous chapter demonstrated that six weeks of home-based arm cycling is feasible. Although trunk improvements were also observed, the next chapter addresses whether extending the duration to eight weeks will lead to further improvements in the trunk. The other question is whether the home-based arm cycling is as effective as conventional physiotherapy exercise. In this chapter, a randomised controlled trial study was carried out to address these questions.

Abstract

Introduction: Current rehabilitation methods for improving trunk function in individuals with an incomplete spinal cord injury (SCI) are often complex and require regular trips to physiotherapy clinics, consuming a significant amount of time. Therefore, there is a need for innovative approaches to improve trunk function. Different rehabilitation methods are available, including task-oriented exercises that involve the repetition of specific tasks to improve, and a neuromodulation approach, where improvement occurs through cortical reorganisation. The study in chapter 4 has shown improvements in forward reaching abilities and voluntary control of the trunk muscles. However, it remains unknown to which extend the effects of arm cycling compare with that of conventional trunk exercise. In this randomised controlled trial study, we examined the effects of an eight-week trunk exercise programme including two groups: one group practicing arm cycling and one group engaging in upright sitting exercise. Both groups performed additional upper-body exercise videos. **Methods**: Seventeen individuals with an incomplete SCI were recruited. Participants were randomly allocated to the arm cycling group or the upright sitting group and performed the exercise 30 minutes per day, five times per week for eight weeks. Both groups additionally followed online upper-body exercise videos three times per week. Assessments took place before and after completing the exercise programme and involved performing seated multidirectional reach tasks and two postural tasks, namely the rapid shoulder flexion task and the external perturbation task. Trunk muscle activity was measured from the erector spinae using high-density surface electromyography (HDEMG) during the tasks from which the muscle activation and spatial distribution of activation were extrapolated. A motion capture system was used to record reflections of the markers placed on the wrists and trunk, and centre of pressure from the force plate participants were sitting on. Perspectives of the participants to the exercise protocol, clinical application of the home-based exercise, and received support during the exercise programme were explored in a focus group and data were analysed with a thematic analysis. **Results:** Due to the low sample size, descriptive analysis was performed. Eight of the seventeen individuals discontinued the exercise during the training programme. Of the remaining nine participants, adherence in the arm cycling group was 96.25% for the arm cycling and 93.75% for the upper-body exercise videos. In the upright sitting group, adherence was 95.5% for the upright sitting exercise and 96.88% for the upper-body exercise videos. During the postural tasks, greater trunk trajectories and earlier onsets of the erector

spinae and anterior deltoid in the rapid shoulder flexion task were observed in both groups at post-assessment. In addition, slightly greater reaching distance, and displacement of the trunk and centre of pressure were seen in both groups during the multidirectional reach tasks after training. Notably, the trunk activation and spatial distribution differed between the two groups. In the multidirectional reaching tasks, erector spinae activity was lower in the arm cycling group and accompanied by a centroid located more cranially following the exercise. Conversely, the erector spinae activity was larger in the upright sitting group, accompanied by a centroid located more caudally. This same activity pattern is observed in the external perturbation task, but in the rapid shoulder flexion task, erector spinae activity was lower in both groups while the centroid was not different in the arm cycling group and located more caudally in the upright sitting group. The qualitative component of the study reveals that the need for social support received from family and intrinsic motivation to perform the exercise were factors related to adherence to the exercise. **Conclusion:** Home-based arm cycling or upright sitting exercise, in combination with conventional upper-body exercises seem to have positive effects on trunk function in individuals with chronic SCI. The improvements in both groups were accompanied with distinct patterns in trunk muscle activity. Exercise compliance is moderate and future studies could explore the option to increase social support and intrinsic motivation to reduce dropout rates.

5.1 Introduction

Difficulties with controlling the trunk muscles is a common phenomenon after spinal cord injury (SCI). Such challenges may lead to postural instability that impacts daily activities, including self-care and sports (Altmann et al., 2017; Milosevic, Gagnon, et al., 2017; Milosevic et al., 2015; Noreau et al., 1993). Conventional rehabilitation aimed at improving trunk function includes, but is not limited to, sitting balance training (Kim et al., 2010; Tamburella et al., 2013; Unger, Chan, et al., 2019) reaching training (Choe et al., 2018), upper-body exercise (Bjerkefors et al., 2007; Herzog et al., 2018; Sung et al., 2015), and whole-body exercise (de Oliveira et al., 2019; Galea et al., 2018; Tsai et al., 2021). However, carrying out such training is often complex as it requires individuals to commute to a physical exercise clinic and needs substantial input from professionals to ensure the exercises being performed correctly. These prerequisites pose significant barriers for the individuals with SCI to receive continuing rehabilitation after discharge from the hospital. Hence, innovative rehabilitation strategies are needed to improve trunk function in individuals with a chronic SCI.

Rehabilitation strategies that may lead to improved trunk function include the process of re-learning specific tasks, often referred to as task-oriented exercise (Bayona et al., 2005; Jeon et al., 2015; Rensink et al., 2009; Stein et al., 2008). Although a clear definition is lacking in the literature, task-oriented exercise generally involves practicing specific tasks repeatedly. For example, previous studies have assessed the effectiveness of seated balance training on trunk function and reported improvements in static and dynamic balance in SCI and stroke (Betker et al., 2007; Boswell-Ruys et al., 2010; Kim et al., 2010). It has been suggested that the mechanism underlying the functional improvements consists of directly engaging the corticospinal tract, a descending motor pathway that mediates the voluntary movements (Fouad & Tetzlaff, 2012). For example, reaching was improved following six weeks of reaching training in rats that was accompanied with sprouting of the injured corticospinal tracts (Girgis et al., 2007).

Conversely, others have suggested a neuromodulation approach, where the desired task is learned in an alternative way by recruiting spared pathways as a result of cortical reorganisation (Christiansen & Perez, 2018; Filli & Schwab, 2015; Long et al., 2017; Matthews et al., 2004; Moxon et al., 2014). The neuromodulation approach may involve distinct underlying mechanisms by targeting spared pathways. For example, functional relations between the trunk and arm muscles exist during reaching, wherein the trunk acts as a stabiliser while the arms extend toward their target, and this functional interplay between the trunk and arms is even more pronounced when the target is placed at the maximum reaching distance, giving the trunk a more integrated role to support the arm in reaching the target (Kaminski et al., 1995). On a neurophysiological level, contracting the arm muscles induces an increase in corticospinal excitability within the contralateral uncontracted muscle (Chiou et al., 2018) and these interactions appear to be present in individuals with SCI (Chiou & Strutton, 2020). Furthermore, there seems to be a positive relation between corticospinal excitability and functional outcome, with higher motor evoked potentials (MEPs) reflecting higher trunk control during a rapid shoulder flexion task and reaching task (Chiou & Strutton, 2020). Further interactions are also observed between these modalities and can prime each other, as modulation of the corticospinal excitability influences the motor output and vice versa. For example, increased hand motor output in SCI was observed after repeated stimulation (Long et al., 2017). Moreover, increased MEPs were found after 30 minutes of arm cycling in able-bodied individuals, with the effects lasting for up to 20 minutes after the arm cycling was completed (Chiou et al., 2020). This priming effect is also observed on a functional level, as performing physical exercise a few days prior to competition improves neuromuscular performance (Harrison et al., 2020).

Arm cycling primarily engages upper limb muscles including the biceps brachii, triceps brachii, and to a lesser extend the trunk muscles, and is found to be suitable for improving cardiorespiratory fitness and seated balance (Chaytor et al., 2020; Chiou et al., 2022; Williams et al., 2020). Moreover, due to the interactions between the arms and trunk, it may improve trunk function indirectly by targeting spared corticospinal tracts. Chapter 4 reported increased corticospinal excitability, higher reaching distance and higher total trajectory of the centre of pressure during a seated forward reaching task, and a higher total trajectory of the trunk and higher trunk muscle activity during a self-initiated perturbation task after a six-week home-based arm cycling exercise programme in individuals with SCI.

However, certain questions have emerged from the findings in Chapter 4. For example, improvements in trunk function were small and inconsistent. While there is currently no consensus on the recommended exercise duration, a duration of six weeks appears to be the lower threshold among exercise studies in SCI (Chiou et al., 2022; Hicks et al., 2011). In addition, a review study on stroke rehabilitation revealed more substantial trunk performance improvements in a study that implemented eight weeks of trunk exercise compared to studies with a lower exercise duration (Cabanas-Valdes et al., 2013). Therefore, the question remains whether a longer duration leads to greater and more consistent improvements in trunk function. In addition, Chapter 4 included one arm cycling group and did not include a SCI group performing conventional exercise. The second question is whether home-based arm cycling is equal to or potentially superior to conventional home-based trunk exercise to improve trunk function in individuals with SCI.

We therefore assessed the effects of an eight-week home-based trunk exercise programme on trunk function during postural tasks and functional reach tasks. We compared two groups, an arm cycling group, that may improve trunk function by exercising the muscles indirectly (neuromodulation approach), and an upright sitting group, that might improve trunk function via a task-oriented approach. Both groups additionally underwent conventional therapeutic exercise training for trunk control that may act as priming exercise to facilitate the arm cycling and upright sitting exercise. We hypothesised that both groups improve trunk function, and that the arm cycling group may demonstrate greater improvements compared to the upright sitting group by combining a neuromodulation approach to target spared corticospinal tracts with conventional upper-body exercise.

5.2 Methods

5.2.1 Participants

Seventeen individuals with a chronic cervical or thoracic SCI were initially enrolled for the present randomised controlled trial (RCT) study, recruited between March 2022 and September 2023. Recruitment is still in progress to reach a total of 30 participants. Individuals were recruited from the Midland Centre for Spinal Injuries at the Robert Jones and Agnes Hunt Orthopaedic Hospital in the United Kingdom, as well as via the social media channels of relevant associations and charities affiliated with SCI. Inclusion criteria were as follow: 1) minimum of one year since sustaining the injury, 2) the ability to voluntarily move the arms, 3) capacity to sit independently without backrest support, 4) some residual muscle function in the trunk, and 5) being at least 16 years of age. During the recruitment process of a previous unpublished study, we recognised that individuals with an injury lower than T6 could also encounter difficulties with trunk functioning. The criteria regarding the level of injury were therefore extended to include individuals with a C1 – T12 injury, according to the International Standards for Neurological Classification of Spinal Cord Injury. Notably, no American Spinal Cord Injury Impairment Scale (AIS) criteria were included as in the previous chapter (4), it was observed that participants with a complete injury demonstrated trunk muscle activity during arm cycling exercise and perturbations, which is in line with the findings of previous studies (Bjerkefors et al., 2009; Williams et al., 2020). Furthermore, the AIS assessments lacks an evaluation of trunk motor function and hence, individuals with an AIS A-D were included as they may benefit from the exercise to improve trunk function (Rupp et al., 2021). The Health Research Authority West Midlands - Edgbaston Research Ethics Committee granted the ethics (21/WM/0047). Participants gave their written informed consent and the study adhered to the ethical principles for medical research, stated in the Declaration of Helsinki. Participants were assessed in the laboratories located on the campus of the University of Birmingham.

5.2.2 Procedure and exercise training programme

Enrolled participants were randomly allocated into the arm cycling exercise group or upright sitting exercise group (Fig. 5.1). A minimisation randomisation approach was utilised, based on the AIS score, using Sealed Envelope Ltd 2022 (Sealed Envelope Ltd, 2022). The experimenters and participants were aware of the specific group assignments. All data processing and analyses were performed by the same experimenter. The unsupported upright sitting exercise was chosen as it is a common type of conventional physiotherapy exercise (Burns et al., 2017). Participants in the arm cycling group were provided with an arm bike (Pedal Exerciser with Digital Display, NRS Healthcare, Coalville, UK) for home-based exercise. Instructions were given to place the arm bike on a flat, stable surface with the axis of the pedals at shoulder height, and to keep pedalling at 60 rotations per minute from an upright seated position without back support to engage the trunk muscles. Exercise intensity was kept at level four, corresponding to ‘somewhat hard’ on the modified CR-10 Borg Scale (Borg, 1998). To ensure a constant exercise intensity throughout the programme, the resistance of the arm bike was increased by adjusting a handle located on the rear of the arm bike if they perceived the exercise as being less than ‘somewhat hard’. Participants in the upright sitting group were asked to sit on a flat, stable surface without back support and to place the feet on the floor. From this position, participants were instructed to keep an upright posture to engage the trunk muscles and gradually release the hands to challenge trunk balance. Both groups carried out the exercise five times 30 minutes per week for the duration of eight weeks.

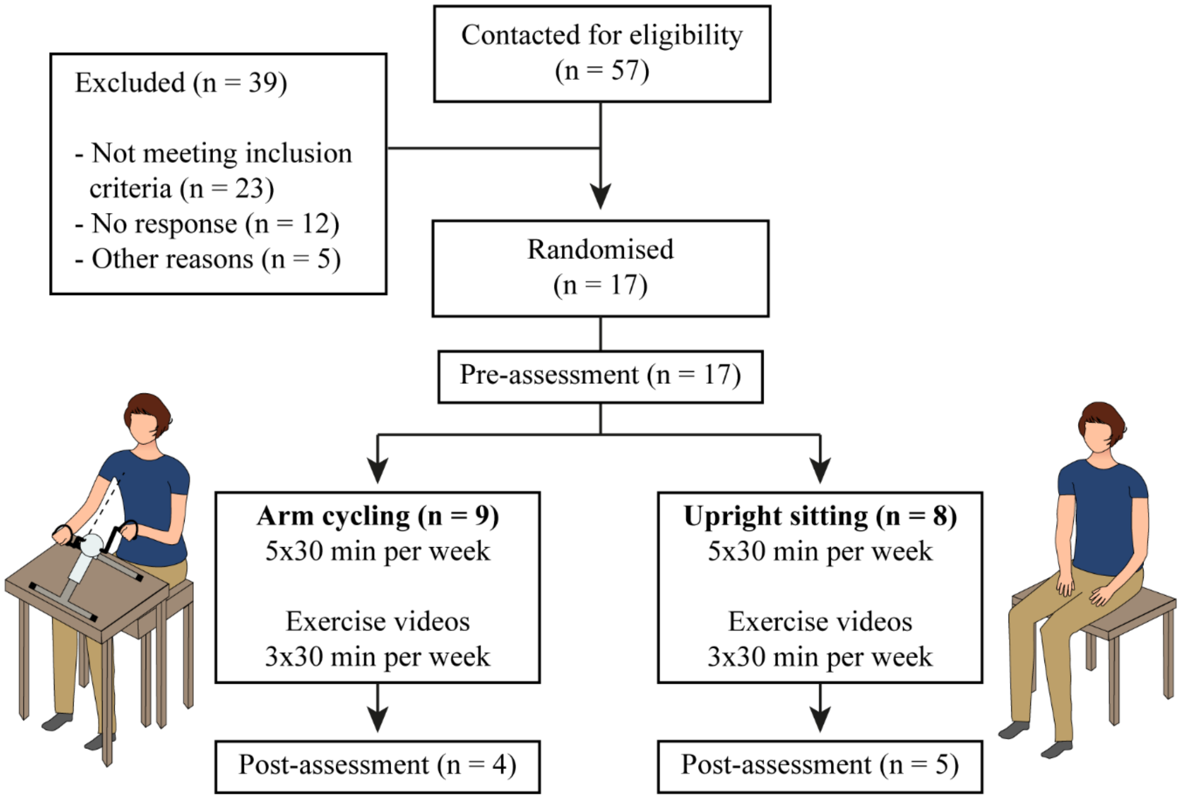

Figure 5.1. Study flowchart. Individuals were randomly allocated to the arm cycling group (left) or upright sitting group (right) using a minimisation randomisation approach. Both groups performed the exercise five times thirty minutes per week for eight weeks, with additional online upper-body exercise videos three times 30 minutes per week. Participants were assessed before starting the exercise programme and returned to the laboratories after they completed the eight weeks of home-based exercise.

In addition to the group-specific exercise, both groups engaged in online upper-body exercise videos three times per week, accessible at https://www.youtube.com/@joerivanhelden2218/videos. A new video was available for each of the eight weeks and increased progressively in exercise intensity. The exercises in the videos targeted the trunk muscles and the cardiovascular system, and consisted of a range of conventional trunk exercises, including a warming up, boxing, coordination and stability exercises, and stretching. Participants documented their exercise progress on provided sheets and were contacted bi-weekly by the researcher to assess exercise progression. In cases where participants were interrupted during the exercise programme, for example due to injury or other complications, they were asked to first regain their exercise level before they stopped the exercise before continuing logging the exercise sessions. Upon completion of the eight-week exercise training programme, participants returned to the laboratories within one week and were asked to continue with the exercise up until the day before the day of the post-assessment.

5.2.3 Assessment

Participants visited the laboratory before and after the trunk exercise training programme to perform multidirectional reaching tasks in the sagittal plane (forward reaching) and coronal plane (lateral reaching), the rapid shoulder flexion task, and the external perturbation task from a seated position on a chair with a force plate on top. The chair had no back support, the hips and knees were positioned in a 90-degree angle, and the feet were placed flat on the floor (Fig. 5.2). A support block was provided if the feet were not able to reach the floor. Participants gave an estimation of their height and weight.

In the multidirectional reaching tasks, participants first raised their least affected arm in the sagittal plane (forward reaching) or their left/right arm in the coronal plane (lateral reaching). From this starting position, participants then reached as far as possible whilst maintaining trunk balance before returning to the starting position (Fig. 5.2). The other hand remained on their lap and did not contribute with the movement. In the rapid shoulder flexion task, a red light-emitting diode (LED; visual stimulus) was affixed to a height-adjustable tripod, located at a one metre distance from the participant's eye level (Fig. 5.2B left). Seated with both arms on the sides of the force plate, participants initiated rapid shoulder flexion movements by flexing bilateral shoulder muscles with extended arms as quickly as possible in response to the visual stimulus. In the external perturbation task, participants were asked to extend their least affected arm at shoulder height and maintain this position throughout the task. Perturbations were induced by releasing a hollow tube containing circular weights placed inside the tube, matching 5% of the participant's body mass, from a 45-degree angle. The tube was released within one second following a verbal cue from the experimenter (Fig. 5.2B right). Padding and an accelerometer were attached to the tube to prevent discomfort during impact and to identify the moment of perturbation, respectively. Five repetitions were performed in all tasks.

