TRUNK MUSCLE ACTIVATION PATTERNS DURING WALKING WITH ROBOTIC EXOSKELETONS IN PEOPLE WITH HIGH THORACIC MOTOR-COMPLETE SPINAL CORD INJURY

by

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B.Sc.PT, King Saud University, 2008

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF

THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

in

THE FACULTY OF GRADUATE AND POSTDOCTORAL STUDIES

(Kinesiology)

THE UNIVERSITY OF BRITISH COLUMBIA

(Vancouver)

April 2017

Abstract

Background: Maintaining postural stability during sitting or standing depends critically on motor function in the trunk muscles. Trunk muscle function is typically assumed to be poor or absent in people with a complete spinal cord injury (SCI) at or above the thoracic level. However, recent studies have revealed sparing of trunk muscle function in people with high-thoracic motor-complete SCI, opening up the possibility for training techniques to improve their function. The Lokomat and Ekso are used in gait rehabilitation for people with SCI, but it remains unknown how much they engage those trunk muscles that are normally activated during walking. These devices provide gait training in different methods. In Lokomat, the trunk is rigidly and passively supported by a body weight support harness, which could imply lesser recruitment of postural muscles. In contrast, the Ekso requires continuous weight shifting from one limb to the other to trigger steps, which could lead to better postural muscle activation.

Objective: To compare trunk muscle activation patterns during Ekso- vs Lokomat-assisted walking in people with high-thoracic motor-complete SCI.

Methods: 8 individual with C7-T4 chronic motor-complete SCI were recruited. Subjects performed 3 walking conditions (at matched speeds): Lokomat-assisted walking (Loko-TM), Ekso-assisted walking on treadmill (Ekso-TM), and Ekso-assisted walking overground (Ekso-OG). Surface electromyography (EMG) signals were recorded bilaterally from rectus abdominis (RA), external oblique (EO), and erector spinae (ES) and normalized to (attempted) maximum voluntary contraction (MVC). EMG amplitudes were compared during baseline (lying supine)

(BAS) and across the 3 walking conditions. EMG onset and total activity times were compared across the 3 walking conditions.

Results: Trunk EMG amplitudes were significantly higher in Ekso-TM compared to both Loko-TM and BAS. RA and ES amplitudes were not different during Loko-TM walking compared to BAS. When Ekso-OG was compared to Ekso-TM, only ES amplitude was significantly different. Onset and total activity times were not significantly different across the walking conditions

Conclusion: Ekso-assisted walking was better in activating trunk muscles than the Lokomat-assisted walking. These results suggest that Ekso could possibly be used to train trunk strength and improve sitting postural control in people with high-thoracic motor-complete SCI.

Preface

The idea of this project was developed through discussions with my thesis supervisor Dr. Tania Lam about the benefits of gait training (in Ekso and Lokomat) for people with complete SCI. Dr. Mark Carpenter and Dr. Janice Eng contributed in the concept formation. The hypotheses and research design was developed by myself in consultation with Dr. Lam and Dr. Amanda Chisholm, a postdoctoral fellow with Dr. Lam.

All data collection and analysis were performed by myself under the guidance of Dr. Lam. Dr. Mark Carpenter suggested EMG timing data analysis and statistical analysis.

This project was approved by the Clinical Research Ethics Board of UBC (“Ekso”, H15-03040).

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Acknowledgements

First and foremost, I thank God for giving me this opportunity and granting me the capability and strength to complete this wonderful journey.

This journey started when I met Dr. Tania Lam, my thesis supervisor, in 2012 at the International Exhibition & Conference on Higher Education in Riyadh, Saudi Arabia. From that day, Dr. Lam has provided me with support and guidance throughout the application process at UBC. She has assuredly continued her support and guidance after I started my Masters program in 2014. I have always been interested in research, but throughout my journey and because of her enduring guidance, I enjoyed and loved doing research. I am gratefully and sincerely thankful to her for this amazing experience.

To my committee members, Dr. Janice Eng and Dr. Mark Carpenter, I am sincerely thankful for your valuable insights and continuous support.

I would like to express my gratitude to King Fahad Medical City for making this journey possible. My gratitude extends to the past and present members of the Human Locomation Laboratory at ICORD for their support throughout this journey. My special thanks are owed to Dr. Amanda Chisholm and Alison Williams for their help in the long data collection sessions.

Lastly, I would like to express my sincere thanks for my family for their support. I am deeply grateful for Emtenan, my wife, and Hessah, my daughter for their love, sacrifice and support. I could not have done this without you!

Chapter 1: Introduction

Sustaining a spinal cord injury (SCI) is a traumatic and devastating event that has a severe impact on a person's life. The consequences of such injury can be physical, social and psychological in nature (Dijkers, 1997; Kennedy & Rogers, 2000; Kennedy, Lude, & Taylor, 2005; Leduc & Lepage, 2002). It is estimated that there are 12-58 cases per million of SCI annually worldwide (van den Berg, Castellote, Mahillo-Fernandez, & de Pedro-Cuesta, 2010). Spinal cord injuries could occur as a result of traumatic or non-traumatic injuries to the spinal cord. Motor vehicle accidents and falls are the most common causes of traumatic SCI (Singh, Tetreault, Kalsi-Ryan, Nouri, & Fehlings, 2014; van den Berg et al., 2010). Non-traumatic SCI are caused by other diseases affecting the spine, such as vertebral spondylosis, tumors, vascular ischemia, congenital diseases and inflammatory conditions (New, Rawicki, & Bailey, 2002; van der Putten, Stevenson, Playford, & Thompson, 2001).

Depending on the level and severity of the injury, a SCI could result in various levels of paralysis causing severe mobility and functional limitations. Many of these functional limitations arise from the loss of postural control and the ability to maintain sitting balance due to complete or partial paralysis of the trunk muscles (Seelen, Potten, Huson, Spaam, & Reulen, 1997). However, trunk muscle function is usually overlooked during SCI classification. The International Standards for Neurological Classification of Spinal Cord Injury is used world-wide for evaluating and classifying SCI. However, it relies on sensory tests only to evaluate motor function in the thoracic segments of the spinal cord, which could result in uncertain assumptions about the motor function of these segments (Kirshblum et al., 2011). Electromyography, ultrasound, and transcranial magnetic stimulation have been used in several studies to provide evidence that there could be sparing of motor function in the abdominal muscles below the level of injury in high thoracic motor-complete SCI (Bjerkefors, Carpenter, Cresswell, & Thorstensson, 2009; Bjerkefors et al., 2014; 2015). These findings have implications for rehabilitation as any preserved abdominal muscle function has the potential for further improvements in postural control and function (Chen et al., 2003; Fujita et al., 2015). Therefore, finding rehabilitative techniques to reactivate and train these muscles could improve postural control and stability in persons with SCI.

In able-bodied individuals, the axial muscles are rhythmically activated during walking (Anders et al., 2007; de Sèze, Falgairolle, Viel, Assaiante, & Cazalets, 2007; Tang, Woollacott, & Chong, 1998). Robotic exoskeletons, such as the Lokomat and Ekso, are used in gait rehabilitation for people with SCI, but it remains unknown the extent to which they engage and have the potential to retrain those trunk muscles that are normally activated during walking. The Lokomat and Ekso use different methods to provide gait training. In the Lokomat, gait training is provided on a treadmill with the trunk passively supported by an overhead harness that provides weight support. However, the user's body is rigidly held within the Lokomat, which could imply lesser degree of recruitment of postural muscles. In contrast, gait training in the Ekso is provided overground and requires continuous participation from the user to maintain balance while shifting weight from one limb to the other in order to activate the Ekso's legs to walk. This mechanism could lead to better postural muscle activation. Therefore, the overall objective of this study was to characterize and compare the activation patterns of the axial muscles during walking with the Ekso and the Lokomat in people with high thoracic motor-complete SCI. It is anticipated that improved understanding of the potential for different rehabilitation therapies to recruit and possibly strengthen the trunk muscles could have implications for improving postural control in SCI, thereby enhancing functional performance in daily activities.

1.1 Clinical assessment of neurological damage due to spinal cord injury

Injury to the spinal cord may occur at various levels of the spine affecting the neurological fibers at and below that level. The level and severity of injury determine the extent of sensory and motor deficits and the classification of the SCI. The spinal cord consists of 31 segments: eight cervical, twelve thoracic, five lumbar, five sacral and one coccygeal. Injuries at the cervical spine level are the most common, representing 54% of all injuries, followed by thoracic- and lumbar-level injuries representing 24 and 19% of all injuries, respectively (van den Berg et al., 2010). High thoracic injuries account for two thirds of all thoracic injuries (Goebert, Ng, Varney, & Sheetz, 1991) making the majority of SCIs occurring above T6 level. An SCI can also be characterized as complete or incomplete. Complete spinal cord injuries account for 55% of all SCIs (Rahimi-Movaghar et al., 2013; M. Wyndaele & Wyndaele, 2006), and are defined as the absence of sensory and motor function below the level of injury and extending to the lowest sacral segment. An incomplete SCI is defined by partial preservation of sensory and/or motor functions in all of the spinal segments below the injury level (Kirshblum et al., 2011).

Each spinal segment has a pair of dorsal (sensory) and ventral (motor) roots that merge together to form spinal nerves projecting from each side of the spinal segment. The skin over the entire body can be divided into sensory regions (dermatomes) that are innervated by these sensory nerve roots. Likewise, motor roots innervate the muscles and form myotomes. Each myotome consists of a single motor nerve root and all the muscles that it innervates (Cho, 2015). The International Standards for Neurological Classification of Spinal Cord Injury (ISNCSCI) assessment of the level and severity of a spinal cord injury relies on the systematic clinical examination of the sensation and muscle strength as mapped by these dermatomes and certain 'key' myotomes, respectively. In the sensory examination, light touch and pin prick sensation are tested on key points in 28 dermatomes from C2 to S4-5 on the right and left sides of the body. The motor examination is based on manual muscle testing of key muscles representing 10 myotomes from the upper (C5-T1) and lower (L2-S1) limbs on both sides of the body. The presence of non-key muscle activity can be documented but is not used in determining motor levels or scores (Kirshblum et al., 2011). Therefore, the INSCSCI assessment relies only on the sensory tests to determine the level and completeness of the lesion in the thoracic segments of the spinal cord, which results in uncertain assumptions about the motor function of the axial muscles.

There are two major descending pathways that travel through the spinal cord to innervate the trunk muscles: the anterior corticospinal tract, which originates in the motor cortex and controls the voluntary movement of the proximal musculature, and the vestibulospinal tract, which originates from the brainstem and controls axial muscles to maintain postural stability during sitting, standing and walking (Lemon, 2008). According to the site of the lesion, a spinal cord injury could affect axial muscle innervation through these tracts. The anterior corticospinal tract and the vestibulospinal pathways descend in the ventral column of the spinal cord white matter and terminate in the cervical and upper thoracic spinal segments except the lateral vestibulospinal pathway, which descends through the ventrolateral and ventral regions of the spinal cord white matter (Blumenfeld, 2010). The majority of abdominal muscles are innervated by the intercostal nerves that arise from the anterior rami of the thoracic spinal nerves from T7-T11, whereas the erector spinae muscles of the back are innervated by the posterior rami of the cervical, thoracic and lumbar nerves (Leonard & Collection, 1995). Thus, lesions to the anterior cord in the cervical or upper thoracic tract could result in damage to these tracts.

1.2 Trunk impairment and functional implication after SCI

Axial muscles have a major role in maintaining sitting and standing postural stability (Masani et al., 2009). In sitting and standing positions, trunk muscles are activated to support the spine and maintain stability during different postures. For instance, the superficial lumbar multifidus (MF), internal oblique (IO), and erector spinae (ES) muscles tend to be activated more during erect sitting compared to slump sitting position while rectus abdominis (RA) and external oblique (EO) remain activated in both positions (O'Sullivan et al., 2002). In standing, superficial MF, IO and ES muscles activity significantly decrease as subjects moved from erect standing into sway standing (when participants relax and allow the pelvis to translate anteriorly relative to the trunk). Conversely, RA muscle and EO increase in activity in the sway standing position (O'Sullivan et al., 2002).

The ability to maintain postural stability either during sitting or standing is important for people with spinal cord injury to perform daily functional activities (Chen et al., 2003; Janssen-Potten, Seelen, Drukker, & Reulen, 2000; Scivoletto et al., 2008). Seated postural stability is especially significant because the majority of people with SCI need to perform their daily functional activities while in a seated position. For example, transfers, grooming, showering, eating, reaching and dressing all require seated stability, whether in a wheelchair, regular chair, commode or over the edge of the bed. Indeed, performance in these activities is correlated to the ability to maintain sitting balance (Chen et al., 2003). Consequently, SCI individuals with poor sitting balance usually have reduced level of physical activity, participation in sport and quality of life (J. Douglas, 2005). Thus, improving seated postural stability is an essential goal in most SCI rehabilitation programs.

1.3 Evaluation of trunk control in SCI reveals sparing of motor function below the level of injury

Clinical assessments of trunk control in SCI typically rely on functional tests of postural stability (Boswell-Ruys, Sturnieks, et al., 2009b; Field-Fote & Ray, 2010; Lynch, Leahy, & Barker, 1998; Sprigle, Maurer, & Holowka, 2007). Reach tests such as the modified Functional Reach test, the Reach Area task, and the Bilateral Reach evaluate postural stability by testing the ability of people with SCI to reach in different directions while seated unsupported without losing balance (Lynch et al., 1998; Sprigle et al., 2007). Other tests include the Upper Body Sway test, which measures how much the person with SCI sway in unsupported quiet sitting and the T-shirt test, which measures the time required to put on and take off a t-shirt to evaluate sitting balance (Boswell-Ruys, Sturnieks, et al., 2009b). However, these tests could be limited in their ability to identify the reliance on compensatory strategies (Potten, Seelen, Drukker, Reulen, & DROST, 1999; Seelen, Potten, Drukker, Reulen, & Pons, 1998; Seelen & Vuurman, 1991) to complete these tasks.