High-density surface electromyography (HDEMG). To acquire myoelectric data, two electrode grids (GR08MM1305, OT Bioelettronica, Turin, Italy) were positioned on the skin overlaying bilateral erector spinae muscles. The electrode grid was organised in 13 rows of channels by 5 columns of channels with an eight-millimetre interelectrode distance. The channel's diameter was 1mm. A perforated foam layer was attached to the electrode grid, and conductive paste (AC Cream, Spes Medica, Genoa, Italy) was evenly distributed over the perforated foam layer to fill its cavities. To obtain HDEMG recordings with optimal signal-to-noise ratio and low skin impedance, the participant's skin around the area where the electrode would be placed was carefully prepared by gently removing hairs with razors, abrading the skin with gel (Nuprep Skin Prep Gel, Weaver and Company, CO, USA), and cleaned with alcohol skin wipes (GAMA Healthcare, Hertfordshire, UK). The spine of the participant was then palpated to locate the 12th thoracic spinous process (T12) and bilateral reference markings were placed two centimetres lateral to T12. The bottom row of the electrode grid's channels was placed on this reference mark in a vertical orientation, ensuring parallel alignment with the spine (Fig. 5.2C). To ensure placing the electrodes was performed consistently on the same participant between pre- and post-assessments, the space between anatomical features such as scars and birthmarks to the electrode grid was measured in the pre-assessment and used as guidance in the post-assessment. Pre-amplifier ground electrodes were placed over the skin of bilateral iliac crest and the amplifier ground electrode was placed over the skin of the 7th cervical spinous process. All electrodes were connected to a bioelectrical signal amplifier (Quattrocento, OT Bioelettronica, Turin, Italy) with incoming data sampled at 2048Hz, a 150-amplification gain applied, and bandpass filtered at 10-500Hz using the amplifier's 16bits analogue-to-digital converter. OTBioLab+ was used for data recordings.

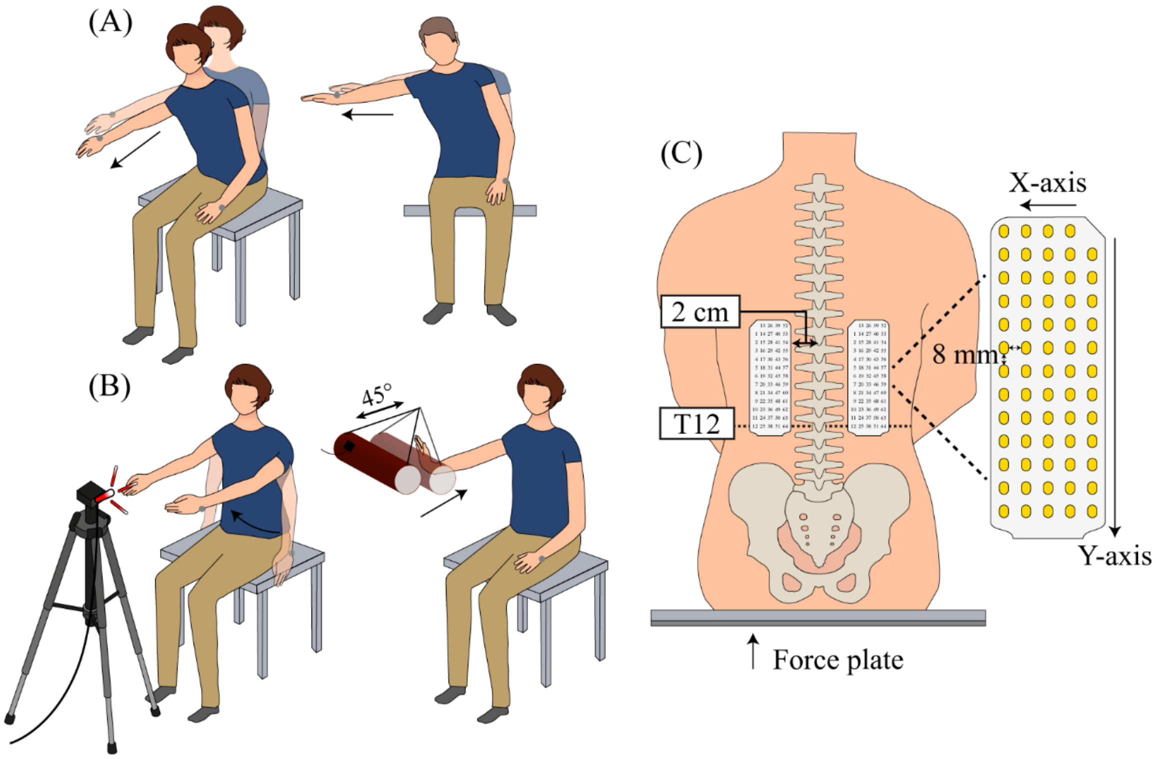

Figure 5.2. Tasks and electrode grid placement. Participants performed multidirectional reaching tasks in the forward direction (A left) and lateral directions (A right), and two postural tasks, namely rapid shoulder flexion (B left) and the external perturbation task (B right) from a seated position. (C) The bottom row of the electrode grids were placed at bilateral reference points, two centimetres lateral from the 12th thoracic spinous process, while ensuring that the top of the electrode grids were also placed two centimetres from the spine.

Kinematics. To collect movement of the trunk and arms, three reflective markers were positioned over the skin of the first thoracic spinous process and bilateral ulnar styloid processes. An infrared motion capture system (Smart DX 6000, BTS Bioengineering Corp, Quincy, MA, USA) recorded the marker's reflections at 250Hz. Seated centre of pressure was recorded with a force plate (BTS P6000, BTS Bioengineering Corp, Quincy, MA, USA), also sampled at 250Hz. BTS Bioengineering Corp software was used to record data. A transistor switch was connected to both the EMG bioelectrical signal amplifier and the BTS system and was used during the data collection to indicate when a repetition started and ended in each task and for offline data alignment.

Trunk impairment scale. The Trunk Impairment Scale (TIS; supplementary materials 8.7) is a clinical scale to examine trunk motor impairment following stroke or multiple sclerosis (Verheyden et al., 2004; Verheyden et al., 2006). The tool assesses static and dynamic sitting balance, and trunk coordination from a seated position, with its score ranging from 0 to 23. A lower score indicates a higher trunk impairment and has a test–retest reliability of 0.96, interobserver reliability of 0.99, and an adequate validity (Verheyden et al., 2004). The TIS was used to complement the HDEMG and functional data.

5.2.4 Qualitative study

Participants who had previously taken part in either the arm cycling group of the current study or a previous arm cycling exercise study consisting of six weeks of arm cycling, five 30-minute sessions per week (Chapter 4), were invited to attend an online focus group. A qualitative approach was chosen to gather insight into the acceptability and feasibility of the exercise format, and to further improve the programme for future studies. Three individuals expressed their interest to participate in the online focus group. A semi-structured interview format was chosen to obtain targeted information while allowing open discussions. The one-hour focus group was conducted using Zoom, which is found to be a suitable online videoconferencing platform to collect qualitative data, with audio recording enabled for subsequent offline data transcription (Archibald et al., 2019). Thirteen questions were being asked after the introduction, covering three themes of interest: 1) the home-based arm cycling exercise protocol, 2) the clinical applications of home-based exercise, and 3) the support received during the exercise programme (Supplementary materials 1).

5.2.5 Data processing and analysis

All data processing was performed in MATLAB R2021a (Mathworks, Natic, MA, USA). The first step was applying a second-order bandpass digital Butterworth filter with a range of 20–350Hz. Repetitions of the tasks were then identified based on the peak signals obtained from data of the transistor switch. The dataset subsequently followed two rounds of visual screening. In the first visual screening, noisy channels or channels containing artefacts were interpolated with data from neighbouring channels using a predefined criterium: at least two good-quality channels were required from the row adjacent to the noisy channel, and at least one good-quality channel in the same column (the channel above or below the noisy channel) was required in order to perform the interpolation. In the second visual screening, differential signals were generated by computing the difference between adjacent monopolar channels along rows. This produced a 12-row by 5-column grid matrix, with one channel absent in the top-left corner of the grid. During this stage, noisy channels were removed from the grid matrix. This included channels for which the criterium in the first visual screening could not be applied. In total, 4.72% of the channels were removed.

A grid matrix was then generated for each repetition, obtained as the root mean square (RMS) values of the differential channels. Then, the maximum RMS value within the grid matrix was determined and any channels with RMS values lower than 70% of this maximum RMS value were excluded to improve the sensitivity to regional activity (Vieira et al., 2010). Two parameters were derived from the remaining 30% of channels: an average RMS amplitude and the y-axis of the centroid. The y-axis of the centroid represents the centre of the distribution of RMS values and its position can shift along the cranial-caudal axis, depending on the variations in topographic muscle activity.

Multidirectional reaching tasks. The multidirectional reaching tasks were separated into two phases: a reaching phase (starting position to farthest reaching point) and a returning phase (farthest reaching point back to starting position). Analysis was performed on the electrode grid opposite to the reaching arm in forward reaching, e.g., when the participant used the right arm to reach forward, the electrode grid on the left erector spinae was analysed. In lateral reaching, the direction to which participants were able to reach further (left of right direction) was considered for analysis, with again the electrode grid opposite to the reaching arm considered for analysis. For example, when the participant used the left arm to reach, the electrode grid on the right erector spinae was analysed.

Rapid shoulder flexion. The electromyographic onset of the anterior deltoid and erector spinae were visually identified. This involved plotting the rectified EMG signals, accompanied by a horizontal reference line set at three times the standard deviation multiplied by the mean baseline EMG activity. The mean baseline was calculated from a 100-millisecond window preceding the visual stimulus (Hodges & Bui, 1996). The EMG onset was then identified as the moment when the rectified EMG signal intersected the horizontal reference line. The calculated onset from the erector spinae was then used for the anticipatory postural adjustments (APA) window (Tsao et al., 2009). This window consisted of the onset of the erector spinae, plus 50 milliseconds. The shoulder flexion window was calculated from the onset of the wrist movement on the least affected arm to the highest point in the wrist marker's vertical plane. The wrist movement onset, i.e., reaction time, was defined as the moment when the wrist marker crossed a predefined horizontal reference line, calculated as the baseline of 500ms prior to the visual stimulus plus three standard deviations (Abboud et al., 2018). To identify APA onset delays, the absolute values from the difference between the ES and anterior deltoid were calculated.

External perturbation task. The perturbation moment was identified from a large peak in the accelerometer data. Using this point of impact, APAs were calculated from a -100 to +50ms analysis window, and compensatory postural adjustments (CPAs) were calculated from a +50 to +200ms analysis window (Kaewmanee et al., 2020).

Kinematics. The kinematic parameter maximal displacement was calculated from the trunk and wrist markers and from the centre of pressure as the distance between the minimal and maximal points. Forward-backward movements were used for the forward reaching task, rapid shoulder flexion task, and the external perturbation task. For lateral reaching, the left-right movements were used to calculate the maximal displacement. The total trajectory was calculated from these movements as the absolute difference between subsequent timepoints. The HDEMG and kinematic parameters were summarised by taking the average values from the task's repetitions.

Qualitative study. The audio recordings were transcribed offline. A thematic analysis was then conducted on the transcribed data using NVivo 14. An inductive approach was chosen, followed by coding and categorising relevant semantic themes within the data (Braun et al., 2016).

5.2.6 Statistical analysis

IBM SPSS Statistics (Version 29) was used to perform analysis. Due to the low sample size and therefore a lack of sufficient power in the current ongoing study with nine participants having pre- and post-data, results are reported descriptively without statistical analyses applied. The percentage change is reported in-text, calculated as post-pre/pre values. Raw values are displayed in the figures and the mean and standard deviations (SD) are reported in Table 5.2, 5.3, and 5.4.

5.3 Results

After contacting individuals for participation in the study, 23 of those did not meet the criteria due to a low level of injury (T9-L4), no difficulties with trunk control, or not able to sit independently. Of the seventeen enrolled participants, eight participants did not continue with the exercise programme due to personal reasons (2), pectoralis tendon injury unrelated to the study (1), medical reasons (2), or non-specific challenges in life that made it difficult to continue with exercising (3). Nine participants completed the core exercise programme (age 52.8 ± 15.6 years; seven males; two AIS A, two AIS B, two AIS C, three AIS D; level of injury C2 – T7; 7.7 ± 6.4 years since injury). Of the nine participants, four participants were enrolled in the arm cycling group (age 55.5 ± 5.3 years; two males; one AIS A, two AIS C, one AIS D; level of injury C2 – T7; 8.8 ± 8.4 years since injury), and five participants were enrolled in the upright sitting group (age 50.6 ± 21.3 years; five males; one AIS A, two AIS B, two AIS D; level of injury C4 – T7; 6.8 ± 5.3 years since injury). Demographics of all the recruited participants are displayed in Table 5.1. One participant who was initially placed in the arm cycling group switched to the upright sitting group. The decision was made after the participant mentioned to have blood in the urine after the arm cycling exercise. One participant in the arm cycling group was an extreme outlier in all normalised RMS results and is therefore removed from the RMS analyses. This was possibly due to a low baseline RMS (2.27 μV) combined with a low body mass index (BMI; 20.3), leading to high normalised RMS results (Nordander et al., 2003).

Table 5.1. Demographics of enrolled SCI participants.

ID	Sex	Age (years)	AIS score	LoI	TSI (years)	Intervention	Completed sessions (40) (completed videos, 24)	BMI
P01	F	52	D	C6-7	1	Arm cycling	36 (18)	25.6
P02	M	50	D	C4	15	Upright sitting	40 (24)	29.5
P03	M	53	B	C5-6	7	Upright sitting	-	21.5
P04	F	36	B	C6-7	2	Arm cycling	-	22.3
P05	M	60	C	C2-3	2	Arm cycling	40 (24)	27.8
P06	M	48	A	T7	6	Upright sitting	40 (24)	25.1

P07	M	60	A	T7	17	Arm cycling	38 (24)	30.1
P08	M	32	A	T7-8	0.5	Arm cycling	-	26.6
P09	M	59	B	C5-6	36	Arm cycling	-	23.8
P10	F	59	C	T6	5	Arm cycling	-	21.1
P11	F	31	A	T4-5	20	Upright sitting	-	20.8
P12	M	69	D	C4	8	Upright sitting	40 (24)	28.4
P13	F	43	A	T7	12	Upright sitting	-	28.5
P14	M	17	B	C5	1	Upright sitting	33 (21)	24.0
P15	M	69	B	C4-5	4	Upright sitting	38 (3)	20.2
P16	M	68	C	C3-4	22	Arm cycling	-	32.8
P17	F	50	C	C5-6	15	Arm cycling	40 (24)	20.3

AIS: the American Spinal Injury Association Impairment Scale, F: female, M: male, C: cervical, T: thoracic, LoI: level of injury, TSI: time since injury. Number of expected completed sessions is 40, and number of expected completed videos is 24.

5.3.1 Exercise compliance

Exercise adherence in the arm cycling group was 96.25% for the arm cycling exercise, and 93.75% for the upper-body exercise videos. In the upright sitting group, exercise adherence was 95.5% for the upright sitting exercise, and 80% for the upper-body exercise videos. The lower percentage of the upper-body exercise videos in the upright sitting group was due to one participant not being able to continue with the upper-body exercise videos after two weeks. Exercise adherence is 96.88% if this participant is excluded.

Common reported adverse effects in the arm cycling group were manageable stiffness/pain in the shoulders, arms, neck, or back related to the arm cycling (3), although in two out of three participants the stiffness/pain was reduced after three weeks of exercise. The majority of participants increased the intensity of the arm cycling exercise after the first three weeks by increasing the resistance of the arm bike. No adverse effects were reported in the upright sitting group.

5.3.2 High-density EMG outcomes

The details including mean and standard deviation (SD) of the HDEMG results are presented in Table 5.2. The details including mean and SD of the functional results are displayed in Table 5.3, and the details including mean and SD of the Trunk Impairment Scale (TIS) are reported in Table 5.4. The results of the left and right side (HDEMG and motion) in the rapid shoulder flexion task did not differ and are averaged together.

In the anterior deltoid onset during the rapid shoulder flexion task, three participants improved in the arm cycling group (19.3% change) and four participants improved in the upright sitting group (14% change) by having shorter deltoid onsets (Fig. 5.3). In the erector spinae onset, three participants in the arm cycling group had shorter erector spinae onsets (23.6% change) and four participants in the upright sitting group had shorter erector spinae onsets (14% change). In the difference between the erector spinae and anterior deltoid onsets, two participants in the arm cycling group had a smaller difference (78.9% change), and two participants in the upright sitting group had a smaller difference (33.6% change).