In recent years, there has been a move towards developing more precise assessment tools to evaluate trunk muscle function. Manual palpation of the abdominal muscles during different trunk tasks has been used to assess trunk function in Paralympic athletes (Altmann, Groen, van Limbeek, Vanlandewijck, & Keijsers, 2013; Pernot et al., 2011). Ultrasound has also been used for assessing abdominal muscle activity by measuring the changes in the muscle thickness (Ferreira et al., 2011; Hodges, Pengel, Herbert, & Gandevia, 2003; Teyhen et al., 2007). The use of electromyography (EMG) has also been demonstrated as an effective and reliable method to measure abdominal muscle activity and function (Bjerkefors et al., 2014). In a study by Bjerkefors et al. (2014) of people with SCI, the sensitivity and specificity of ultrasound and manual palpation of abdominal muscles were compared to that of surface EMG. Participants with motor-complete SCI ranging from C4 to T5 and matched able-bodied participants were tested while performing four different trunk tasks: trunk flexion, trunk rotation to left and right and hollowing maneuver. Ultrasound showed high specificity in measuring voluntary muscle activity but had poor sensitivity in all tasks. Manual abdominal muscle palpation was more sensitive in detecting abdominal muscle function than ultrasound, but with less specificity. However, both methods had similar overall agreement and likelihood ratios with EMG (Bjerkefors et al., 2014).

The development of these more precise methods of trunk assessment has revealed the presence of abdominal muscle activity below the level of injury in individuals with motor-complete SCI who would not otherwise be expected to have spared trunk function (Bjerkefors et al., 2009; 2014; 2015). Bjerkefors et al. (2009) assessed trunk muscle activation in a person classified as T3 complete SCI by recording intramuscular EMG signals in response to balance perturbations. They found that the person could activate his trunk muscles voluntarily and also in response to sitting balance perturbations (Bjerkefors et al., 2009). Similarly, abdominal muscle activity has been detected by using surface EMG while individuals classified as T6 and above motor-complete SCI performed different trunk muscle tasks while lying supine: trunk flexion, trunk rotation to left and right, trunk lateral flexion to the left and right, hollowing maneuver and Valsalva maneuver (Bjerkefors et al., 2015). Surface EMG data showed voluntary muscle activity in one or more of the abdominal muscles while the participants performed the trunk tasks

(Bjerkefors et al., 2015). In the same study, transcranial magnetic stimulation (TMS) was used to investigate the connectivity of the motor tracts below the injury level. Motor evoked potentials were observed in the abdominal muscles of all these subjects, despite being clinically classified with motor-complete SCI (Bjerkefors et al., 2015). Squair et al. (2016) also showed that persons with motor-complete SCI had some observable activation in muscles below the level of injury in response to corticospinal or vestibulospinal stimulation (Squair, Bjerkefors, Inglis, Lam, & Carpenter, 2016). These findings are valuable because they reveal sparing of motor function in muscles that are assumed to be denervated (based on neurological injury level). This has implications for rehabilitation as any preserved abdominal muscle function has the potential for further improvements in postural control and function (Chen et al., 2003; Fujita et al., 2015).

1.4 Trunk muscle activation during locomotion

In addition to their role in sitting and standing (Masani et al., 2009), the axial muscles are also sequentially recruited during walking and other rhythmic motor tasks (Beliez, Barrière, Bertrand, & Cazalets, 2015; de Sèze et al., 2007). During walking, the whole body is involved. The lower extremities are the main walking actuators, but the arms and trunk are also involved. Indeed, successful locomotion requires not only the production of forces that propel the body into motion, but also forces that maintain postural stability (Earhart, 2013).

1.4.1 Recruitment of axial muscles during locomotion: animal studies

Detailed studies in animals have revealed an organized pattern of coordinated activation of muscle groups across the body (Falgairolle, de Sèze, Juvin, Morin, & Cazalets, 2006). For example, forward swimming movement in lampreys is achieved by left and right alterations of locomotor burst activity and sequential rostro-caudal activation of trunk muscles which result in a propagated wave moving the body forward (Grillner & Wallén, 2002). Notably, this coordinated rostro-caudal activation was also found in the isolated spinal cord and the pattern of EMG activity obtained from the spinal animals was similar to those obtained from the intact ones (Grillner & Wallén, 2002; Wallén & Williams, 1984). The spinal networks that control this activity consist of segmental oscillators distributed bilaterally along the spinal cord called the central pattern generators (CPGs) (Falgairolle et al., 2006). The CPGs are clusters of interconnected neurons that are capable of producing different types of rhythmic motor behaviors, such as swimming and walking, in the absence of sensory input (Falgairolle et al., 2006). The timing of the burst activity in the oscillators is critical for locomotion in lampreys. The rostro-caudal activation of the trunk muscles is achieved by a phase lag between bursts in adjacent segments. Oscillatory networks on both sides of each segmental level are coupled locally to the next segmental oscillators and to the distant segments by long propriospinal interneurons to coordinate the timing of activation (Falgairolle et al., 2006; Miller & Sigvardt, 2000).

Similar spinal organization to control trunk movements had also been found in quadrupeds. In the salamander (or newt), the EMG pattern during swimming is characterized by a rhythmic activation of the myomeres and a tonic activation of the limb muscles (as the limbs are held against the body). The activation of the epaxial musculature follows a lamprey-like rostrocaudal wave down the length of the body, but the propagation stalls at 2 sites along the trunk, at the segments located at the fore- and hindlimb level (Delvolve, Bem, & Cabelguen, 1997). During stepping, both myomeres and limb muscles are rhythmically activated, however, two waves of activity are initiated in the anterior and posterior regions of the trunk and travel in opposite directions to generate synchronous activity in the mid-trunk (Delvolve et al., 1997; Falgairolle et al., 2006). These two patterns of axial muscle activity in salamanders were proposed to be influenced by the limb CPGs in different ways according to the mode of locomotion (Delvolve et al., 1997). During swimming, the propagated wave is accelerated by an extra tonic excitation generated by the limbs CPGs and sent to the segmental networks nearby the limbs, whereas during walking, the axial oscillators are entrained by the limb CPGs (Delvolve et al., 1997).

Activation of the trunk muscles in synchrony with limb muscles has also been reported in different species of mammals (Falgairolle et al., 2006). For example, in walking spinal cats, the lumbar trunk muscles contract bilaterally with two bursts of activity per step cycle, similar to activation patterns of intact cats (Zomlefer, Provencher, Blanchette, & Rossignol, 1984). A study on neonatal rats has also found a rhythmic sequential change in trunk curvature during the step cycle (Falgairolle & Cazalets, 2007). In that study, recordings from multiple ventral roots were made to determine the pattern of coordination in the isolated spinal cord. It was found that during locomotor-like activity, rhythmic ventral root motor bursts propagate caudo-rostrally in the sacral and the thoracic spinal cord regions. Also, when isolated, the thoracic, lumbar and sacral regions were capable of generating right and left alternating motor bursts. However, the rhythmic activity generated by the thoracic and sacral areas is slower than the lumbar area (Falgairolle & Cazalets, 2007).

Studies on adult rats have found that rhythmic hindlimb locomotor activity is driven by the circuitry in the lumbar region. Neuronal circuitry capable of rhythmogenesis is distributed throughout the lumbar enlargement (Cowley & Schmidt, 1997; Kremer & Lev-Tov, 1997; Saunders, Rath, & Hodges, 2004). However, a study on the functional consequences of a spinal cord contusion at the lumbar level in adult rats has found that rhythmic hindlimb motor activity is dominated by circuitry in the L1 and L2 segments of the intact spinal cord (Magnuson et al., 2005). This CPG located in the rostral part of the lumbar enlargement is proposed to provide rhythmic locomotor output to neighboring rhythmic elements that in turn transfers and modulates the output to segmental motor neurons (Magnuson et al., 2005). Falgairolle et al., (2007) expands on this view to incorporate the entire spinal cord proposing that in an intact spinal cord, the lumbar area imposes its own timing on the thoracic and sacral spinal cord generators (Falgairolle & Cazalets, 2007). The model proposed by Falgairolle et al., (2006) is that there are bilateral chains of rhythmic elements at each segmental level. These rhythmic elements are responsible for the propagation of activity and axial muscle control. Each segment is connected to the adjacent segment by a local circuit interaction. The local circuit interactions between adjacent segments mediate the longitudinal propagation of motor activity. Additionally, there are long propriospinal pathways that project over many segments along the spinal cord that are also involved in the coordination of the propagated activity. Left-right alternation of burst activity is regulated by cross-cord inhibitory connections in each segment. Fore- and hind limbs as well as axial motor activity are dominated by hindlimb CPG circuitry located in the L1 and L2 segments of the intact spinal cord. Therefore, the coordinated axial motor activity in the caudo-rostral direction is influenced by the lumbar CPG (Falgairolle et al., 2006).

1.4.2 Axial muscle activation patterns during human walking

Achieving successful locomotion is more challenging and complex in human bipedal walking than quadrupeds. This is due to the smaller base of support in bipedal gait, the long single-support stance phase, and the fact that 2/3 of the body's mass is located in the head, arm and trunk segments (Winter, Ruder, & MacKinnon, 1990). With these extra challenges, the axial muscles need to counter-balance the upper body acceleration and help maintaining its steadiness during walking (de Sèze et al., 2007; Tang et al., 1998; Winter & Yack, 1987).

Kinematic studies of the trunk during walking showed a general inclination of the trunk in the sagittal plane with lateroflexion on each side per gait cycle in the frontal plane and a phase opposition between higher and lower trunk rotations in the horizontal plane (Ceccato, de Sèze, Azevedo, & Cazalets, 2009; Feipel, De Mesmaeker, Klein, & Rooze, 2001). The general inclination of the trunk in the sagittal plane occurs during the preparatory phase of gait initiation until the double support phase with a decrease in lordosis angle. This inclination oscillates cyclically during walking, with peak inclination occurring just before double support and the lowest just after double support. In the frontal plane, the trunk bends towards the side of the first stance leg during the preparatory phase until the middle of the unloading phase. This bending reverses towards the side of the first swing passing through an aligned position at the transition between unloading and swing phase until the middle of the double support phase. In the horizontal plane, the thoracic region of the trunk rotates towards the swing leg and the direction of the rotation inverts around the double support phase (Ceccato et al., 2009).

Trunk muscles are sequentially activated during walking and have been noted along with the hip muscles to play several roles to maintain upper body steadiness (de Sèze et al., 2007; Tang et al., 1998). For instance, the head-arm-trunk flexion moment, which result from the posterior hip acceleration at heel strike is counter-balanced by the activation of the trunk and hip extensor muscles (Winter & Yack, 1987). Activity in the ES, gluteus maximus and hamstrings muscles is initiated prior to heel strike and remains active during the first half of the stance phase of walking to maintain the upright posture of the trunk (Tang et al., 1998). Lower limb, abdominal and back muscles contribute to the angular acceleration of the trunk during walking. A study investigating the contribution of individual muscles to sagittal and frontal plane angular accelerations of the trunk in walking found that during the initial double support phase, the back and hip-flexor muscles accelerated the trunk backward, while the hamstring, abdominal and gluteus muscles accelerated it forward (Klemetti, Steele, Moilanen, Avela, & Timonen, 2014). In the frontal plane during double support, the abdominal and back muscles on each side are primarily responsible for producing the angular accelerations for their side of the body. During single support phase in the sagittal plane, muscles that contributed to trunk angular movement during the double-support phase had the same role, but the contribution of individual muscles varied with time. For example, the contribution of the hip flexors in the swing limb (contralateral side) decreased from the initial double support phase to the end of single support phase. However, abdominal and back muscles had large contributions to the trunk angular acceleration in both the sagittal and frontal planes (Klemetti et al., 2014). Therefore, enhancing the function of the abdominal and back muscles could improve postural stability during locomotion.

Activation of the trunk muscles is modulated throughout the gait cycle and each muscle has a different activation onset time and pattern (Saunders, Schache, Rath, & Hodges, 2005; Waters & Morris, 1972; White & McNair, 2002). As aforementioned, the peak activity for the ES muscles occur just before heel-strike to control forward rotation of the trunk (White & McNair, 2002; Winter & Yack, 1987). However, its EMG activity considerably decreases after heel strike (White & McNair, 2002). RA, IO and EO muscles have been reported in several studies to have two patterns of EMG activity during locomotion (Callaghan, Patla, & McGill, 1999; Sheffield, 1962; Waters & Morris, 1972; White & McNair, 2002; Winter & Yack, 1987).

In the majority of able-bodied participants in these studies, RA muscle activity was low and constant throughout the gait cycle. However in a small group of participants, RA was active at heel strike (White & McNair, 2002), and in another study, RA was active at mid stance in 50% of the participants (Waters & Morris, 1972). The IO muscle in the majority of participants showed continuous activity throughout the gait cycle (Waters & Morris, 1972; White & McNair, 2002), although 36% of the participants in the White et al. study had a peak activity at mid to late stance phase of each leg (White & McNair, 2002). Similar to IO, the EO muscle had a low and constant activity throughout the gait cycle in the majority of participants (Callaghan et al., 1999; White & McNair, 2002). However, 19% of the participants in the White et al. study showed peak EMG activity in the EO muscle occurring close to heel strike (White & McNair, 2002).

Trunk activation pattern also has been noted to change with walking speed. In a study by Anders et al. (2007), trunk muscle activation in able-bodied participants was investigated by recording surface EMG during treadmill walking at different speeds. They observed that each muscle had a different activation pattern throughout the gait cycle. With increasing walking speed, the phase dependent activation remained similar, but the mean amplitudes increased generally (Anders et al., 2007). RA was most activated at ipsilateral heel strike, and at ipsilateral as well as contralateral propulsion. In the IO and EO, peak EMG amplitude occurred during contralateral propulsion phase. Also, distinct but smaller amplitude peaks for IO occurred at ipsilateral heel strike and pad (the ball of the foot) contact and for EO with the contralateral heel strike. For the MF and ES, peak amplitude was observed for both at heel strike (Anders et al., 2007). Also, activation peaks at ipsilateral heel strike and pad contact as well as during contralateral heel strike and propulsion phase increased with increasing speed. However, low-level activations during stance phases were independent from walking speed (Anders et al., 2007).