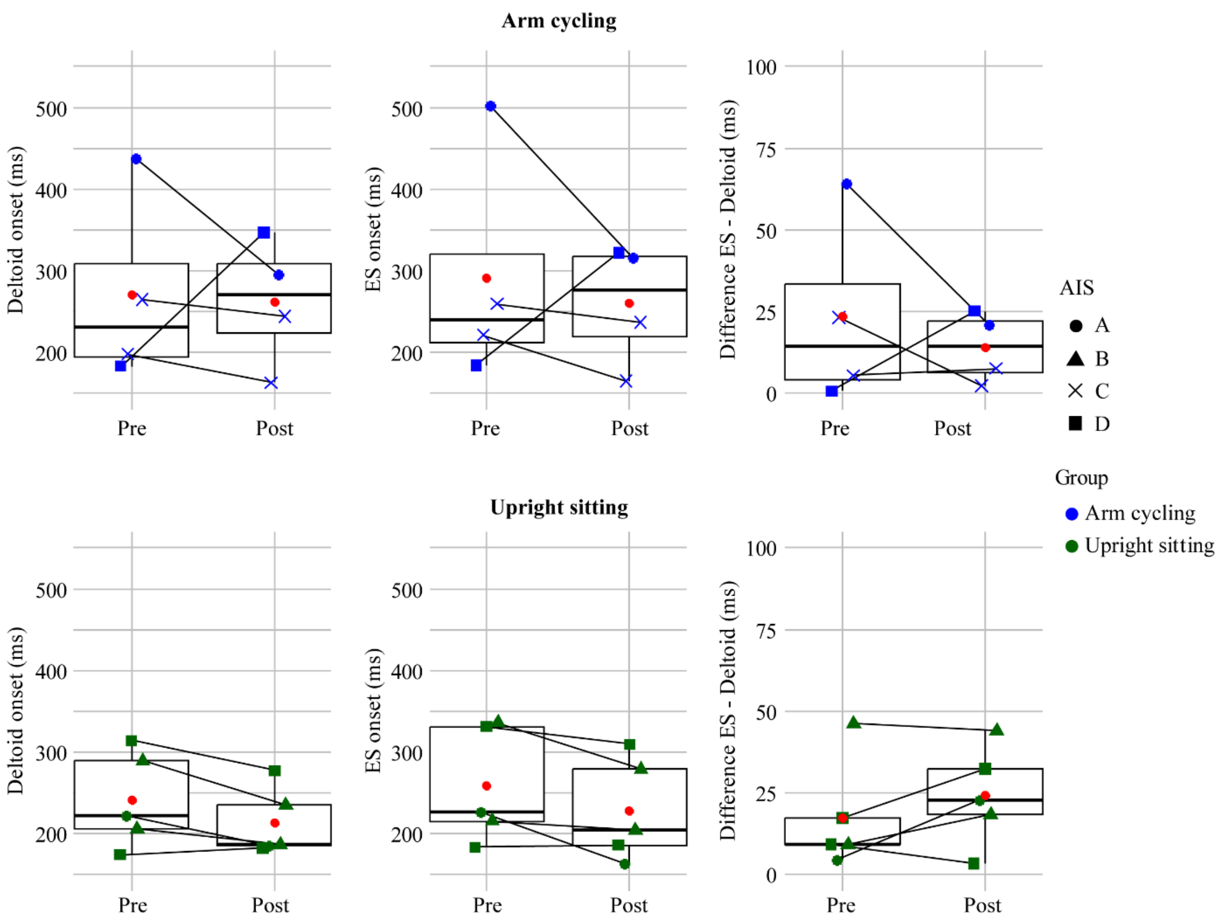

Figure 5.3. Onset results. The rapid shoulder flexion onsets in the arm cycling group (top) and upright sitting group (bottom), including the onset of the anterior deltoid (left), onset of the erector spinae (centre), and the difference between the erector spinae and anterior deltoid (right). The median is represented as a thin horizontal line located in each box. The hinges of the box correspond to the first quartile (25th percentile) and the third quartile (75th percentile). The vertical lines above and below the hinges of the box, i.e., whiskers, extend to the interquartile range multiplied by 1.5. The mean is displayed as a red dot. AIS: American spinal injury association impairment scale, ES: erector spinae, ms: milliseconds.

In the shoulder flexion window of the rapid shoulder flexion task, three out of three participants had a lower RMS (23.6% change) in the arm cycling group, while two participants in the upright sitting group had a lower RMS (42.2% change; Fig. 5.4). In addition, one participant in the arm cycling group (28.1% change) and two participants in the upright sitting group (13.4% change) had a y-axis centroid that shifted more cranially in the post-assessment. In the APA window, three out of three participants had a lower RMS in the arm cycling group (14.4% change), while three participants in the upright sitting group had a lower RMS (12.8% change). In addition, two participants in the arm cycling group (8% change) and one participant in the upright sitting group (27.6% change) had a y-axis centroid that shifted more cranially in the post-assessment.

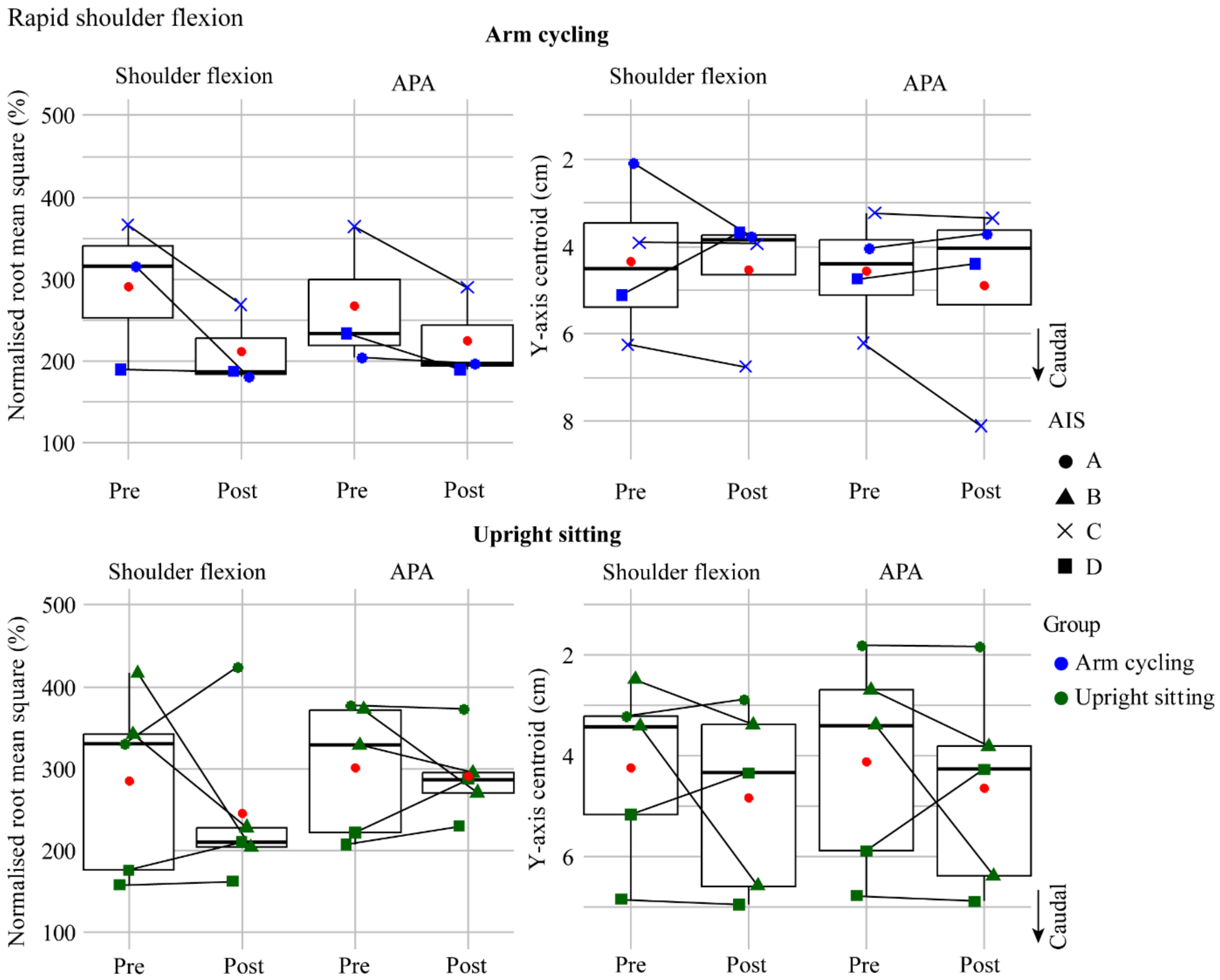

Figure 5.4. HDEMG results in the rapid shoulder flexion task. The results are shown for the arm cycling group (top) and upright sitting group (bottom). Two analysis windows were used, namely the shoulder flexion window (left) and the APA window (right). The median is represented as a thin horizontal line located in each box. The hinges of the box correspond to the first quartile (25th percentile) and the third quartile (75th percentile). The vertical lines above and below the hinges of the box, i.e., whiskers, extend to the interquartile range multiplied by 1.5. The mean is displayed as a red dot. AIS: American spinal injury association impairment scale, APA: anticipatory postural adjustments, cm: centimetres.

In the APA window of the external perturbation task, three out of three participants had a lower RMS in the arm cycling group (17.3% change), while none of the participants in the upright sitting group had a lower RMS (Fig. 5.5). In addition, one participant in the arm cycling group (34.8% change) and one participant in the upright sitting group (2.8% change) had a y-axis centroid that shifted more cranially in the post-assessment. In the CPA window, two out of three participants had a lower RMS in the arm cycling group (26.2% change), while none of the participants in the upright sitting group had a lower RMS. In addition, two participants in the arm cycling group (27.9% change) and two participants in the upright sitting group (17.1% change) had a y-axis centroid that shifted more cranially in the post-assessment.

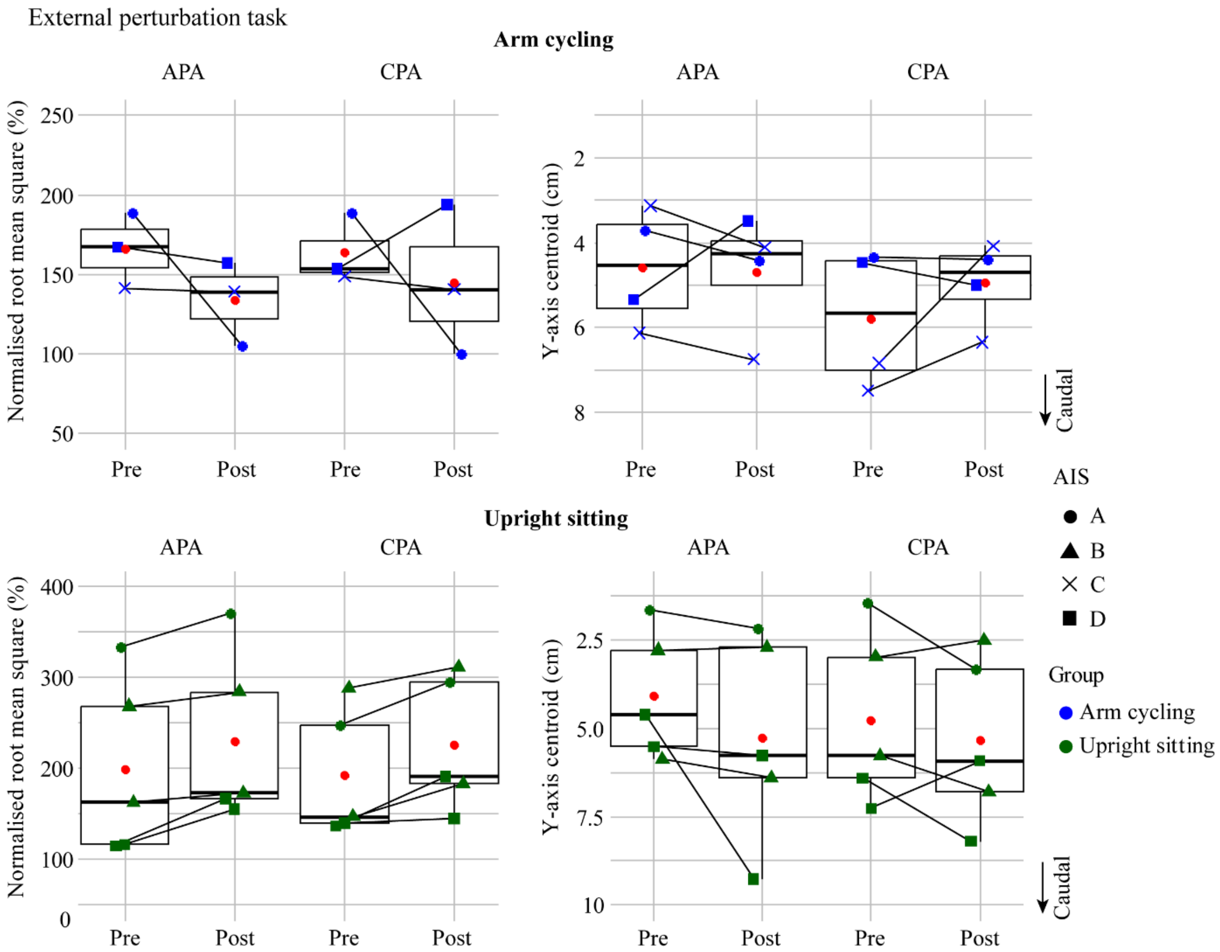

Figure 5.5. HDEMG results in the external perturbation task. Results are shown for the arm cycling group (top) and upright sitting group (bottom). Two analysis windows were used, namely the anticipatory postural adjustment (APA; left) window and the compensatory postural adjustment (CPA; right) window. The median is represented as a thin horizontal line located in each box. The hinges of the box correspond to the first quartile (25th percentile) and the third quartile (75th percentile). The vertical lines above and below the hinges of the box, i.e., whiskers, extend to the interquartile range multiplied by 1.5. The mean is displayed as a red dot. AIS: American spinal injury association impairment scale, APA: anticipatory postural adjustments, CPA: compensatory postural adjustments, cm: centimetres.

In the reaching phase of forward reaching, one out of three participants had a lower RMS in the arm cycling group (36.8% change), while two of the participants in the upright sitting group had a lower RMS (24.2% change; Fig. 5.6). In addition, one participant in the arm cycling group (32.7% change) and one participant in the upright sitting group (9.1% change) had a y-axis centroid that shifted more cranially in the post-assessment. In the returning phase of forward reaching, two out of three participants had a lower RMS in the arm cycling group (23.5% change), while two of the participants in the upright sitting group had a lower RMS (29.5% change). In addition, two participants in the arm cycling group (7% change) and one participant in the upright sitting group (14.8% change) had a y-axis centroid that shifted more cranially in the post-assessment. In the y-axis centroid difference, two participants in the arm cycling group (704.7% change) and four participants in the upright sitting group (592.3% change) had a larger y-axis centroid difference in the post-assessment.

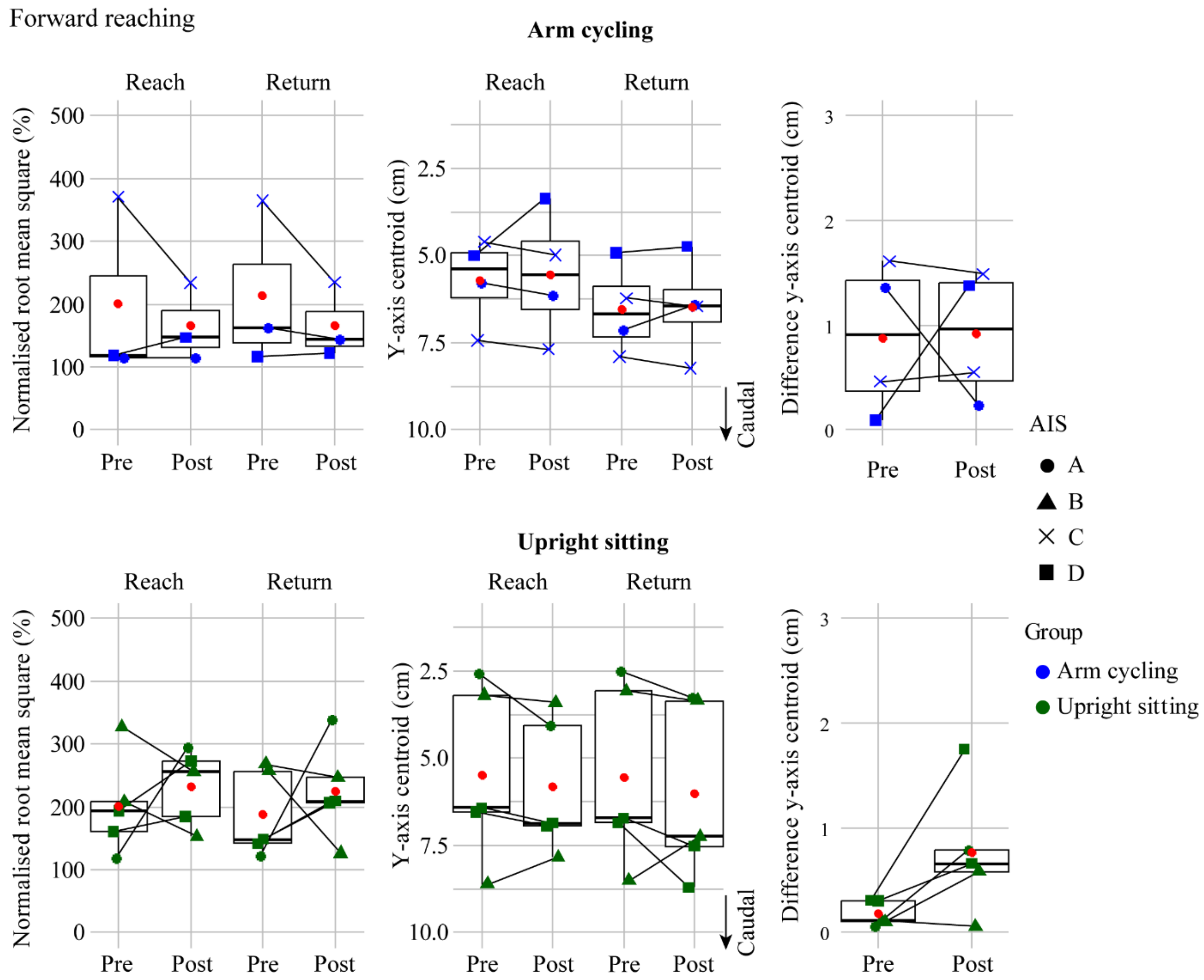

Figure 5.6. HDEMG results in forward reaching. The results are shown for the arm cycling group (top) and upright sitting group (bottom). The reaching task is separated in a reach phase and a return phase. The median is represented as a thin horizontal line located in each box. The hinges of the box correspond to the first quartile (25th percentile) and the third quartile (75th percentile). The vertical lines above and below the hinges of the box, i.e., whiskers, extend to the interquartile range multiplied by 1.5. The mean is displayed as a red dot. AIS: American spinal injury association impairment scale, cm: centimetres.

In the reaching phase of lateral reaching, one out of three participants had a lower RMS in the arm cycling group (27.8% change), and one participant in the upright sitting group had a lower RMS (3.28% change; Fig. 5.7). In addition, two participants in the arm cycling group (14.2% change) and three participants in the upright sitting group (18.6% change) had a y-axis centroid that shifted more cranially in the post-assessment. In the returning phase of lateral reaching, two out of three participants had a lower RMS in the arm cycling group (14.4% change), while one participant in the upright sitting group had a lower RMS (26.9% change). In addition, one participant in the arm cycling group (16.4% change) and three participants in the upright sitting group (10.6% change) had a y-axis centroid that shifted more cranially in the post-assessment. In the y-axis centroid difference, two participants in the arm cycling group (6223.4% change) and two participants in the upright sitting group (685.6% change) had a larger y-axis centroid difference in the post-assessment. The large percentage change in the arm cycling group is due to very low pre-assessment values (close to zero) and high post-assessment values.