The speed and mode of locomotion also affects the pattern of recruitment of the trunk muscles and their respiratory and postural coordination. In a study by Saunders et al. (2004), participants walked and ran on a treadmill at different speeds while EMG activity was recorded from deep and superficial abdominal muscles. Similar to Anders et al. study, all trunk muscles showed increased activation with speed except transverse abdominis (TrA). At low speeds, TrA was activated tonically, but when speed increased, periods of inactivity of TrA (possibly due to increased intra-abdominal pressure) were noted following the ipsilateral toe-off phase. Additionally, when participants walked and ran at the same speed, there was a significant increase in the duration of EMG activity of ES and deep and superficial MF muscles with the change from walking to running, however the tonic activation of TrA was not affected. Saunders et al. (2004) also identified a dual postural and respiratory modulation for TrA, IO and OE muscles, but no respiratory activity was identified for the paraspinal muscles. Remarkably, as locomotor speed increased, postural demand increased, but the TrA, IO and EO muscles respiration's demand decreased. This was explained as that during locomotion, the central nervous system has to coordinate abdominal muscle activity to simultaneously control expiratory airflow and postural control, however under certain conditions it may give one system a priority (Saunders et al., 2004).

Similar to cats, lumbar ES muscles during human locomotion contracts bilaterally with two burst of activity per step cycle (Thorstensson, Carlson, Zomlefer, & Nilsson, 1982). In fact, the metachronal propagation is not only restricted to animals. In a study by de Seze et al., (2007), EMG recordings were obtained from back muscles across various trunk levels while participants performed different locomotor behaviors: forward walking (FW), backward walking (BW), amble walking (arms moved in phase with ipsilateral leg), walking on hands and knees (HK), walking on hands with the knees on the edge of a treadmill (Hand), and swinging arms while standing (Swing). Back muscle activation and the direction of the motor wave differed according to the walking condition. Double bursts of rhythmic activity with rostro-caudal propagation occurred during FW, BW and HK conditions, and with a stationary motor wave in amble walk condition, while Swing and Hands conditions produced a monophasic rhythmic activity with a caudo-rostral propagation. These results show specificity in the temporal pattern elicited in the axial muscles that depend on the performed motor task. These similarities between human (de Sèze et al., 2007) and rat data (Falgairolle & Cazalets, 2007) indicate that comparable mechanisms could be at work, which suggest that despite the more complex coordination, the coordination of trunk activity during bipedal walking is based on the same bilaterally-distributed chain of oscillators identified in the lamprey, but with limb CPGs and the associated interconnected pathways described in the model of Falgariolle et al. (Falgairolle et al., 2006).

1.5 Gait training as a potential strategy to facilitate trunk muscle activation

Dynamic postural control is a major contributor to independent gait performance (Winter, 1995). As reviewed above, the trunk muscles are sequentially activated during locomotion to maintain upper body steadiness (de Sèze et al., 2007; Tang et al., 1998). Gait training exoskeletons are commonly used to train walking function in people with SCI, but it remains unknown how much they engage postural control muscles that are normally activated during walking (Anders et al., 2007). Successfully engaging and training these muscles during walking with exoskeletons could possibly enhance their activation.

Various gait orthosis have been used to facilitate walking for people with complete SCI, starting with the knee-ankle foot orthosis (KAFO), first introduced in the 1950s as a walking brace for people with lower thoracic and lumbar SCI (Mikelberg & Reid, 1981; Rusk, 1964). Soon after that, a pelvic component was added to it forming the hip-knee-ankle-foot orthosis (HKAFO) to train people with higher thoracic SCI (Rusk, 1964). It consists of bilateral knee-ankle-foot orthoses that are connected together with hip joints. The HKAFO provides mediolateral stability during stance and prevent the pelvis from tilting downward on the swing leg to assist foot clearance during swing. Persons with paraplegia can walk using traditional HKAFOs and crutches with a swing-through gait pattern. However, this gait pattern has high levels of energy consumption as it exerts high loads on the upper limbs (Noreau, Richards, Comeau, & Tardif, 1995). The reciprocal gait orthosis (RGO) was then introduced as a more effective modification of the traditional HKAFOs (R. Douglas, Larson, D'Ambrosia, & McCall, 1983). A key feature of the RGO is its hip mechanism, hip extension in one leg assist hip flexion of the other leg when stepping. This is achieved by linking the two legs of the RGO together by a band, two cables or a push-pull rod to transfer movement from one leg to the other (Harvey, 2008). While the RGO is more effective than the traditional HKAFOs in improving gait parameters for people with SCI, its energy expenditure was also high (Arazpour, Bani, & Hutchins, 2012; Jefferson & Whittle, 1990).

The powered gait orthoses or powered robotic exoskeletons were introduced later to lower the energy expenditure. In these devices, the lower limbs are moved by electrically motorized actuators acting at the hips and knees. Robotic exoskeletons can be divided into two categories: treadmill-based robotic exoskeletons, and those that provide gait training overground. In treadmill-based robotic exoskeletons, such as the Lokomat (Hocoma, Switzerland) or the lower-extremity powered exoskeleton (LOPES) (University or Twente, Netherlands), hip and knee actuators assist the lower limbs to move through the gait cycle while the user's body weight is partially supported through an overhead harness system. Body weight support treadmill training (BWSTT), whether manually-assisted or robot-assisted, has arguably received the most attention in recent years in gait rehabilitation research for people with SCI (Hicks et al., 2005; Hornby, Zemon, & Campbell, 2005; Lam et al., 2015; Protas et al., 2001; Thomas & Gorassini, 2005; Wernig, Nanassy, & Muller, 1998; Wirz et al., 2005). Through BWSTT, participants can gain intensive and repetitive practice of walking while being safely supported to their capacity.

Continued technological developments have seen the availability of devices that enable overground gait training. These devices are powered by wearable rechargeable batteries and have an exoskeleton with joints that correspond to those of the human body's lower limbs. Several devices are commercially available for personal or rehabilitation use, such as the ReWalk (ReWalk Robotics, Israel), the Indego (Parker Hannifin Corporation, USA) and the Ekso (Ekso Bionics, USA). All these devices require the use of a hand-held assistive walking aid (wheeled walker or forearm crutches). However, the control of walking varies between these devices. In the ReWalk, a controller is used to switch between sitting, standing and walking modes. Steps are triggered by a tilt sensor worn in the pelvic brace that detects upper body forward flexion (Zeilig et al., 2013). Similar to the ReWalk, the Indego relies on upper body forward tilt to trigger stepping. It has a control system that estimates the user's center of pressure (CoP) and uses the distance between it and the location of the ankle joint to trigger the stepping and switch between sitting, standing, and walking (Quintero, Farris, Hartigan, Clesson, & Goldfarb, 2011). The Ekso uses a different mechanism for stepping as it depends on the user's ability weight shift from side to side. It has adjustable lateral and forward targets that the user has to achieve to trigger each step. Unlike the treadmill-based exoskeletons, walking with these devices require weight shifting, maintaining standing balance, and repositioning of the assistive device (walker or forearm crutch). However, both the treadmill-based and the overground robotic exoskeletons have the advantage of reducing the energy consumption compared to the mechanical orthoses, such as the RGO (Arazpour et al., 2015). In fact, one study has found that the Ekso has a similar energy expenditure to walking in persons without disability (Jochen Kressler et al., 2014).

Both the Lokomat and Ekso robotic exoskeletons facilitate gait training for people with SCI (Alcobendas-Maestro et al., 2012; Kressler et al., 2014; Lam, Eng, Wolfe, Hsieh, & Whittaker, 2007; van Hedel, 2006), but it remains unknown how they engage postural muscles that are normally activated during standing and walking. BWSTT has not been shown to be successful in improving standing balance in people with motor-incomplete SCI (Alexeeva et al., 2011). In an RCT by Alexeeva et al (2011), they compared BWS ambulation on a fixed track and on a treadmill with comprehensive physical therapy for improving walking speed and standing balance in chronic motor-incomplete SCI. They found that significant improvement in standing balance was noted when BWS ambulation was delivered on the overground fixed track or with comprehensive physical therapy but not with treadmill-based BWS ambulation (Alexeeva et al., 2011). The reason was likely that the overground walking challenges standing balance and the users need to continuously reposition their body and the assistive walking device to maintain balance before taking the next step (Alexeeva et al., 2011). Similarly, research on individuals with multiple sclerosis showed no activity in the postural muscles (RA, EO, ES and MF) while participants walked with a BWS system on a treadmill (Swinnen, Baeyens, Pintens, Van Nieuwenhoven, Ilsbroukx, Clijsen, et al., 2014a). Treadmill-based gait training with the trunk passively supported by a harness implies less challenge to postural stability, and therefore less postural muscle activity (Swinnen, Baeyens, Pintens, Van Nieuwenhoven, Ilsbroukx, Clijsen, et al., 2014a). Consequently, BWSTT might not trigger postural muscles and movements of the trunk that are important for balance control.

1.6 Summary and rationale

Motor function in the thoracic segments of the spinal cord is usually overlooked because standard clinical assessments have relied only on the sensory tests to infer the level and completeness of the lesion in the thoracic segments of the spinal cord. Indeed, recent studies using targeted approaches to assess the trunk have revealed sparing of trunk muscle function in individuals with SCI classified with thoracic or cervical motor-complete injuries. Therefore, finding training techniques to recruit this preserved muscle function in the trunk could enhance their activation and potentially lead to better improvements in postural control and function.

Trunk muscles are sequentially activated in a specific pattern according to the performed locomotor task. The timing of this rhythmic activity in the trunk muscles is suggested to be controlled by the spinal cord CPGs and influenced by lower limb CPGs. The Lokomat and Ekso are two robotic exoskeletons that have been developed as tools to retrain walking function in people with SCI. But it remains unknown how well they engage the axial muscles that are normally activated during walking. The Lokomat provides gait training on a treadmill with the trunk passively supported by an overhead harness with varying levels of body weight support, depending on the functional status of the subject. Although modulating the level of body weight support has been touted as a key factor in facilitating locomotor recovery, it also implies lesser degree of recruitment of postural muscles (since the body is supported and held rigidly within the Lokomat). In contrast, gait training with the Ekso is provided overground and requires active participation from the users to reposition their body and the assistive walking device to maintain balance before taking the next step. It should be expected, therefore, that using the Ekso could better facilitate axial muscle recruitment, and ultimately, postural control.

Therefore, the purpose of this study was to characterize and compare the activation patterns of the trunk (abdominal and back) muscles during walking with two different robotic exoskeletons (Lokomat and Ekso) in people with high thoracic motor-complete SCI. A secondary aim was to reference the activation patterns of the axial muscles elicited from these two exoskeletons in people with SCI with those normally observed during regular overground walking in able-bodied individuals.

1.7 Specific aims:

Aim 1A: To compare the amplitudes of the trunk muscle activity during quiscent Lokomat-assisted treadmill walking (Loko-TM) vs. Ekso-assisted walking on a treadmill (Ekso-TM) in people with high thoracic motor-complete SCI.

Aim 1B: to compare the timing of trunk muscles activity during Loko-TM walking to Ekso-TM walking in people with high thoracic motor-complete SCI.

Aim 1C: To determine the effect of the hand-held walking aid on trunk muscle activation patterns (amplitude and timing) during Ekso-assisted walking in people with high thoracic motor-complete SCI by comparing Ekso assisted walking overground (Ekso-OG) with Ekso-TM.

Aim 2: To compare the trunk muscle activation patterns elicited during Ekso- and Lokomat-assisted walking with those recorded from able-bodied participants during Ekso and Lokomat assisted walking as well as regular overground walking at matched speeds.

1.8 Specific hypotheses:

Hypothesis 1a: Trunk muscles will have higher EMG amplitude during Ekso-TM walking compared to baseline (supine lying) and similar amplitudes during Loko-TM walking compared to baseline in people with high thoracic motor-complete SCI.

Hypothesis 1b: The activation patterns of the trunk muscles will have similar timing but greater mean EMG amplitude during Ekso-TM walking compared to Loko-TM walking in people with high thoracic motor-complete SCI.

Hypothesis 2: The timing and mean EMG amplitude of the trunk muscles will not be different between Ekso-OG and Ekso-TM conditions in people with high thoracic motor-complete SCI.

Chapter 2: Methods

2.1 Study design

Cross-sectional.

2.2 Study participants

Participants with SCI were recruited to this study if they met the following inclusion criteria: 1) had chronic (≥9 months post-injury) motor-complete (ASIA A or B) spinal cord injury at C7-T6 with bilateral functional upper extremity strength; 2) were in a stable medical condition; 3) involved in a standing program and were able to tolerate standing on a standing frame for at least 30 minutes; 4) were 19 to 65 of age; 5) within the capacity limits of the Lokomat and Ekso (weight <100kg, height between 157 and 188 cm, standing hip width <47.5 cm, and near normal range of motion in hips, knees and ankles); and 6) were able to understand and follow directions; 7) had been trained to walking with the Ekso and had just achieved their self-selected comfortable Ekso-assisted overground walking speed of 1 km/h. The exclusion criteria were: 1) SCI onset less than 9 months; 2) age under 19 years or over 65 years; 3) were pregnant 4) had a medical condition that affect their capacity to exercise, such as cardiovascular conditions and orthopedic conditions; 4) significant hip, knee, ankle range of motion limitation; 5) leg length discrepancy >1.25 cm in the upper leg or 2 cm in the lower leg; 6) spasticity classified 4 (rigidity) on modified Ashworth's scale; 7) spinal instability; 8) uncontrolled autonomic dysreflexia; 9) open skin ulceration on buttocks or surfaces in contact with Lokomat or Ekso;10) uncontrolled orthostatic hypotension; or 11) did not receive gait training on Ekso and Lokomat.

Able-bodied participants with the following inclusion criteria were recruited: 1) were 19 to 65 years of age; 2) were in a stable medical condition; 3) were able to tolerate an upright posture for 30 minutes 4) were able to understand and follow directions. The exclusion criteria are: 1) under 19 years of age or over 65 years of age; 2) had a medical condition that affect their capacity to exercise, such as cardiovascular conditions and orthopedic conditions; 3) unable to understand and follow directions.

2.3 Procedures

All study measurements were conducted at the Human Locomotion Laboratory at the Blusson Spinal Cord Center (ICORD) in a single recording session.