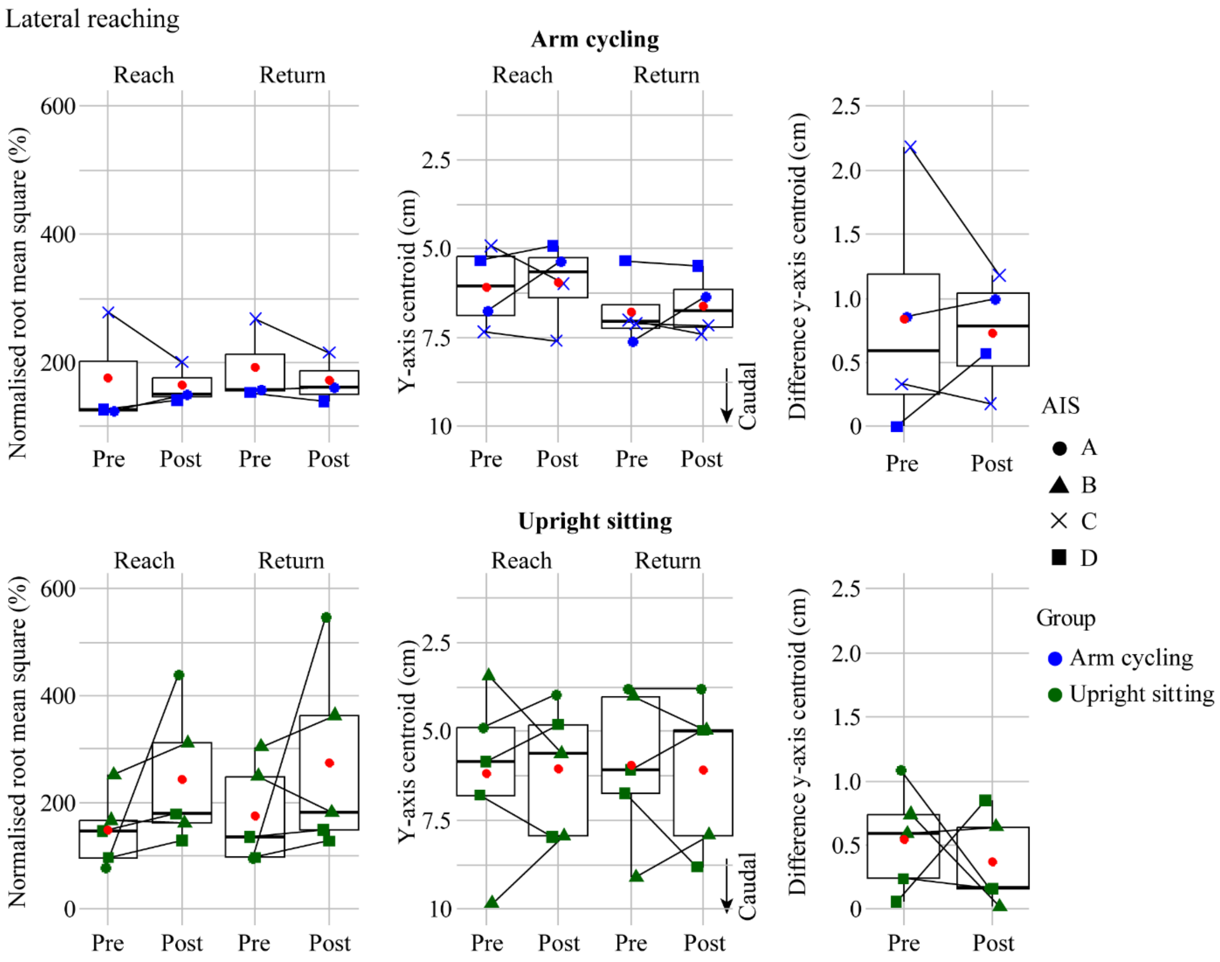

Figure 5.7. HDEMG results in lateral reaching. The results are shown for the arm cycling group (top) and upright sitting group (bottom). The reaching task is separated in a reach phase and a return phase. The median is represented as a thin horizontal line located in each box. The hinges of the box correspond to the first quartile (25th percentile) and the third quartile (75th percentile). The vertical lines above and below the hinges of the box, i.e., whiskers, extend to the interquartile range multiplied by 1.5. The mean is displayed as a red dot. AIS: American spinal injury association impairment scale, cm: centimetres.

Table 5.2. Summary of the HDEMG results.

Task	Parameter	Pre: mean (SD)	Post: mean (SD)
Rapid shoulder flexion	Shoulder flexion - RMS	Arm: 290.72 (90.76) Sit: 284.79 (112.48)	Arm: 212.33 (49.05) Sit: 245.93 (102.87)
	Shoulder flexion - y-axis centroid	Arm: 4.34 (1.78) Sit: 4.22 (1.76)	Arm: 4.54 (1.48) Sit: 4.82 (1.85)
	APA - RMS	Arm: 267.82 (84.71) Sit: 301.55 (81.43)	Arm: 225.78 (55.89) Sit: 291.39 (52.50)
	APA - y-axis centroid	Arm: 4.56 (1.26) Sit: 4.10 (2.13)	Arm: 4.89 (2.19) Sit: 4.63 (2.05)
External perturbation	APA - RMS	Arm: 165.91 (23.89) Sit: 199.41 (97.47)	Arm: 133.92 (26.32) Sit: 230.18 (94.30)
	APA - y-axis centroid	Arm: 4.58 (1.40) Sit: 4.09 (1.81)	Arm: 4.69 (1.43) Sit: 5.27 (2.90)
	CPA - RMS	Arm: 163.68 (22.02) Sit: 192.15 (71.18)	Arm: 144.83 (47.01) Sit: 225.50 (73.38)
	CPA - y-axis centroid	Arm: 5.79 (1.62) Sit: 4.78 (2.45)	Arm: 4.96 (1.00) Sit: 5.35 (2.38)
Forward reaching	Reach - RMS	Arm: 201.32 (146.94) Sit: 201.62 (78.33)	Arm: 165.51 (61.84) Sit: 232.25 (60.52)
	Reach - y-axis centroid	Arm: 5.72 (1.25) Sit: 5.47 (2.52)	Arm: 5.55 (1.83) Sit: 5.83 (1.96)
	Return - RMS	Arm: 214.23 (132.32) Sit: 187.52 (69.14)	Arm: 166.62 (60.01) Sit: 225.39 (77.35)
	Return - y-axis centroid	Arm: 6.55 (1.29) Sit: 5.54 (2.61)	Arm: 6.47 (1.43) Sit: 6.02 (2.54)
	Y-axis centroid difference	Arm: 0.88 (0.72) Sit: 0.18 (0.12)	Arm: 0.92 (0.62) Sit: 0.77 (0.62)
Lateral reaching	Reach - RMS	Arm: 176.27 (88.25) Sit: 147.85 (68.76)	Arm: 164.37 (31.97) Sit: 244.14 (129.81)
	Reach - y-axis centroid	Arm: 6.09 (1.14) Sit: 6.17 (2.40)	Arm: 5.96 (1.17) Sit: 6.07 (1.82)
	Return - RMS	Arm: 193.05 (65.05) Sit: 176.20 (94.65)	Arm: 171.63 (39.51) Sit: 273.68 (179.00)
	Return - y-axis centroid	Arm: 6.76 (0.98) Sit: 5.95 (2.17)	Arm: 6.60 (0.87) Sit: 6.10 (2.15)
	Y-axis centroid difference	Arm: 0.84 (0.96) Sit: 0.54 (0.41)	Arm: 0.73 (0.45) Sit: 0.37 (0.36)

RMS: root mean square, APA: anticipatory postural adjustments, CPA: compensatory postural adjustments, SD: standard deviation, Arm: arm cycling group, Sit: upright sitting group.

5.3.3 Functional outcomes

One participant did not have clear wrist movements during forward reaching and lateral reaching and is therefore excluded for that parameter. Three participants were not able to maintain balance during the RSF task and therefore the total trajectory measurements from those participants have been excluded.

In rapid shoulder flexion, three participants in the arm cycling group had a lower reaction time (24.3% change), while four participants in the upright sitting group had a lower reaction time (19.2% change; Fig. 5.8). In addition, two out of three participants in the arm cycling group (61% change), and three out of three participants in the upright sitting group had a higher anterior-posterior total trajectory of the trunk (34.7% change). Finally, one out of three participants in the arm cycling group (17.8% change), and three out of three participants in the upright sitting group had a higher anterior-posterior total trajectory of the centre of pressure (11.3% change).

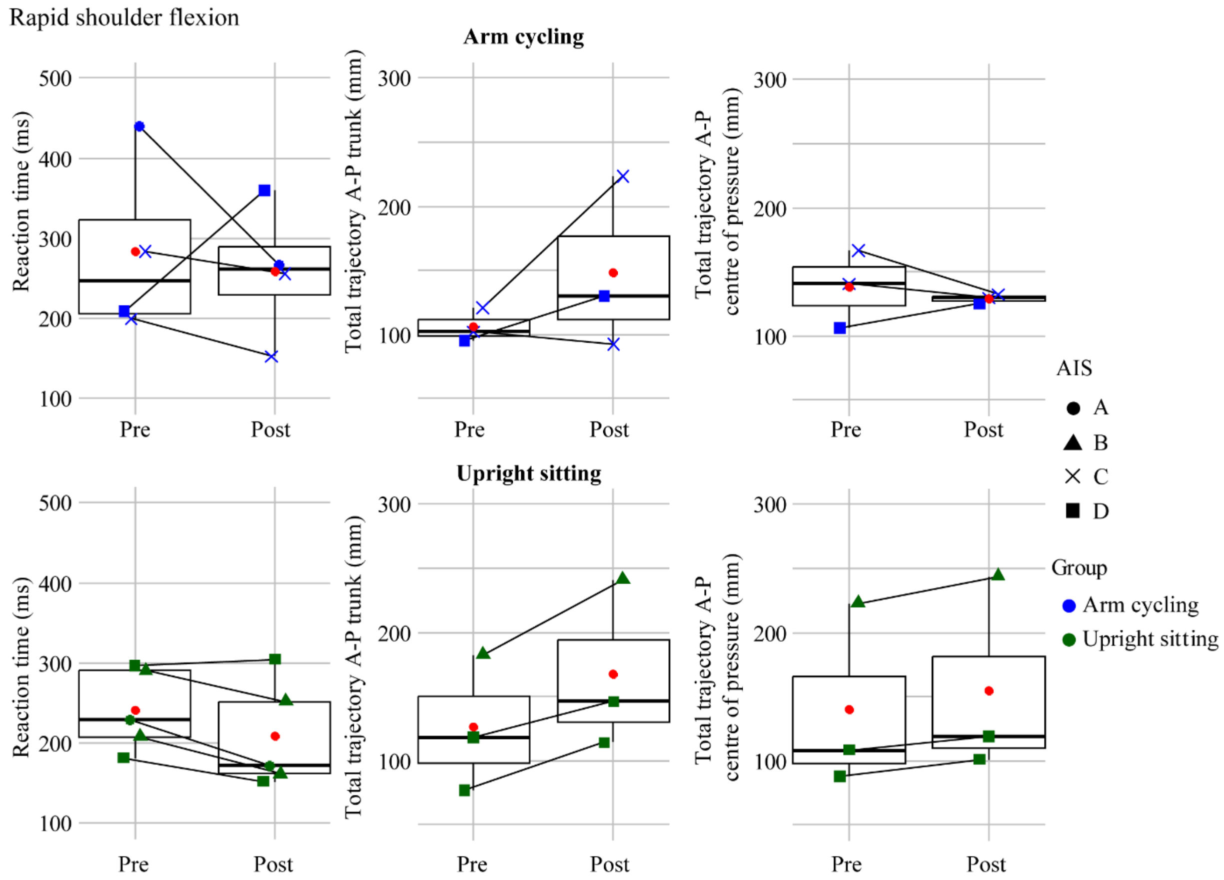

Figure 5.8. **Kinematic results of the rapid shoulder flexion task.** Results are shown for the arm cycling group (top) and upright sitting group (bottom). The reaction time (arm cycling n = 4; upright sitting n = 5), total trajectory of the trunk (arm cycling n = 3; upright sitting n = 3), and centre of pressure (arm cycling n = 3; upright sitting n = 3) are displayed. The median is represented as a thin horizontal line located in each box. The hinges of the box correspond to the first quartile (25th percentile) and the third quartile (75th percentile). The vertical lines above and below the hinges of the box, i.e., whiskers, extend to the interquartile range multiplied by 1.5. The mean is displayed as a red dot. AIS: American spinal injury association impairment scale, A-P: anterior-posterior, mm: millimetres, ms: milliseconds.

In the external perturbation task, all four participants in the arm cycling group (137.7% change), and four participants in the upright sitting group (69.9% change) had a higher anterior-posterior total trajectory of the trunk in the APA window (Fig. 5.9). In the CPA window, one participant in the arm cycling group (63% change), and none of the participants in the upright sitting group had a higher anterior-posterior total trajectory of the trunk. In addition, three participants in the arm cycling group (63.4% change), and all five participants in the upright sitting group (43.8% change) had a higher anterior-posterior total trajectory of the centre of pressure in the APA window. In the CPA window, none of the participants in the arm cycling group, and two participants in the upright sitting group (20.3% change) had a higher anterior-posterior total trajectory of the centre of pressure.

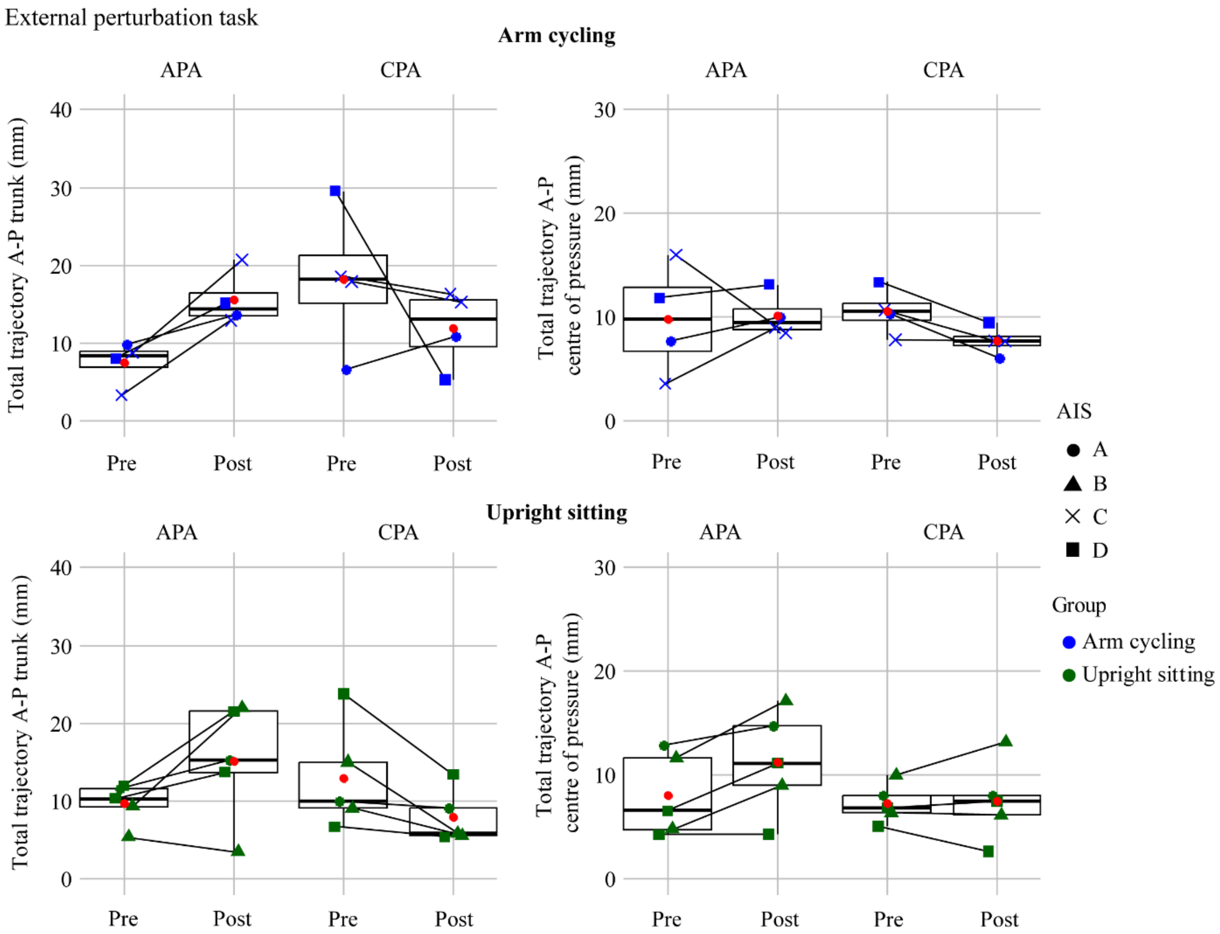

Figure 5.9. **Kinematic results of the external perturbation task**. Results are shown for the arm cycling group (top) and upright sitting group (bottom). The total trajectory of the trunk and centre of pressure are depicted in two analysis windows: anticipatory postural adjustments (APAs) and compensatory postural adjustments (CPAs). The median is represented as a thin horizontal line located in each box. The hinges of the box correspond to the first quartile (25th percentile) and the third quartile (75th percentile). The vertical lines above and below the hinges of the box, i.e., whiskers, extend to the interquartile range multiplied by 1.5. The mean is displayed as a red dot. AIS: American spinal injury association

impairment scale, A-P: anterior-posterior, APA: anticipatory postural adjustments, CPA: compensatory postural adjustments, mm: millimetres.

In forward reaching, three participants in the arm cycling group (37.9% change), and two participants in the upright sitting group (51.4% change) had a higher anterior-posterior displacement of the wrist (Fig. 5.10). In addition, three participants in the arm cycling group (35.2% change), and three participants in the upright sitting group (73.9% change) had a higher anterior-posterior displacement of the trunk. Finally, two participants in the arm cycling group (68.8% change), and three participants in the upright sitting group (45.1% change) had a higher anterior-posterior displacement of the centre of pressure.

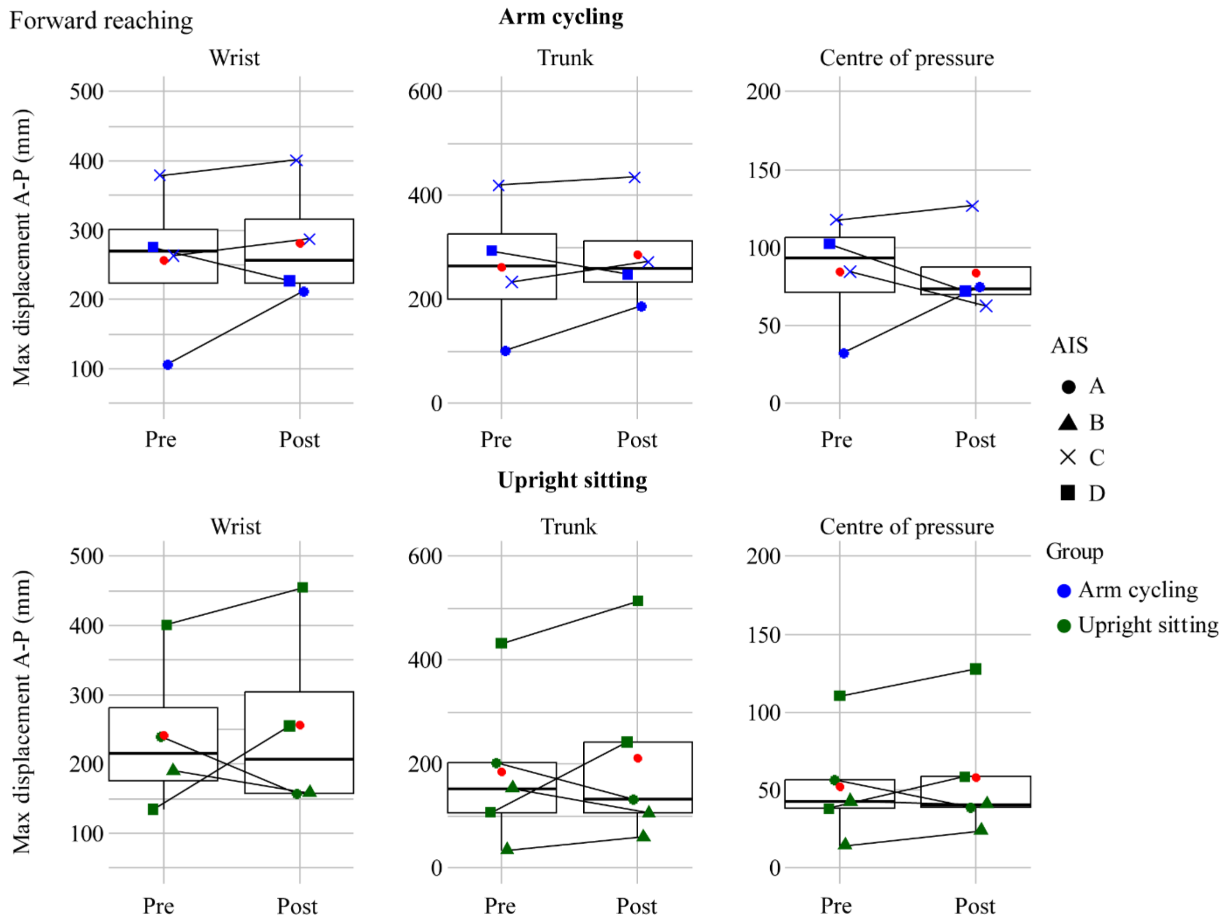

Figure 5.10. Kinematic results of the forward reaching task. Results are shown for the arm cycling group (top) and upright sitting group (bottom). The maximal displacement of the wrist (arm cycling n = 4; upright sitting n = 4), trunk (arm cycling n = 4; upright sitting n = 5), and centre of pressure (arm cycling n = 4; upright sitting n = 5) are shown. The median is represented as a thin horizontal line located in each box. The hinges of the box correspond to the first quartile (25th percentile) and the third quartile (75th percentile). The vertical lines above and below the hinges of the box, i.e., whiskers, extend to the interquartile range multiplied by 1.5. The mean is displayed as a red dot. AIS: American spinal injury association impairment scale, A-P: anterior-posterior, mm: millimetres.

In lateral reaching, all four participants in the arm cycling group (35.2% change), and three participants in the upright sitting group (52.5% change) had a higher medial-lateral displacement of the wrist (Fig. 5.11). In addition, three participants in the arm cycling group (42.3% change), and two participants in the upright sitting group (66.1% change) had a higher medial-lateral displacement of the trunk. Finally, three participants in the arm cycling group (47.6% change), and four participants in the upright sitting group (51.1% change) had a higher medial-lateral displacement of the centre of pressure.

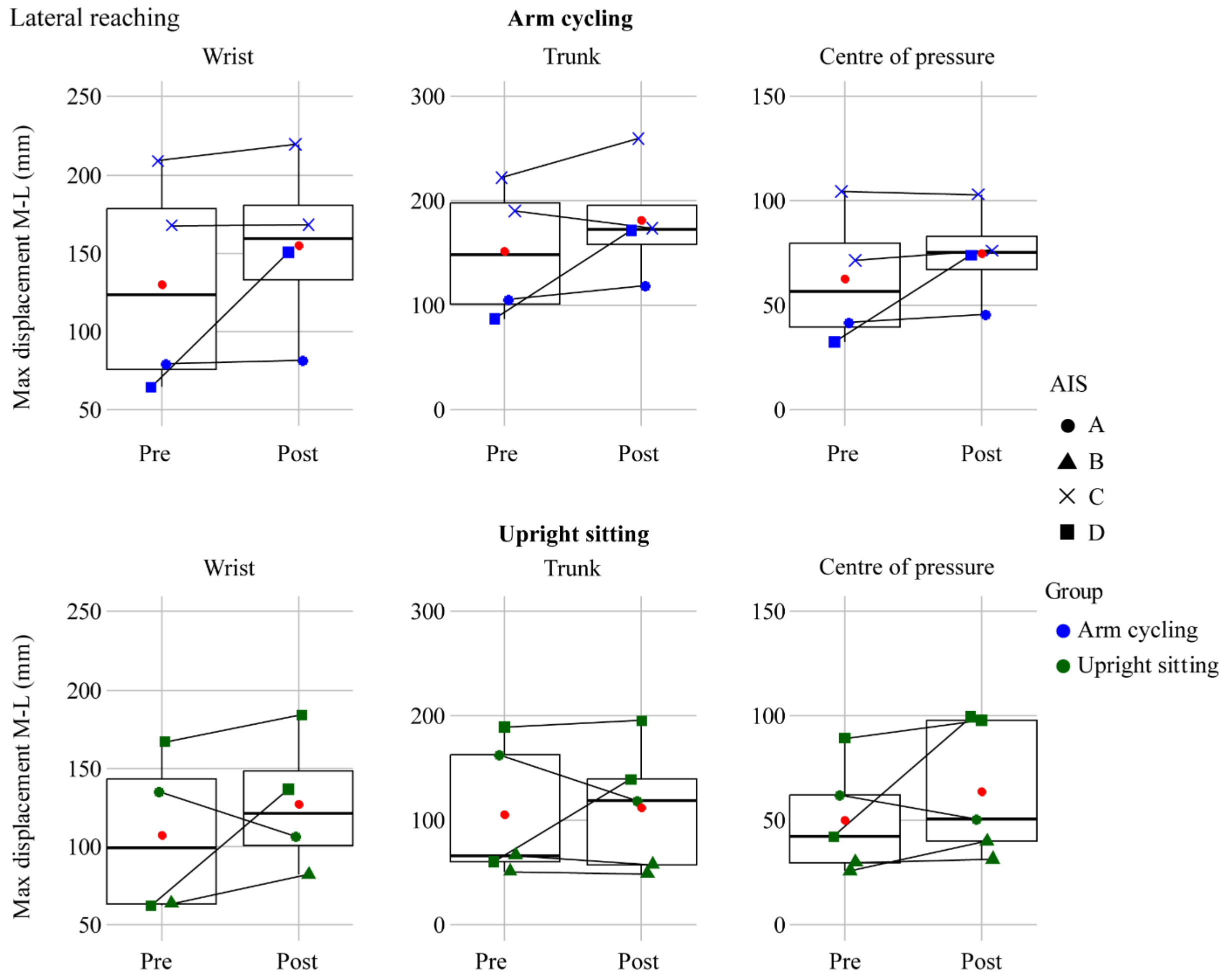

Figure 5.11. Kinematic results of the lateral reaching task. Results include maximal displacement of the wrist (arm cycling n = 4; upright sitting n = 4), trunk (arm cycling n = 4; upright sitting n = 5), and centre of pressure (arm cycling n = 4; upright sitting n = 5). The median is represented as a thin horizontal line located in each box. The hinges of the box correspond to the first quartile (25th percentile) and the third quartile (75th percentile). The vertical lines above and below the hinges of the box, i.e., whiskers, extend to the interquartile range multiplied by 1.5. The mean is displayed as a red dot. AIS: American spinal injury association impairment scale, M-L: medial-lateral, mm: millimetres.

Table 5.3. Summary of the functional results.

Task	Parameter	Pre: mean (SD)	Post: mean (SD)
Rapid shoulder flexion	Reaction time	Arm: 283.30 (111.60) Sit: 241.35 (50.84)	Arm: 258.95 (84.76) Sit: 208.46 (66.87)
	Trunk total trajectory A-P	Arm: 105.95 (13.24) Sit: 128.48 (43.72)	Arm: 148.68 (67.35) Sit: 167.22 (66.08)
	CoP total trajectory A-P	Arm: 137.81 (30.38) Sit: 170.78 (85.89)	Arm: 129.00 (3.73) Sit: 154.57 (77.85)
External perturbation	APA: trunk total trajectory A-P	Arm: 7.51 (2.90) Sit: 9.74 (2.66)	Arm: 15.61 (3.52) Sit: 15.21 (7.51)
	APA: CoP total trajectory A-P	Arm: 9.81 (5.35) Sit: 8.05 (3.96)	Arm: 10.17 (2.10) Sit: 11.28 (4.99)
	CPA: trunk total trajectory A-P	Arm: 18.21 (9.34) Sit: 12.91 (6.79)	Arm: 11.96 (5.01) Sit: 7.90 (3.46)
	CPA: CoP total trajectory A-P	Arm: 10.58 (2.27) Sit: 7.30 (1.86)	Arm: 7.75 (1.41) Sit: 7.52 (3.81)
Forward reaching	Wrist displacement A-P	Arm: 256.08 (112.50) Sit: 241.59 (114.85)	Arm: 281.69 (86.00) Sit: 256.44 (140.19)
	Trunk displacement A-P	Arm: 262.43 (132.45) Sit: 185.76 (151.11)	Arm: 286.09 (105.70) Sit: 211.04 (182.29)
	CoP displacement A-P	Arm: 84.29 (37.08) Sit: 52.49 (35.81)	Arm: 84.04 (28.91) Sit: 58.07 (40.83)
Lateral reaching	Wrist displacement M-L	Arm: 130.34 (69.45) Sit: 107.08 (52.46)	Arm: 155.05 (56.89) Sit: 127.35 (43.88)
	Trunk displacement M-L	Arm: 151.54 (65.13) Sit: 106.16 (64.63)	Arm: 181.39 (58.11) Sit: 112.23 (60.54)
	CoP displacement M-L	Arm: 62.67 (32.53) Sit: 50.03 (26.15)	Arm: 74.86 (23.50) Sit: 64.01 (32.49)

A-P: anterior-posterior, M-L: medial-lateral, CoP: centre of pressure, APA: anticipatory postural adjustments, CPA: compensatory postural adjustments, SD: standard deviation, Arm: arm cycling group, Sit: upright sitting group.

In the TIS assessment, four participants in the arm cycling group (11.70% change), and three participants in the upright sitting group (22.78% change) had a higher TIS total score. In the static subscale of the TIS, two participants in the arm cycling group (75% change), and one participant in the upright sitting group (16.67% change) had a higher score. In the dynamic subscale of the TIS, three participants in the arm cycling group (23.61% change), and one participant in the upright sitting group (100% change) had a higher score. In the coordination subscale of the TIS, one participant in the arm cycling group (25% change), and three participants in the upright sitting group (72.22% change) had a higher score.

Table 5.4. Summary of the Trunk Impairment Scale (TIS) results.

Parameter	Pre: mean (SD)	Post: mean (SD)
Static subscale	Arm: 5.75 (1.89) Sit: 5.20 (2.17)	Arm: 7.00 (0.00) Sit: 5.40 (2.30)
Dynamic subscale	Arm: 7.00 (2.58) Sit: 4.60 (4.98)	Arm: 8.00 (2.16) Sit: 4.80 (4.82)
Coordination subscale	Arm: 4.25 (1.26) Sit: 3.40 (1.82)	Arm: 4.00 (1.83) Sit: 4.40 (1.82)
Total score	Arm: 17.00 (0.82) Sit: 13.20 (8.11)	Arm: 19.00 (1.41) Sit: 14.60 (8.08)

SD: standard deviation, Arm: arm cycling group, Sit: upright sitting group.

5.3.4 Qualitative results

Three SCI individuals participated in the online focus group. Two individuals completed the eight-week arm cycling exercise programme and one participant was recruited from a previous six-week arm cycling exercise study (Chapter 4) but dropped out due to medical reasons. Nevertheless, the participant was still asked to participate in the focus group as the input remained valuable.

Table 5.5. SCI demographics in the qualitative study.

ID	Sex	Age (years)	AIS score	LoI	TSI (years)	Intervention	Completed sessions (completed videos)	BMI
P01	F	52	D	C6-7	1	Arm cycling	36 (18)	25.6
P02	M	60	C	C2-3	2	Arm cycling	40 (24)	27.8
P03	M	54	B	C5	19	Arm cycling (six weeks)	-	-

AIS: the American Spinal Injury Association Impairment Scale, F: female, M: male, C: cervical, LoI: level of injury, TSI: time since injury.

Exercise protocol. All three participants required assistance from their partner to set up the arm bike at home but were positive about the home-based exercise programme to increase physical fitness. The number of assessments (3) were found to be adequate. All three participants were able to keep themselves motivated throughout the exercise training programme. Advise on how to improve adherence to the exercise study was mentioned to be individual-dependent as all three participants were motivated from the start of the programme. One participant proposed conducting the exercise in a group setting rather than on an individual basis.

Clinical application. As for the exercise location, it was noted that a therapy department offers more access to physiotherapists and equipment and once the participants returned home after their initial rehabilitation, they no longer had access to the clinic.

Therefore, all three participants bought exercise equipment to use at home, such as free weights, resistance bands, and Thera bikes. However, all three participants expressed their enthusiasm for exercising at home. Two participants found the intensity of the exercise adequate, while one participant found the arm exercise challenging but enjoyable.

Support. Participants mentioned that they received sufficient support for carrying out the exercise at home. One participant needed to make adjustments at home to secure the arm bike on a table. There was no clear preference for receiving support from the research team and included text messages, emails, and phone calls and seems to be individual-dependent. Suggestions for enhancing recruitment strategies for the study included reaching out to charities such as the Spinal Injuries Association, the neurology department of hospitals, support groups, healthcare organisations, advocates within spinal units, and physiotherapists. Interestingly, two participants mentioned that they learned about the study by chance. One participant received information about the study during a Spinal Injuries Association meeting, and one participant looked on the website of a research institute. It is worth noting that indeed, both these organisations facilitated recruitment. One participant suggested that offering a monetary incentive might increase recruitment numbers. Regarding the participant's preference of initial contact for study participation, most expressed a preference for first being contacted by email, followed up by a phone call. In terms of potential reasons for not participating in the study, factors such as the extend of the disability, lack of motivation, and travel distance were mentioned. In addition, one female participant also noted that from a mother's point of view, it was occasionally challenging to engage in the exercise due to distractions from her children.

5.4 Discussion

The study examined the effects of an eight-week exercise training programme involving either upright sitting exercise or arm cycling exercise, along with upper-body exercise videos on trunk control during postural and functional reach tasks. Improvements were observed in both groups during the postural tasks, with faster reaction times, higher total trajectory of the trunk, and a lower RMS in the rapid shoulder flexion task, accompanied with earlier deltoid and ES onsets. In the external perturbation task, a higher total trajectory of the trunk was found in the APA window, and a lower total trajectory of the trunk in the CPA window in both groups. In the multidirectional functional reaching tasks, slightly higher displacements of the trunk, wrist and centre of pressure were found in both groups. HDEMG results differed between the two groups (see details below). Results are interpreted cautiously as no statistical analyses have been applied to the results of this ongoing study, but overall improvements were observed in both groups following the exercise, with an acceptable exercise compliance, and warrants continuation of the study.

The functional improvements are in keeping with previous studies, which found improvements in the trunk after task-specific upright sitting exercise (Betker et al., 2007; Boswell-Ruys et al., 2010; Kim et al., 2010; Tamburella et al., 2013) or after exercising the trunk indirectly by way of arm cycling exercise (Williams et al., 2020). In comparison with Chapter 4, the improvements observed in trunk and wrist displacements during the multidirectional reaching tasks are similar to the results described in Chapter 4, as well as the lower reaction time and greater anterior-posterior trunk total trajectory during the rapid shoulder flexion task. In addition, and new in this study, is that participants in the external perturbation task had a higher trunk- and centre of pressure total trajectory was found in the APA window, while these measures were lower in the CPA window. One possibility is that participants were better able at utilising APAs, consequently leading to lower CPAs, which is also found in elderly people in response to predictable perturbations, resulting in greater postural stability (Kanekar & Aruin, 2014). Another possible explanation is that participants were sitting more upright in the post-assessment as a result of the exercise programme, which might lead to more postural sway. However, this is a speculation and more markers need to be placed in future studies, for example to quantify whether individuals are using a more upright posture (Willigenburg et al., 2013).