2.3.1 Assessment of impairment

Participants with SCI underwent a standard neurologic examination, the ISNCSCI, to evaluate motor and sensory function and classify their injury (Kirshblum et al., 2011). The motor score of the ISNCSCI is a 5-point grading scale ranging from 0 (total paralysis) to 5 (active movement through full range of motion against full resistance) to measure upper and lower extremities muscle strength. A score out of 50 is summed for each side. The sensory score of the ISNCSCI measures light touch and pin prick sensation at each dermatome using a 3-point grading scale ranging from 0 (absent) to 2 (normal). A score out of 112 is recorded for each light touch and pinprick sensation. The ISNCSCI examination was conducted by an experienced registered nurse working in a spinal cord injury unit.

2.3.2 Trunk function and balance assessment

Participants with SCI performed a trunk function and balance test that was developed to classify para-kayak athletes (Aaslund & Moe-Nilssen, 2008a). The test consisted of a series of manual muscle tests and functional trunk tests (Appendix A). For the manual muscle tests, the participants performed seven trunk muscle tasks: trunk flexion, trunk rotation to the right and left, trunk side bending to the right and left, trunk lumbar extension and trunk and hip extension. Each task was scored on a 0-2 scale where 0 indicated the participant inability to perform the task or had no palpable muscle activity, 1: the participant is able to partially perform the task and had detectable contractile activity, and 2: is able to complete the full range of motion of the task. As for the functional tests, the participants performed a series of static and dynamic sitting balance tasks, as well as, perturbation tasks while sitting on plinth or a wobble cushion. Similar to the manual muscle tests, the functional tasks were scored on a 0-2 scale according to the participant's ability to perform the task. The maximum score for the manual muscle tests and functional tests is 84. Finally according to the participants' scores, the test classifies them into 3 clusters: cluster 1 is (0-16 points), cluster 2 (17-68 points), and cluster 3 (69-84). This test was suggested to be a valid method to assess specific trunk function in para-kayak athletes and can be used in defining whether the athlete had no, partial or full trunk function (Aaslund & Moe-Nilssen, 2008a).

2.3.3 Data Collection Testing Protocol

2.3.3.1 Maximum (attempted) voluntary contraction

In order to normalize the electomyographic (EMG) signals from the trunk muscles during the walking tests, a series of EMG recordings were collected from each participant while attempting to perform a maximum voluntary contraction (MVC) of the following muscles, bilaterally: RA, EO, and ES. Surface EMG sensors (EMG sensor SX230-1000, Biometrics, Newport, UK) were placed on each muscle as follows: RA - 3 cm lateral and 2 cm caudal to umbilicus; EO - 2 cm below the lowest point of the rib cage (Bjerkefors et al., 2015); ES - 2 cm lateral to the L4-L5 spinous processes (Cholewicki, Panjabi, & Khachatryan, 1997). The skin area was prepared by shaving and cleansing using alcohol swabs to reduce skin impedance before placing the electrodes. Adhesive tape was applied to secure the electrode with the skin. EMG data were recorded through a portable data acquisition system (DataLOG, Biometrics, Newport, UK) with a ground reference placed around the wrist (R506 Wrist Strap, Biometrics, Newport, UK). EMG signals were recorded at a sampling frequency of 1000 Hz.

To record RA MVC, participants were lying supine on a plinth and instructed to breath out for 2 seconds, breath in (2 seconds), then breath out (2 seconds), then do an attempted trunk flexion and hold for 5 seconds. A research assistant stabilized the participant's trunk to the plinth by holding them down by the shoulders. Using a similar breathing technique, EO MVC was recorded by asking the participant to perform a lateral trunk flexion to the right and to the left while the participant's shoulder and hip were stabilized. Participants also performed an attempted back extension for 5 seconds while lying prone and the shoulders stabilized against the plinth. Each test was repeated 2 times with 1 minute of rest between contractions.

In addition to the MVC, baseline EMG activity (BAS) for all muscles was recorded while participants lay relaxed on the plinth. This was used to define quiescent background trunk muscle EMG amplitude.

Breathing was monitored during the MVC and the walking trials by a custom made thermocouple (a temperature sensor) placed under the participants' right or left naris. Breathing was monitored by the change in the air temperature, warm air (expiration), and cold air (inspiration) (Noah, Boliek, Lam, & Yang, 2008). Data recorded from the thermocouple was sampled at 1000 Hz.

2.3.3.2 Walking trials

Foot switches (FS4, Biometrics, Newport, UK) were placed under the heel and big toe of each foot to determine heel strike and toe off for each step. An accelerometer (ACL300, Biometrics, Newport, UK) was placed on the spinous process of C7 to detect the trunk acceleration. Data recorded from the foot switches and accelerometer was sampled at 1000 Hz. The EMG electrodes, ground reference, accelerometer and thermocouple were connected to 2 portable dataports (PS900, Biometrics, Newport, UK). The portable systems were connected over Bluetooth to a data management and analysis software (DataLOG, Biometrics, Newport, UK).

Data were recorded while participants walked in three walking conditions: 1) Ekso overground (Ekso-OG); 2) Ekso on a treadmill (Ekso-TM); and 3) Lokomat (Loko-TM). Ekso and Lokomat walking conditions were performed in a counterbalanced order.

2.3.3.2.1 Ekso-OG trial

A trained physical therapist took the lead to monitor and instruct the participant on how to transition from sit-to-stand and walk using the Ekso device. Another research assistant walked beside the participant to monitor their safety. The physical therapist provided a familiarization period to allow the participant to become comfortable using the device and set appropriate levels for each gait parameter (e.g. step length, height, and swing time). Participants were asked to walk back and forth along a 14-m walkway at their comfortable speed while tethered on an overhead track to provide support in case of falling.

Participants had previously completed prescribed Ekso training (concurrent clinical study), and achieved "ProStep" walking mode on the Ekso and a walking speed of at least 1 km/h (0.3 m/s; the lowest treadmill speed of the Lokomat). Speed was calculated from the time taken to traverse the middle 10 meters of the 14-m walking, as measured by a stopwatch. All participants walked with the "ProStep" mode, in which steps are automatically triggered when the Ekso sensed the participant reached weight-shifting targets.

2.3.3.2.2 Ekso-TM trial

In this condition, participants walked with the Ekso on the Lokomat's treadmill while using the handrails for support. The Lokomat's body-weight support system was used as a tether for safety. A physical therapist stood behind the participant for guidance and support while a research assistant increased the speed of the treadmill to ensure it matches with the participant's walking cadence with the Ekso-OG. EMG and kinematic data was recorded for at least 30 steps. Rest breaks were provided as needed.

2.3.3.2.3 Loko-TM trial

Participants were fitted to the Lokomat with cuffs around the mid-thigh, upper shank, and lower shank as well as a waist belt to provide trunk support. An overhead suspension system that is positioned over the treadmill was used to provide BWS through a wearable harness that was attached to the suspension system. The Lokomat assisted leg movements. The ankles were secured in a neutral position by elastic straps attached around the foot and suspended from a horizontal bar positioned below the knee. The amount of BWS through the suspension system was adjusted to 50% of the participant's body-weight. Participants were checked for proper stance limb kinematics (i.e. upright posture, hip and knee joints extended) during walking. The treadmill speed was matched to the other walking conditions. EMG and kinematic data were recorded for at least 30 steps. Rest breaks were provided as needed.