The centre of pressure findings are different between the two groups. While the upright sitting group improved in forward reaching and rapid shoulder flexion, with greater anterior-posterior centre of pressure displacement and greater centre of pressure total trajectory, respectively, the arm cycling group did not improve in these measurements. One possible explanation is that the legs were more involved in the post-assessment of the arm cycling group as a result of different compensatory strategies, leading to lower centre of pressure measurements, as suggested by others (Field-Fote & Ray, 2010). This is also in line with the interpretations of another study who found no differences in the centre of pressure in the forward direction between able-bodied individuals and SCI individuals (Gauthier et al., 2013). Indeed, others assessed reaching tasks with additional force plates under the feet (Willigenburg et al., 2013). However, during the assessment in the current study, experimenters and helpers were surrounding the participant to ensure safety, so no valid data has been obtained from force plates located under the feet of the participant. Nevertheless, using additional force plates might be worth considering for future studies in this population.

Novel in this study is the use of HDEMG to characterise the spatial properties of erector spinae activity during the postural- and reaching tasks. Compared to the results of Chapter 4, the arm cycling group demonstrated, in addition to the lower RMS in forward reaching, also a lower RMS in the lateral reaching- and perturbation tasks. Combined with the improvements in the functional tasks, it seems possible that more efficient movements were made during the tasks by lowering the required muscle activation in order to successfully carry out the task. What could explain the lower RMS across tasks in the current study? A dose-response effect might lead to further trunk improvements by adding two weeks of additional arm cycling exercise compared to the six-week arm cycling exercise programme. One review study involving stroke individuals argued that sitting balance and trunk performance, measured with the trunk impairment scale, were most improved following a trunk exercise programme study of eight weeks compared to studies with a lower exercise programme duration (Cabanas-Valdes et al., 2013; Saeys et al., 2012). Another possibility is that general exercise, such as arm cycling, combined with task-specific trunk exercise might lead to additional improvements compared to arm cycling alone. However, there are currently no studies assessing the effects of combined exercise on trunk function in SCI, and one review study involving SCI populations was inconclusive about the effects of combined exercise on function in SCI due to the low-quality studies (Bochkezanian et al., 2015). Therefore, future studies could include a separate arm cycling group and a group performing combined arm cycling exercise with task-specific trunk exercise to assess whether the combined exercise group shows additional improvements on trunk function.

Noteworthy is that the functional improvements were accompanied with discrete activity characteristics in the erector spinae. The slightly higher reaching distance in the multidirectional reaching tasks was accompanied by a reduced erector spinae activation and a cranial shift in its distribution in the arm cycling group, whereas the upright sitting group demonstrated the opposite pattern with a higher erector spinae activation and a caudal shift in its distribution. Interestingly, the upright sitting group also demonstrated a larger difference in the centre of the distribution (y-axis barycentre) between the reaching and returning phase of the movement, while in lateral reaching there was no such difference between the two groups. A similar pattern was observed in the external perturbation task, with a lower erector spinae activation and a more cranial shift in its distribution in the arm cycling group, and a higher erector spinae activation combined with a more caudal shift in its distribution in the upright sitting group. However, in the rapid shoulder flexion task, erector spinae activation was lower in both groups, while the shift in its distribution was again located more caudally in the upright sitting group compared to the arm cycling group.

The observed differences in HDEMG characteristics between the two groups may be attributed to the mechanisms underlying the different types of exercise each group underwent. Given that arm cycling targets the trunk in an indirect way and involves additional muscles to execute the exercise compared to upright sitting exercise, the arm cycling may induce neuroplasticity in the brain which seems to be related to improvements in function (Chiou & Strutton, 2020; Fujiwara et al., 2001; Hoffman & Field-Fote, 2007; Jo & Perez, 2020; Kisiel-

Sajewicz et al., 2020; Oudega & Perez, 2012). Conversely, the upright sitting group directly targets the erector spinae muscles, which are involved in maintaining an upright sitting posture (Caneiro et al., 2010; Seelen et al., 1997). It could be that the upright sitting group, by strengthening the erector spinae muscles directly, adopted different sitting positions, for example by involving more of the lumbopelvic region, that may lead to a shift in the distribution of activity (Caneiro et al., 2010; O'Sullivan et al., 2006). Indeed, improving trunk stability by non-invasive spinal electrical stimulation seems to increase erector spinae activity, accompanied with posture improvements by having less trunk curvature (Eginyan et al., 2021; Rath et al., 2018).

Another possibility that might explain the differences in the activation and its distribution in the erector spinae is that both groups developed new postural strategies as a result of training the spared muscles (Milosevic, Yokoyama, et al., 2017; Potten et al., 1999; Seelen et al., 1998). After SCI, individuals with a high thoracic injury seem to activate non-postural muscles, such as the latissimus dorsi, the upper part of the trapezius, pectoralis, serratus anterior, and upper portion of the thoracic erector spinae to maintain sitting balance, whereas this activation pattern is less in individuals with a low thoracic SCI (Seelen et al., 1997). Following an exercise programme involving conventional physiotherapy in acute SCI, individuals with both a high and low thoracic injury developed distinct new muscle activation patterns for sitting balance, with individuals with a high thoracic injury activating the abovementioned compensatory muscles, and individuals with a low thoracic injury activating the lumbar region of the erector spinae for restoring sitting balance (Seelen et al., 1998). This might also apply to the arm cycling group, as it is possible that during the course of the exercise programme, a different and more efficient strategy was adopted in order to successfully carry out the reaching movement and maintain postural stability during the perturbation tasks that might explain the differences in the activation and its distribution in the erector spinae.

Based on the qualitative assessment, the home-based exercise programme seems to be acceptable for individuals with SCI. The duration and intensity of the exercise, as well as the number of assessments were found to be adequate. The need for social support to set up the equipment was reported by all participants, as well as the need of motivation to continue with the exercise programme, which is in line with the predictive factors that influence adherence (Bachmann et al., 2017; Essery et al., 2017; Tiu et al., 2022). Although it was mentioned that in a physiotherapy setting there are professionals and equipment available, all were positive about the home-based exercise approach and received adequate support from the research team during the programme and might facilitate the feeling of being more in control of their own rehabilitation after discharge (Unger, Singh, et al., 2019). The drop-out rate was higher in the current study compared to the previous six-week arm cycling exercise programme described in Chapter 4. One could argue that, by adding two additional weeks of exercise, compliance also reduces as a function of exercise programme duration. Another possibility would be that 240 minutes of weekly exercise might be too intense for the SCI individuals in the current study, as current recommendations for SCI are 130 minutes of cardio exercise in combination with six sets of strength exercise per week (Martin Ginis et al., 2018). Furthermore, a lack of social support and motivational factors may have been present in some participants who discontinued with the exercise programme. A recommendation for future studies would be to address these factors to increase adherence and reduce dropouts. For example, in one 16-week virtual-based exercise intervention with 168 SCI participants, psychological constructs were incorporated into the exercise programme, including self-management, social support, and self-efficacy, and reported a participant retention of 79% (Froehlich-Grobe et al., 2022).

Limitations are present in the study. First, no statistical analyses have been applied due to the low sample size and interpretations should be made cautiously. However, trends in the current data demonstrate slight improvements and warrants further continuation of the study. Once a full dataset has been collected, statistical analyses and subgroup analyses can be applied to solidify conclusions. Second, a total of two electrode grids and three reflective markers were used and make it difficult to provide insight into the underlying mechanisms of the improvements. Adding more electrode grids might shed light on the involvement of other muscles and its synergies such as the lumbar erector spinae and the latissimus dorsi to infer possible compensatory strategies and postural stability during the tasks (Masani et al., 2009; Seelen et al., 1998; Seelen et al., 1997). Additional markers could be placed on the thoraco-lumbar spine to assess postural changes and its effects on trunk muscle activity (Caneiro et al., 2010; O'Sullivan et al., 2006). Placing more electrode grids and markers may tire the participant as it requires more time, but additional experimenters can be present during the assessment to reduce the required time to place the extra electrode grids and markers.

Conclusion

Our results demonstrate home-based exercise could be an option as continuing rehabilitation for trunk function in individuals with chronic SCI. Both arm cycling exercise and task-specific seated exercise induced changes in trunk function in individuals with SCI, accompanied with different patterns of erector spinae activity. The current preliminary findings are promising and warrants further continuation of the study to acquire a full dataset to eventually perform statistical analyses to strengthen the conclusions whether an eight-week home-based trunk exercise programme can improve trunk function in individuals with a chronic SCI.

6. General discussion

6.1 Summary

Chapter one provides an overview of the literature about SCI, trunk function, and the current approach to rehabilitation in the UK. Trunk function is often compromised in people with SCI due to damage to the spinal cord that affects balance and posture in this patient population. Several stressors in the NHS such as longer waiting lists for physiotherapy, staff shortages lead to suboptimal trunk rehabilitation for people with chronic SCI once they return home. Therefore, there is a pressing need for a novel approach to trunk rehabilitation for individuals with SCI. Arm cycling is a popular form of exercise that can be carried out by people with SCI at home and without supervision from experts. However, its effectiveness on improving trunk function in people with chronic SCI was not known. Therefore, the identified knowledge gap which led to subsequent studies in this thesis was whether arm cycling can improve trunk function in people with SCI.

Chapter two described a study aimed at establishing the reliability of an electromyographic technique, known as HDEMG. While HDEMG is capable of extracting several spatiotemporal features from muscles, it remained unclear whether these features were reliable both within the same day and between days. The RMS and mean frequency derived from HDEMG during static (trunk extension and reverse trunk extension), dynamic (trunk flexion and trunk lateral flexion), and functional tasks (multidirectional reaching tasks) were the most reliable features between days, while the reliability of the barycentre was dependent on the task. The barycentre was reliable in both static tasks, dynamic trunk flexion, and lateral reaching, while the reliability was moderate in forward reaching. The study demonstrated the capability of HDEMG to reliably measure activity from the thoracic erector spinae muscles during goal-directed voluntary trunk movements and multidirectional reaching between different days. These findings confirmed the suitability of the use of HDEMG for assessment neuromuscular function in our planned subsequent observation (Chapter four) and RCT (Chapter five) studies.

With the reliability of HDEMG established, the study described in Chapter three assessed the difference in patterns of activation of the thoracic segment of the erector spinae between both able-bodied people and individuals with chronic SCI during multidirectional reaching and two postural tasks (rapid shoulder flexion and the external perturbation task). The main findings were that, in contrast to able-bodied individuals, the SCI group recruited different parts of the thoracic erector spinae during postural tasks and lost discrete control of the muscle during functional reaching tasks. Specifically, participants with SCI exhibited activity in the caudal portion of the thoracic erector spinae during the postural tasks. Additionally, the activation pattern in able-bodied individuals during forward reaching, with a higher muscle activation during the forward reaching phase compared to the returning phase of the movement, was not observed in the SCI group. These findings reveal task-dependent compensations of trunk motor control for stability following SCI.

Building further on prior research regarding the neurophysiological connections between the arms and trunk muscles during voluntary isometric contractions and arm cycling movements in able-bodied individuals, Chapter four initially demonstrated the facilitative effects of a single bilateral rhythmic arm cycling session on corticospinal excitability projecting to the erector spinae in able-bodied controls and also in people with SCI. This was followed up by an arm cycling exercise programme of six weeks to investigate exercise feasibility and effects on corticospinal excitability and trunk function. After completion of the arm cycling exercise programme, modest improvements were found in reaching distance during forward reaching and in trunk trajectory during rapid shoulder flexion. Additionally, a greater muscle activity in the erector spinae was found, as well as higher MEP amplitudes. The results demonstrated improved neuromuscular function and corticospinal output to the erector spinae muscles. Adherence to the exercise was excellent across participants. The findings suggest that arm cycling is a suitable and effective form of exercise that can be carried out from home for continuing trunk rehabilitation in people with chronic SCI. However, the improvements in neuromuscular control and function were not clear and inconsistent. In addition, Chapter three suggests that the compensatory strategies were task-dependent following SCI. This raised the questions whether different interventions with distinct focuses could influence the outcomes of trunk rehabilitation.

The fifth Chapter therefore describes the results of a randomised-controlled trial study. The study compared the effects of arm cycling with upright sitting, a conventional task-specific physiotherapy exercise, on trunk function in people with chronic SCI. Both groups engaged in upper-body exercise videos to investigate whether such exercise facilitates the effectiveness of the group-specific exercise. A focus group was also carried out to reveal perceptions associated with home-based exercise. Participants in both groups made small improvements in reaching distance, and trunk- and centre of pressure displacements during the reaching tasks. In the postural tasks, a greater trunk trajectory and earlier anterior deltoid onsets and erector spinae onsets were found in both groups. These improvements were accompanied by different patterns of muscle activity. The arm cycling group demonstrated decreased muscle activity, located in the cranial portion of the erector spinae during the tasks. Conversely, the upright sitting group demonstrated increased muscle activity, located more in the caudal portion of the erector spinae during the tasks. These differences could reflect task-specific improvements in neuromuscular control and/or compensatory mechanisms to maintain stability during the tasks. The focus group highlighted the importance of social support and intrinsic motivation contributing to home-based exercise adherence. Overall, the results suggest that while engaging in arm cycling or upright sitting, in combination with upper-body exercise at home, has positive effects on trunk function in people with chronic SCI, the therapeutic effects of the two types of interventions on neuromuscular control of the ES were different.

Finally, Chapter six summarised key findings of this thesis, discussed the results from individual chapters as a whole and clinical implications, analysed strengths and limitations of the thesis, and proposed future directions beyond the thesis.

6.2 Home-based arm cycling exercise improves trunk function in chronic SCI

The arm crank exercise has been noted to have positive effects on the maximum rate of oxygen uptake, peak power, seated balance with closed eyes, wheelchair mobility, and decreasing risk factors of cardiovascular disease in people with SCI (Bresnahan et al., 2019; Brizuela et al., 2020; DiCarlo, 1988; El-Sayed & Younesian, 2005; Ordonez et al., 2013; Rosety-Rodriguez et al., 2014; Williams et al., 2020). The research reported in Chapter 4 contributes to the understanding of the effects of arm crank exercise in chronic SCI. More specifically, it reveals that thirty minutes of arm cycling alters the strength of the response of the corticospinal pathways in relaying signals from the cortex to the erector spinae muscles in people with chronic SCI, subsequently leading to neuromuscular and functional improvements. The six-week exercise programme was found to be feasible, demonstrated by a high compliance rate, which is particularly encouraging given that adherence to home-based physical rehabilitation exercise programmes tends to be lower compared to standard rehabilitation (Essery et al., 2017). While the six-week exercise programme demonstrated to be feasible and effective in enhancing trunk function in people with chronic SCI, the results of the functional- and HDEMG outcomes were somewhat scattered. This variability prompted to extend the exercise programme to eight weeks. Another question was whether arm cycling is as effective as or more effective than traditional SCI rehabilitation. Although the study described in Chapter 5 is currently ongoing, initial findings indicate that both arm cycling and conventional physiotherapy, i.e., upright sitting exercise, combined with upper-body exercise videos, induce alterations in trunk function in individuals with chronic SCI. Once a full dataset is obtained, statistical analyses will be applied to assess whether arm cycling, and upright sitting improve trunk function outcomes. Additionally, comparisons between the exercise groups will be made to assess whether one form of exercise exhibits greater efficacy over the other.

The findings of Chapters 4 and 5 demonstrate that home-based unsupervised therapeutic exercise, including arm cycling exercise, general upper-body exercise, and task-oriented sitting training improves trunk function. This offers an accessible and alternative approach for trunk rehabilitation for individuals with chronic SCI. The exercise can be conducted at home without the need for supervision, removing reliance on physiotherapists and transportation to a physiotherapy clinic. This approach potentially allows people with SCI to allocate more time on rehabilitation, which is a crucial advantage considering the challenges faced by current NHS services in the UK, as well as for individuals with restricted access to exercise facilities (Anderson, 2004; Soopramanien et al., 2020; Yang et al., 2021).

It was previously shown that both types of exercise, arm cycling exercise and task-oriented upright sitting training improve trunk function (Kim et al., 2010; Tamburella et al., 2013; Unger, Chan, et al., 2019; Williams et al., 2020). In this thesis it was demonstrated that the spatial patterns of erector spinae muscle activity that were accompanied with the functional improvements differed between the arm cycling and upright sitting exercise groups. In other words, the two types of therapeutic exercise induced distinct changes in the trunk muscles. The differences in these neuromuscular characteristics may be related to different mechanisms of each training modality. The improvements found after arm cycling may be due to recruiting spared pathways, also known as a neuromodulation approach (Christiansen & Perez, 2018; Filli & Schwab, 2015; Long et al., 2017; Matthews et al., 2004; Moxon et al., 2014). Arm cycling may induce neuroplasticity in the brain which seems to be related to improvements in function (Chiou & Strutton, 2020; Fujiwara et al., 2001; Hoffman & Field-Fote, 2007; Jo & Perez, 2020; Kisiel-Sajewicz et al., 2020; Oudega & Perez, 2012). Conversely, the upright sitting training is a form of task-oriented exercise, wherein a specific task is re-learned, that targets the trunk muscles in a direct way, possibly strengthening the erector spinae muscles (Bayona et al., 2005; Jeon et al., 2015; Rensink et al., 2009; Stein et al., 2008). This could lead to additional compensatory motor control strategies in the trunk, for example by increasing the involvement of the lumbopelvic region (Caneiro et al., 2010; O'Sullivan et al., 2006). These different forms of exercise induce training-specific neuromuscular changes in the erector spinae as described in this thesis, establishing fundamental evidence underpinning mechanisms of specific types of therapeutic exercise interventions for trunk rehabilitation. Notably, both groups engaged in upper-body exercise videos. A recommendation for future research is to incorporate additional groups, such as an arm cycling only group, upright sitting only group, and combined exercise groups including arm cycling with upper-body exercise videos and upright sitting with upper-body exercise videos. Including separate groups could enhance our understanding of the underlying mechanisms contributing to improved trunk function and whether combined exercise, such as arm cycling with upper-body exercise videos is more effective than a single form of exercise, i.e., arm cycling only.

One critical point is the duration and intensity of an exercise programme. The drop-out rate in the RCT study (Chapter 5) was considerable, with eight out of 17 participants discontinuing participation, compared to four out of 15 participants in the six-week exercise programme (Chapter 4). One possible explanation is the high intensity of the exercise, totalling 240 minutes per week which is higher than current exercise recommendations for individuals for SCI (Martin Ginis et al., 2018). Furthermore, previous research suggests that exercise compliance tends to decrease with a higher number of exercises (Bachmann et al., 2017). The upper-body exercise videos consisted of approximately ten exercises performed in 30 minutes and could contribute to the higher dropout rate in the RCT study. Several reviews have highlighted the dose-response of exercise prescription to improve function. Although engaging in arm cycling for six weeks improves trunk function, the duration is on the lower end among exercise studies in SCI (Chiou et al., 2022; Hicks et al., 2011). In addition, a review focussing on rehabilitation in stroke survivors described that an exercise programme of eight weeks leads to significant improvements in trunk function compared to studies with a lower programme duration (Cabanas-Valdes et al., 2013).

Given that home-based exercise is linked to a lower exercise adherence (Bachmann et al., 2017), clinicians prescribing exercise to individuals with SCI could consider these factors, namely the dose-response effect and the risk of dropout. The dose-effect response of eight weeks over six weeks may lead to further improvements in trunk function but risks of dropping out or lower adherence to the exercise. In addition, Chapter 5 highlighted the role of social support and self-motivation in adhering to the exercise, also found by others (Bachmann et al., 2017). Clinicians could assess whether their patients have adequate social support at home and the self-motivation to continue with the exercise and based on the outcome, prescribe a six-week or eight-week exercise programme to improve trunk function, thereby offering person-specific programmes based on their preferences. In addition, future studies involving SCI populations could explore alternative platforms like virtual group-exercise programmes, where multiple participants engage in computer-assisted exercises together. This approach may offer benefits over exercising alone, including increased social support that, in turn, could improve adherence (Finley et al., 2021; Jennett et al., 2003; Young et al., 2021).

Placing the findings and approach described in this thesis within the broader context of rehabilitation aligns with recommendations stipulated by the World Health Organization

(Chan, 2013). These recommendations advocate for the removal of access barriers to facilities, the development of alternative rehabilitation approaches, and the utilisation of low-cost equipment. The studies described in this thesis adopt a home-based approach, eliminating physical access barriers and thereby sparing individuals with SCI to commute to rehabilitation services. Furthermore, integrating arm cycling into post-acute rehabilitation strategies offers an alternative way to maximise functioning and becoming as independent as possible during daily activities. Finally, by offering the opportunity to enhance trunk function through home-based rehabilitation, individuals with SCI have the potential to actively participate in their rehabilitation journey after discharge.

6.3 Clinical use of electromyography

Currently, there is a lack of objective measurements for assessing intervention-induced changes in neuromuscular function of the trunk. For example, several intervention studies described in Chapter 1 reported functional improvements in trunk function through various exercise programmes, including conventional physiotherapy exercise, task-specific training, community-based workouts, upper-body exercises, and whole-body exercises (Bjerkefors et al., 2007; Boswell-Ruys et al., 2010; de Oliveira et al., 2019; Kim et al., 2010; Okawara et al., 2022; Sliwinski et al., 2020; Sung et al., 2015; Tamburella et al., 2013; Tsai et al., 2021; Williams et al., 2020). Although these exercise programmes have demonstrated improvements in trunk function, such as reduced swaying during upright sitting, prolonged sitting duration, and increased seated reaching distance, the neuromuscular improvements were not assessed using techniques like EMG.

Using electromyographic methodologies such as EMG enables the assessment of neuromuscular function and the neurophysiology following neurorehabilitation. This approach may contribute to a greater understanding of the underlying mechanisms (Balbinot et al., 2022; Balbinot et al., 2021). For example, using EMG in combination with TMS allows for assessing the corticospinal excitability in SCI populations (Chiou & Strutton, 2020). In addition, EMG amplitudes have been used as an outcome measure in intervention studies with people with SCI to assess muscle activity from relevant muscles. Wirz et al. (2001) assessed EMG activity from the gastrocnemius medialis before and after a locomotor training intervention and showed higher EMG activity over the course of the exercise intervention, demonstrating training-induced improvements. Furthermore, distinctive patterns of activity have been observed during postural control, and different muscle activity patterns have been observed after a locomotor training intervention, indicating redistributed muscle activity after the intervention (Grasso et al., 2004; Seelen et al., 1998).

Despite the benefits of using electromyographic outcome measurements, its use is not widely adopted in clinical research, possibly due to the limitations of EMG (Balbinot et al., 2022; Farago et al., 2023; Merletti et al., 2021). As illustrated in figure 1.4, the small bipolar electrodes are capable of capturing muscle activity from a specific muscle region. To address this limitation, a multi-channel electrode design was developed, allowing for the measurement of muscle activity from a broader muscle area (Campanini et al., 2022; Kilby et al., 2016). This high-density EMG approach offers an opportunity to assess physiological characteristics in both healthy and clinical populations (Campanini et al., 2022; Drost et al., 2006). For example, the technique has been used to quantify functionally-relevant features in patient groups, including motor unit behaviour, fatigue, and muscle fibre conduction velocity (Drost et al., 2006). In addition, the larger recording area allows to assess the topographic muscle activity from a muscle, which is quantified by the centroid. Using the y-axis of the centroid as a location of the centre of the distribution of muscle activity from the erector spinae, novel findings were discovered in Chapters 3, 4, and 5 that were unable to be detected with conventional bipolar EMG. More specifically, examining both able-bodied individuals and people with chronic SCI during functional tasks and postural adjustments revealed differences in the distribution of thoracic erector spinae muscle activity. The distribution of erector spinae activity was located in the caudal portion of the erector spinae in SCI participants, while the distribution of erector spinae activity was located more in the cranial portion of the erector spina in able-bodied individuals. In addition, the activity based on the phase of the movement during the reaching tasks observed in able-bodied individuals was absent in people with SCI.

Uncovering the differences in the spatial distribution of erector spinae activity is important as it presents opportunities for innovative approaches to SCI rehabilitation. For instance, some studies have used bipolar EMG biofeedback to increase muscle activity below the injury (De Biase et al., 2011). Others have combined EMG biofeedback with physiotherapy (Klose et al., 1993). While conventional EMG is not able to assess the spatial distribution of muscle activity, HDEMG could be employed in such biofeedback designs to selectively activate the cranial portion of the erector spinae during postural and functional tasks. In addition, while the current thesis assessed the effects of arm cycling and task-specific upright sitting exercise in combination with upper-body exercise videos, other exercise programmes could be employed to assess its effectiveness in redistributing erector spinae activity. For example, community-based workouts, kayak training, Tai-Chi, and curling all lead to improvements in trunk function in people with SCI (Bjerkefors et al., 2007; de Oliveira et al., 2019; Grigorenko et al., 2004; Qi et al., 2018). It would be interesting to assess whether these exercise programmes lead to redistributed muscle activity, and if proven effective, it provides people with SCI more options to choose from to improve trunk function. However, the current research is focussed on EMG amplitude, and there is potential for broader application of HDEMG in SCI populations (Drost et al., 2006). With the muscle activation patterns of the thoracic erector spinae now established in able-bodied controls during functional and postural tasks, novel SCI clinical rehabilitation strategies can be incorporated. These strategies may emphasise on interventions that focus on redistributing muscle activity rather than solely focussing on changing its EMG amplitude. Clinicians also could use the method to assess whether a given exercise programme is effective in inducing training-specific changes in neuromuscular function and track the progress during the course of the exercise programme.

While HDEMG has the additional benefits over conventional EMG, its utilisation in clinical practice is not widespread. Identified barriers include challenges associated with its application, complex data processing and analysis (Balbinot et al., 2022; Farago et al., 2023; Merletti et al., 2021). During the course of the thesis, there were a couple of points of relevance challenging its user-friendliness: 1) the preparation of the skin including shaving and abrasion were crucial to improve skin conductance and minimise channels of poor quality, 2) fixing the pre-amplifiers together to prevent them clattering against each other and creating artefacts, 3) placing the electrodes on the same location is challenging, 4) the temperamental nature of the HDEMG equipment with frequent crashes. Despite these challenges, usage of HDEMG in clinical settings may be more accessible with proper training of the clinicians. Alternatively, a technician dedicated to HDEMG data acquisition could be present to ensure adequate placement of the electrodes and recordings of the HDEMG data. These suggestions could make the technique more accessible and with the reliability of the HDEMG parameters from the thoracic erector spinae now established of several parameters during static, dynamic, and functional tasks, coupled with recent consensus on its application, analysis and interpretation, the technique is potentially more clinical-friendly for use in clinics and longitudinal studies (Gallina et al., 2022). New opportunities arise for potential applications of this technique, not only in SCI, but also in other patient populations such as low back pain who also exhibit an altered distribution of erector spinae activity during tasks like rowing, object lifting, and a dynamic fatiguing task compared to individuals without low back pain (Arvanitidis et al., 2021; Liechti et al., 2022; Martinez-Valdes et al., 2019; Sanderson, Cescon, et al., 2019; Sanderson, Martinez-Valdes, et al., 2019). The use of HDEMG is further encouraged by multiple review studies who recommend further investigation to integrate the technique as an outcome measure in rehabilitation studies (Balbinot et al., 2022; Wang et al., 2016). This aligns with others who have described changes in the spatial redistribution of muscle activity in populations with pain (Falla & Gallina, 2020).

6.4 Overall strengths, limitations, and future directions

This Doctor of Philosophy (PhD) research involved complex techniques including high-density surface electromyography, a 3-D motion capture system, and TMS assessments in a vulnerable population, namely SCI. The main purpose of the PhD was to establish the underlying mechanisms of specific types of upper-body exercise for trunk rehabilitation, unravelling fundamental evidence of the effectiveness of these exercise programmes on trunk function in people with chronic SCI.

One of the strengths of the PhD project was the multi-centre recruitment approach. Participants were recruited via the recruitment website, local SCI charities and associations, and the Midland Centre for Spinal Injuries at the Robert Jones and Agnes Hunt Orthopaedic Hospital in the UK. I went to the Midland Centre for Spinal Injuries on a bi-weekly basis to sit there behind a desk, opposite of the reception to talk to people with SCI directly and try to recruit them. In addition, I have contacted over 40 charities of which 11 have supported the project by placing the recruitment flyer on their social media channels. Over the course of the PhD project, 68 possible participants have contacted me for potential participation. As discussed in Chapter 5, reasons for not participating were not meeting the inclusion criteria, mostly due to an injury located lower than T11, or not being able to sit independently on a chair. Another reason was no response after contacting them. Despite these efforts, the target of the RCT study was not met as 21 out of 30 SCI participants were recruited. One recommendation for future projects is to contact more spinal cord injury centres, for example the London Spinal Cord Injury Centre at the Royal National Orthopaedic Hospital. Going to the hospital to directly communicate with SCI people was effective as answers and concerns from individuals could be addressed immediately. For example, a couple individuals thought that the training had to be carried out at the University of Birmingham. After explaining that the training could be done from the comfort of their own home and that they only had to come to the University of Birmingham for three assessments, I was able to recruit them. Other RCT studies involving SCI participants adopted similar recruitment strategies, but the recruitment period in those studies is not mentioned (Herzog et al., 2018; Jones et al., 2014; Qi et al., 2018). If a longer recruitment period had been adopted, more SCI individuals could have been recruited. Another possibility would be to adopt a crossover design as this type of design has higher power and statistically more efficient compared to RCT designs (Lim & In, 2021).

A second strength of the PhD projects, which is mentioned throughout the thesis, is a home-based unsupervised approach to exercise. Exercising from home has multiple benefits for individuals with SCI, as commuting using public transport is often challenging. In addition, during periods of lockdowns or increased number of COVID-19 cases, individuals with SCI can continue with the exercise. These barriers would affect people with SCI if they were doing the exercise in a clinic. Home-based rehabilitation is more common in recent years and a review study found that a home-based approach is suitable for people with SCI to improve fitness and function and to maintain health (Oliveira et al., 2021). As discussed earlier, future studies could address social support at home and self-motivation to improve adherence to the exercise, two factors also found by others to promote adherence (Bachmann et al., 2017).

A limitation is the reliability of HDEMG parameters during multidirectional reaching tasks. While the reliability of the centroid is highest in static tasks between sessions, it is lower during dynamic tasks and functional reaching tasks. Specifically, the reliability of functional reaching tasks ranged from moderate to excellent. Although these reliability measures remain acceptable, results of the multidirectional reaching tasks described in Chapters 3, 4, and 5 should be interpreted cautiously. Nevertheless, clear differences in the y-axis of the centroid were observed between able-bodied individuals and individuals with SCI, indicating a shift to the caudal portion of the erector spinae in the SCI group.

A second limitation in the PhD projects was the limited use of electrode grids and markers. In all studies, two electrode grids were positioned over the thoracic erector spinae and three markers were placed over bilateral wrists and the first thoracic spinous process. The low number of electrode grids and markers leaves more room for the interpretations regarding the differences between able-bodied individuals and people with SCI, as well as the observed trunk-related improvements following the exercise programmes in SCI individuals. For example, individuals with SCI may use more compensatory strategies due to a loss of postural control, such as co-contracting non-postural muscles or adopting a pelvic tilt, or having less task-dependent muscle activity that may lead to shifts in the regional activation patterns of the thoracic erector spinae (Bjerkefors et al., 2009; Eginyan et al., 2021; Milosevic, Yokoyama, et al., 2017; Triolo et al., 2013). The changes in the distribution of thoracic erector spinae activity may also be related to neural reorganisation after the SCI (Bareyre et al., 2004; Chiou & Strutton, 2020). The choice of using two electrodes and three markers was based on two factors. The first factor was that people with SCI found it uncomfortable to sit on the force place. If more electrode grids had to be placed, for example above or below the current grids, SCI individuals had to sit longer on the force plate because of the longer time needed for placing the electrodes and the increased risk of addressing poor signals during the data collection. An increased time spent on the hard surface increases the risk of developing pressure sores which we wanted to keep to a minimum (Cullum et al., 1995). The second factor was the processing and analysis of the dataset, and the interpretation of the results. The data of each electrode grid and marker had to be analysed for each of the performed task. Several steps had to be carried out, including rigorous and extensive pre-processing, and cropping of the data. These steps needed a considerable amount of time per participants. Nevertheless, despite using two grids and three markers, the data provided sufficient results to answer the overall aim of the PhD. That is, establishing the underlying mechanisms of specific types of therapeutic exercises for trunk rehabilitation. However, a suggestion for follow-up studies could be to add more electrode grids and markers to assess the factors underlying the improvements in-dept. For example, additional reflective markers could be placed on the spine to assess posture, while extra electrode grids could be placed on the lumbar erector spinae and other non-postural muscles to assess their involvement during the tasks (Caneiro et al., 2010; Claus et al., 2016; O'Sullivan et al., 2006; Potten et al., 1999; Rath et al., 2018). Furthermore, subgroup analyses could be performed once a complete dataset from Chapter 5 has been collected. The level of injury could be factored in, as differences between individuals with a low thoracic injury and a high thoracic injury have been observed (Seelen et al., 1997). These differences may affect the regional activation patterns and other motion parameters.

Engaging in exercise programmes has been shown to have positive effects on the quality of life among people with SCI (Qi et al., 2018; Sliwinski et al., 2020). The observed improvements in trunk function could potentially contribute to improved quality of life (Anderson, 2004). Because the main aim of the PhD was to establish the underlying mechanisms of specific types of therapeutic exercises for trunk rehabilitation, the studies described in Chapter 4 and 5 have not included quality of life questionnaires A suggestion for future research is to assess the effects of unsupervised home-based arm cycling exercise programmes on quality of life using questionnaires that are suitable for SCI populations, such as the spinal cord injury quality-of-life-23 questionnaire (Lundqvist et al., 1997). Furthermore, additional clinical outcome measures could be incorporated in future research to provide a better indication of clinical outcome. Kahn et al (2016) have identified several clinical outcomes measures for individuals with SCI, and divided these outcome measurements into a body structure and function domain, activity domain, and a participation domain. Clinical outcome measures such as the Spinal Cord Independence Measure II (SIM II, an independence scale measuring self-care, respiration and sphincter management, and mobility, or the Functional Independence Measure (FIM) could be incorporated into future studies to assess whether clinically-related changes are observed after the exercise programme (Catz et al., 2001; Keith et al., 1987). Another clinically validated assessment tool for individuals with SCI is the Function in Sitting Test (FIST), consisting of 14-items to evaluate functional seated balance (Palermo et al., 2020).

6.5 Conclusion

It is important for people with chronic SCI to continue with rehabilitation upon returning home after acute care. A particular focus is on trunk function, as it plays a crucial role in supporting daily activities and maintaining quality of life. The thesis provides evidence of the mechanisms underlying the therapeutic effects of arm movements on neuromuscular control and function of the trunk after SCI and the feasibility of home-based unsupervised arm cycling exercise training for trunk rehabilitation in this patient group. Additionally, the thesis reveals a new method for reliable and objective readouts of the exercise interventions which advanced current understanding of compensatory motor control strategies of the trunk following SCI. Furthermore, the thesis supports the notion that the dose and duration of interventions influence the effectiveness of the interventions. Performing arm cycling for six weeks improves neuromuscular functioning of the erector spinae. Increasing the programme with two more weeks and adding upper-body exercise videos has positive effects on trunk function as well, demonstrated by improved reactivity and trunk control during postural tasks. Arm cycling is an alternative approach to rehabilitation that can be performed at home without supervision that provides more opportunities to engage in the exercise compared to traditional rehabilitation approaches. In conclusion, fresh perspectives are provided on the neurophysiological and clinical aspects associated with an exercise intervention with upper extremities for trunk rehabilitation in individuals with SCI.

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8. Supplementary materials

8.1 List of questions asked during the online focus group

Q1: How did you find the exercise protocol (including the videos for some)?

Q2: Was it difficult to install the arm bike at home, or install a device to watch the videos from?

Q3: What did you like about the arm cycling/ video set-up and what could be improved?

Q4: Were the number of assessments adequate? Or were there too many assessments? How often would it be appropriate?

Q5: What do you think of exercising at home vs. exercising in a therapy department?

Q6: Did you find it challenging to keep yourself motivated throughout the entire training period?

Q7: What could be done differently to improve adherence to the exercise?

Q8: What do you think of carrying out arm cycling followed by therapeutic exercise for balance at home?

Q9: Did you receive enough instructions/ support on how to exercise at home?

Q10: In which way would you prefer to receive support? (e.g., text message, email, phone call)

Q11: What could be done differently to recruit new people for the study?

Q12: How would you like to be approached for participation?

Q13: What would be possible reasons not to participate in the study?

8.2 Conference abstract: High-density surface electromyography is reliable in assessing characteristics of trunk extensors during static and dynamic tasks

J.F.L. van Helden, E. Martinez-Valdes, P.H. Strutton, D. Falla, S.Y. Chiou

Introduction: High-density surface electromyography (HDsEMG), which involves recording muscle activity from multiple arrays of electrodes, can be used to assess the spatial distribution of muscle activity. While reliability of HDsEMG has been reported for muscles of the limbs, it has not been established for axial muscles, such as the Erector Spinae (ES), a trunk extensor. The study aimed to establish intra- and inter-session reliability of HDsEMG-derived parameters from the ES during static and dynamic goal-directed voluntary movements, and during functional reaching tasks where the ES acts as a postural muscle. **Methods:** Twenty healthy participants (age 27.9 ± 4.9 years; weight 68.25 ± 11.08 kg; height 169.5 ± 8.5 cm; 10 males; 18 right-handed) performed: 1) static trunk extension (Ito test) and reverse trunk extension, 2) dynamic trunk flexion and lateral trunk flexion, and 3) multidirectional functional reaching tasks. During the tasks, ES activity from the 8^{th} to 12^{th} thoracic vertebrae was recorded using two electrode grids (64 monopolar channels each). The same procedures were repeated in all participants on a different day (between-session interval: 7.5 ± 1.2 days). Root Mean Square (RMS), barycenter, Mean Frequency (MNF), and entropy were derived from differential HDsEMG, and Intra-class Correlation Coefficient (ICC; mixed model, absolute agreement) was calculated for these parameters. **Results:** Good to excellent within-session reliability was found for RMS (ICC .91 - .98), barycenter (.88 - .99), MNF (.88 - .97), and entropy (.79 - .97) for all tasks. Between-session reliability varied across parameters and tasks. For static trunk extension and reverse trunk extension, moderate to excellent reliability was found for all parameters (.62 - .97), albeit poor reliability was found in entropy for the reverse trunk extension. For dynamic trunk flexion and lateral trunk flexion, moderate to excellent reliability was found in RMS (.85 - .92) and MNF (.66 - .93), whereas poor to good reliability was found in entropy (.23 - .51) and the barycenter (.23 - .77). For multidirectional reach tasks, good to excellent reliability was found in RMS (.82 - .91) and MNF (.81 - .92), while poor to excellent reliability was found in barycenter (.49 - .92) and entropy (.21 - .84). **Conclusion:** RMS and MNF derived from the HDsEMG show consistent within- and between-session reliability in goal-directed voluntary movements and postural tasks of the trunk. Hence, HDsEMG is a reliable tool for assessing characteristics of the ES muscle and therefore suitable to be used in quantifying changes in neuromuscular function.

8.3 Conference abstract: Neuromuscular changes during postural adjustments and functional reaching tasks after a home-based arm cycling training programme in individuals with chronic incomplete spinal cord injury

Joeri F L van Helden, Emma Alexander, Hélio V Cabral, Paul H Strutton, Eduardo Martinez-Valdes, Deborah Falla, Joy Roy Chowdhury, Shin-Yi Chiou

Abstract

Objective: To investigate the effect and feasibility of a six-weeks, home-based arm cycling training programme on corticospinal excitability and volitional control of thoracic erector spinae (ES) in individuals with chronic incomplete spinal cord injury (SCI).

Population: Ten individuals with cervical or thoracic SCI (age 59±11 years; 8 males; AIS C-D, level of injury C3-T11, >1-year post-injury) were recruited for a six-weeks home-based arm cycling training programme from the Midland Centre for Spinal Injuries and social media.

Design/Data analysis: All participants underwent thirty minutes of arm cycling, five days a week for six weeks at home and undertook assessments before and after the programme at University of Birmingham. Corticospinal excitability of the ES was assessed via peak-to-peak amplitudes of motor evoked potentials (MEPs) elicited by transcranial magnetic stimulation over the primary motor cortex. Volitional control of the ES was evaluated via muscle activity and movements of the trunk during multidirectional reaching and perturbation tasks, measured by high-density electromyography (EMG) and 3-D motion capture system.

Results: Amplitudes of ES MEPs were increased after the intervention (142.89±43.46% of baseline MEP; $p=0.013$). Participants reached further (pre: 211.83±121.86 mm; post: 239.55±122,33 mm; $p=0.04$) and decreased root-mean-square amplitudes of ES EMG during forward reaching (74.16±20.78% of the baseline; $p=0.035$) at post-assessment. Exercise compliance was 99%.

Conclusion: Individuals with SCI increased corticospinal drive to the ES and improved volitional control of the trunk after the arm-cycling training programme. Exercise adherence was high.

Clinical impact statement: Home-based arm cycling is a feasible programme for trunk control after SCI.

8.4 Ethical approval

West Midlands - Edgbaston Research Ethics Committee
3rd Floor Barlow House
Minshull Street Manchester
M1 3DZ

Please note: This is the favourable opinion of the REC only and does not allow you to start your study at NHS sites in England until you receive HRA Approval.

24 March 2021

Dr Shinyi Chiou Lecturer
University of Birmingham
School of Sport, Exercise and Rehabilitation Sciences University of Birmingham
Edgbaston B15 2TT

Study title:	**Functional activity of upper extremities to improve trunk function after spinal cord injury**
REC reference:	**21/WM/0047**
Protocol number:	**RG_20-149**
IRAS project ID:	**289841**

Dear Dr Chiou,

Thank you for your letter of 18 March 2021, responding to the Research Ethics Committee's (REC) request for further information on the above research and submitting revised documentation.

The further information has been considered on behalf of the Committee by the Chair.

Confirmation of ethical opinion

On behalf of the Committee, I am pleased to confirm a favourable ethical opinion for the above research on the basis described in the application form, protocol and supporting documentation as revised, subject to the conditions specified below.

Good practice principles and responsibilities

The UK Policy Framework for Health and Social Care Research sets out principles of good practice in the management and conduct of health and social care research. It also outlines the responsibilities of individuals and organisations, including those related to the four elements of research transparency:

1. registering research studies
2. reporting results
3. informing participants
4. sharing study data and tissue

Conditions of the favourable opinion

The REC favourable opinion is subject to the following conditions being met prior to the start of the study. Guidance on applying for HRA and HCRW Approval (England and Wales)/ NHS permission for research is available in the Integrated Research Application System.

For non-NHS sites, site management permission should be obtained in accordance with the procedures of the relevant host organisation.

Sponsors are not required to notify the Committee of management permissions from host organisations

Registration of Clinical Trials

All research should be registered in a publicly accessible database and we expect all researchers, research sponsors and others to meet this fundamental best practice standard. It is a condition of the REC favourable opinion that **all clinical trials are registered** on a publicly accessible database within six weeks of recruiting the first research participant. For this purpose, 'clinical trials' are defined as the first four project categories in IRAS project filter question 2. Failure to register a clinical trial is a breach of these approval conditions, unless a deferral has been agreed by or on behalf of the Research Ethics Committee (see here for more information on requesting a deferral: https://www.hra.nhs.uk/planning-and-improving-research/research-planning/research-registration-research-project-identifiers/

If you have not already included registration details in your IRAS application form, you should notify the REC of the registration details as soon as possible.

Further guidance on registration is available at: https://www.hra.nhs.uk/planning-and-improving- research/research-planning/transparency-responsibilities/

Publication of Your Research Summary

We will publish your research summary for the above study on the research summaries section of our website, together with your contact details, no earlier than three months from the date of this favourable opinion letter.

Should you wish to provide a substitute contact point, make a request to defer, or require further information, please visit: https://www.hra.nhs.uk/planning-and-improving-research/application- summaries/research-summaries/

N.B. If your study is related to COVID-19 we will aim to publish your research summary within 3 days rather than three months.

During this public health emergency, it is vital that everyone can promptly identify all relevant research related to COVID-19 that is taking place globally. If you haven't already done so, please register your study on a public registry as soon as possible and provide the REC with the registration detail, which will be posted alongside other information relating to your project. We are also asking sponsors not to request deferral of publication of research summary for any projects relating to COVID-19. In addition, to facilitate finding and extracting studies related to COVID-19 from public databases, please enter the WHO official acronym for the coronavirus disease (COVID-19) in the full title of your study. Approved COVID-19 studies can be found at: https://www.hra.nhs.uk/covid-19-research/approved-covid-19-research/

It is the responsibility of the sponsor to ensure that all the conditions are complied with before the start of the study or its initiation at a particular site (as applicable).

After ethical review: <u>Reporting requirements</u>

The attached document "After ethical review – guidance for researchers" gives detailed guidance on reporting requirements for studies with a favourable opinion, including:

- Notifying substantial amendments
- Adding new sites and investigators
- Notification of serious breaches of the protocol
- Progress and safety reports
- Notifying the end of the study, including early termination of the study
- Final report
- Reporting results

The latest guidance on these topics can be found at https://www.hra.nhs.uk/approvals-amendments/managing-your-approval/.

Ethical review of research sites

NHS/HSC sites

The favourable opinion applies to all NHS/HSC sites taking part in the study, subject to confirmation of Capacity and Capability (in England, Northern Ireland and Wales) or management permission (in Scotland) being obtained from the NHS/HSC R&D office prior to the start of the study (see "Conditions of the favourable opinion" below).

Non-NHS/HSC sites

I am pleased to confirm that the favourable opinion applies to any non-NHS/HSC sites listed in the application, subject to site management permission being obtained prior to the start of the study at the site.

Approved documents

The final list of documents reviewed and approved by the Committee is as follows:

Document	*Version*	*Date*
Contract/Study Agreement template [PIC agreement with NSIC]	v1	28 October 2020
Contract/Study Agreement template [PIC agreement with MCSI]	v1	28 October 2020
Copies of materials calling attention of potential participants to the research [study flyer - patients]	v2	05 March 2021
Copies of materials calling attention of potential participants to the research [study flyer - healthy participants]	v2	05 March 2021
Copies of materials calling attention of potential participants to the research [Radio advertisement]	v1	18 March 2021
Evidence of Sponsor insurance or indemnity (non NHS Sponsors only) [Sponsor indemnity]		01 August 2020
GP/consultant information sheets or letters [GP letter template]	v1	01 March 2021
Interview schedules or topic guides for participants [Exercise instruction experimental group]	v1	04 October 2020
Interview schedules or topic guides for participants [Focus group protocol]	v1	04 October 2020
Interview schedules or topic guides for participants [Exercise instruction control group]	v1	04 October 2020
IRAS Application Form [IRAS_Form_29012021]		29 January 2021
IRAS Application Form XML file [IRAS_Form_29012021]		29 January 2021
Letter from funder [Contract]		17 February 2020
Letter from sponsor [CI and sponsor agreement]		04 October 2020
Letters of invitation to participant [Invitation for participation]	v1	04 October 2020
Non-validated questionnaire [Questionnaire]	v1	04 October 2020
Non-validated questionnaire [TMS questionnaire]	v1	04 October 2020
Organisation Information Document [Organisation information document]	v1	28 October 2020
Other [Response to HRA & HCRW]	v1	18 March 2021
Participant consent form [PCF_healthy]	v1	04 October 2020

Participant consent form [PCF_patient]	V2	01 March 2021
Participant information sheet (PIS) [PIS_patient]	V2	01 March 2021
Participant information sheet (PIS) [PIS_healthy]	V2	01 March 2021
Research protocol or project proposal [Study protocol]	V2	04 March 2021
Sample diary card/patient card [Exercise diary control group]	v1	04 October 2020
Sample diary card/patient card [Exercise diary experimental group]	v1	04 October 2020
Sample diary card/patient card [Reply slip in person]	v1	04 October 2020
Sample diary card/patient card [Reply slip by post]	v1	04 October 2020
Sample diary card/patient card [Data collection sheet template]	v1	04 October 2020
Sample diary card/patient card [Intervention log template]	v1	04 October 2020
Schedule of Events or SoECAT [Schedule of Events]	v1	27 October 2020
Summary CV for Chief Investigator (CI) [CI's CV]		16 October 2020
Summary CV for student [Student CV]		28 October 2020

Statement of compliance

The Committee is constituted in accordance with the Governance Arrangements for Research Ethics Committees and complies fully with the Standard Operating Procedures for Research Ethics Committees in the UK.

User Feedback

The Health Research Authority is continually striving to provide a high-quality service to all applicants and sponsors. You are invited to give your view of the service you have received and the application procedure. If you wish to make your views known please use the feedback form available on the HRA website: http://www.hra.nhs.uk/about-the-hra/governance/quality- assurance/

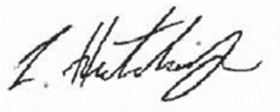
HRA Learning

We are pleased to welcome researchers and research staff to our HRA Learning Events and online learning opportunities– see details at: https://www.hra.nhs.uk/planning-and-improving-research/learning/

IRAS project ID: 289841   Please quote this number on all correspondence

With the Committee's best wishes for the success of this project.

Yours sincerely,



P.P.

Professor John Marriott

Chair

8.5 Trunk Impairment Scale (TIS)

The starting position for each item is the same. The patient is sitting on the edge of a bed or treatment table without back and arm support. The thighs make full contact with the bed or table, the feet are hip width apart and placed flat on the floor. The knee angle is 90. The arms rest on the legs. If hypertonia is present the position of the hemiplegic arm is taken as the starting position. The head and trunk are in a midline position. If the patient scores 0 on the first item, the total score for the TIS is 0. Each item of the test can be performed three times. The highest score counts. No practice session is allowed. The patient can be corrected between the attempts. The tests are verbally explained to the patient and can be demonstrated if needed.

Item				
	Static sitting balance			
1	Starting position	Patient falls or cannot maintain starting position for 10 seconds without arm support	□	0
		Patient can maintain starting position for 10 seconds If score5 0, then TIS total score5 0	□	2
2	Starting position Therapist crosses the unaffected leg over the hemiplegic leg	Patient falls or cannot maintain sitting position for 10 seconds without arm support	□	0
		Patient can maintain sitting position for 10 seconds	□	2
3	Starting position Patient crosses the unaffected leg over the hemiplegic leg	Patient falls	□	0
		Patient cannot cross the legs without arm support on bed or table	□	1
		Patient crosses the legs but displaces the trunk more than 10 cm backwards or assists crossing with the hand	□	2
		Patient crosses the legs without trunk displacement or assistance	□	3
		Total static sitting balance		/7
	Dynamic sitting balance			
1	Starting position Patient is instructed to touch the bed or table with the hemiplegic	Patient falls, needs support from an upper extremity or the elbow does not touch the bed or table without arm support	□	0

	elbow (by shortening the hemiplegic side and lengthening the unaffected side) and return to the starting position	Patient moves actively without help, elbow touches bed or table If score5 0, then items 2 and 3 score 0	□	1
2	Repeat item 1	Patient demonstrates no or opposite shortening/lengthening	□	0
		Patient demonstrates appropriate shortening/lengthening	□	1
3	Repeat item 1	Patient compensates. Possible compensations are: (1) use of upper Extremity, (2) contralateral hip abduction, (3) hip flexion (if elbow touches bed or table further then proximal half of femur), (4) knee flexion, (5) sliding of the feet	□	0
		Patient moves without compensation	□	1
4	Starting position Patient is instructed to touch the bed or table with the unaffected	Patient falls, needs support from an upper extremity or the elbow does not touch the bed or table	□	0
	elbow (by shortening the unaffected side and lengthening the hemiplegic side) and return to the starting position	Patient moves actively without help, elbow touches bed or table If score5 0, then items 5 and 6 score 0	□	1
5	Repeat Item 4	Patient demonstrates no or opposite shortening/lengthening	□	0
		Patient demonstrates appropriate shortening/lengthening If score5 0, then item 6 scores 0	□	1
6	Repeat item 4	Patient compensates. Possible compensations are: (1) use of upper extremity, (2) contralateral hip abduction, (3) hip flexion (if elbow touches bed or table further then proximal half of femur), (4) knee flexion, (5) sliding of the feet	□	0
		Patient moves without compensation	□	1
7	Starting position Patient is instructed to lift pelvis from bed or table at the	Patient demonstrates no or opposite shortening/lengthening	□	0
	hemiplegic side (by shortening the hemiplegic side and lengthening the unaffected side) and return to the starting position	Patient demonstrates appropriate shortening/lengthening If score 5 0, then item 8 scores 0	□	1
8	Repeat item 7	Patient compensates. Possible compensations are: (1) use of upper extremity, (2) pushing off with the ipsilateral foot (heel loses contact with the floor)	□	0

		Patient moves without compensation	□	1
9	Starting position	Patient demonstrates no or opposite shortening/lengthening	□	0
	Patient is instructed to lift pelvis from bed or table at the unaffected side (by shortening the unaffected side and lengthening the hemiplegic side) and return to the starting position	Patient demonstrates appropriate shortening/lengthening	□	1
		If score 5 0, then item 10 scores 0		
10	Repeat item 9	Patient compensates. Possible compensations are: (1) use of upper extremities, (2) pushing off with the ipsilateral foot (heel loses contact with the floor)	□	0
		Patient moves without compensation	□	1
		Total dynamic sitting balance		/10
	Co-ordination			
1	Starting position	Hemiplegic side is not moved three times	□	0
	Patient is instructed to rotate upper trunk 6 times	Rotation is asymmetrical	□	1
	(every shoulder should be moves forward 3 times), first side that moves must be hemiplegic side, head should be fixated in starting position	Rotation is symmetrical	□	2
		If score 5 0, then item 2 scores 0		
2	Repeat item 1 within 6 seconds	Rotation is asymmetrical	□	0
		Rotation is symmetrical	□	1
3	Starting position	Hemiplegic side is not moved three times	□	0
	Patient is instructed to rotate lower trunk 6 times (every knee should be moved	Rotation is asymmetrical	□	1
	forward 3 times), first side that moves Must be hemiplegic side, upper trunk Should be fixed in starting position	Rotation is symmetrical	□	2
		If score 5 0, then item 4 scores 0		
4	Repeat item 3 within 6 seconds	Rotation is asymmetrical	□	0
		Rotation is symmetrical	□	1
		Total co-ordination		/6
		Total trunk impairment scale		/23

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