2.3.3.2.4 Additional and control experiments

To control for the effects of BWS on trunk muscle activity, 3 able-bodied participants additionally performed a Loko-TM condition with 5 kg BWS (the lowest BWS possible during Loko-TM) to be compared with 50% BWS (required of the SCI subjects during Loko-TM condition).

To investigate the potential effects of speed, we asked able-bodied subjects (n=5) to walk on a treadmill without robotic assistance at the same treadmill speed matched to their robotic-assisted walking trials. Additional Ekso-TM and Loko-TM trials at variable speeds were also attempted in SCI subjects who could walk in Ekso-TM with higher speed.

We additionally recorded EMG activity in SCI subjects from ES at T3 and T12 level to observe ES onset at different levels.

2.4 Data analysis

All EMG data were filtered with a sixth-order dual pass Butterworth filter at a high-pass of 30 Hz, rectified, then filtered with a sixth-order dual pass Butterworth filter at a low-pass of 50 Hz using custom-written routines written in MATLAB (Mathworks, Natick, MA, USA). For each MVC trial, a MVC value for each muscle was obtained by calculating the root mean square

(RMS) of a 1000-ms window centered around peak contraction. The average RMS value of the 2 MVC trials was then calculated and used to normalize the EMG data obtained during the walking trials.

Signals from the footswitches were used to divide the data into gait cycles (right heel strike to the next right heel strike). The filtered and rectified EMG data of the walking trials were divided into individual periods synchronized to the gait cycles. The RMS amplitude was calculated over each gait cycle for each muscle in each condition. The mean RMS across all gait cycles in each condition was then calculated for each muscle and normalized to the MVC (i.e. the mean RMS was divided by the MVC mean RMS value and multiplied by 100 to represent EMG amplitude as a percentage of MVC). Then the RMS values for the right and left sides were summed for each muscle for each participant.

EMG onset and total activity times were quantified as a percentage of the averaged gait cycle. The EMG signal for each muscle in each condition was rescaled to the minimum and maximum amplitude of the gait cycle. The minimum EMG amplitude was considered as 0 and the maximum as 100. The threshold for the muscle activity was set at 30% of the maximum muscle contraction (de Sèze et al., 2007). The EMG onset was defined as the earliest time in the gait cycle when EMG amplitude crossed above the threshold and remained there for more than 5% of the gait cycle. EMG burst offset were defined as the point where EMG activity returned below the mean and remained there for more than 5% of the gait cycle. The total percentage of the gait cycle for which each muscle was active was calculated for each walking condition (total activity time). In addition to onset and total activity times, the number of bursts for each muscle in each condition was calculated.

Breathing and accelerometer data were filtered with a fourth-order dual pass Butterworth filter at a low-pass of 1 Hz before it was divided into individual periods (gait cycles) to show breathing activity and trunk acceleration during walking. Breath-to-gait cycle ratio was also calculated by counting the number of breathing cycles (inhalation-exhalation) in the first 20 gait cycles synchronized by the right heel strike of each condition and dividing that by 20 (number of gait cycles). Respiration ratio (respiration/minute) was also calculated for each walking condition. The trunk anterior-posterior and medial-lateral accelerations were calculated from the averaged gait cycle by subtracting the minimum anterior-posterior and medial-lateral accelerations from the maximum in each direction for each walking condition.

Data from the able-bodied participants were recorded and analyzed in the same way to provide a reference and for descriptive purposes.

2.5 Statistical analysis

All statistical tests were analyzed at an alpha of 0.05 using SPSS software. EMG amplitude of each muscle was compared across 4 conditions: BAS, Loko-TM, Ekso-TM, and Ekso-OG. Onset, total activity time, and number of bursts for each muscle, as well as, trunk acceleration were compared across 3 walking conditions (Loko-TM, Ekso-TM, and Ekso-OG). All comparisons were performed using a repeated measures ANOVA. Four *a priori* post-hoc comparisons were performed to compare EMG amplitude between the following pairs of conditions: BAS–Loko-TM; BAS–Ekso-TM; Loko-TM–Ekso-TM; Ekso-TM–Ekso-OG. The Bonferroni correction was used to account for the 4 multiple comparisons (adjusted alpha = 0.05/4 = 0.0125). For EMG onset time, total activity time and number of bursts, 2 *a priori* post-hoc comparisons were planned to compare between Loko-TM–Ekso-TM, Ekso-OG–Ekso-TM (adjusted alpha = 0.05/2 = 0.025). For significantly different results, partial Eta squared was calculated to report effect size. Observed power was also reported. Prior to conducting ANOVA, normal distribution of data was checked by Shapiro-Wilk test. The assumption of Sphericity was tested with Mauchly's test, and when violated, Greenhouse-Geisser correction was applied.

Chapter 3: Results

3.1 Participant characteristics

8 SCI and 8 able-bodied subjects enrolled in this study. All SCI subjects were able to complete all assessment procedures and the three testing conditions with a walking speed ranging between 1-1.4 km/h. Key participant characteristics are summarized in Table 1 and Table 2.

Table 1 Detailed characteristics of participants with SCI

Subject ID	Age (years)	Sex	Height (cm)	Weight (kg)	Years post injury	Level of injury	Sensory score Light touch	Sensory score Pin-prick	Total motor score	AIS	ZPP R/L	Trunk test score	Testing speed (km/h)
S01	33	M	177	68	13	T4	48	49	50	A	T6/T6	4	1.1
S02	41	M	183	92.3	23	T3	41	43	50	A	T3/T5	1	1.3
S03	42	M	170	68	19	C7	66	68	34	B	-	10	1.3
S04	39	F	177	68.6	25	T3	44	42	50	A	T4/T4	6	1.4
S05	32	M	190.5	99.7	7	T4	46	50	50	A	T6/T6	3	1
S06	36	M	177.8	79	1	C7	27	28	29	A	T2/T1	2	1
S07	32	M	175	79	3	C7	42	44	50	B	-	6	1.1
S08	52	M	176.5	75	2	T4	46	46	50	A	T5/T5	10	1.1

Abbreviations: M = male; F = female; AIS = American Spinal Injury Association Impairment Scale; A = complete impairment; B = sensory incomplete; ZPP R/L= zone of partial preservation on the right and left side.

Table 2 Characteristics of able-bodied subjects

Subject ID	Age (years)	Sex	Height (cm)	Weight (kg)	Testing speed (km/h)
C01	26	Male	170	56.7	1
C02	20	Female	170	62	1.4
C03	41	Female	168	68	1.2
C04	28	Male	174	75	1.4
C05	33	Female	167.5	55	1.3
C06	32	Female	169	62.5	1
C07	23	Male	179	83.9	1
C08	24	Male	171.5	72	1.3

3.2 Maximum voluntary contraction

Figure 1 shows trunk muscle activity during MVC trials in SCI subjects and a sample able-bodied subject. All muscles showed higher EMG activity during MVC trials compared to baseline.

Figure 1 Trunk muscle EMG activity during maximum voluntary contractions

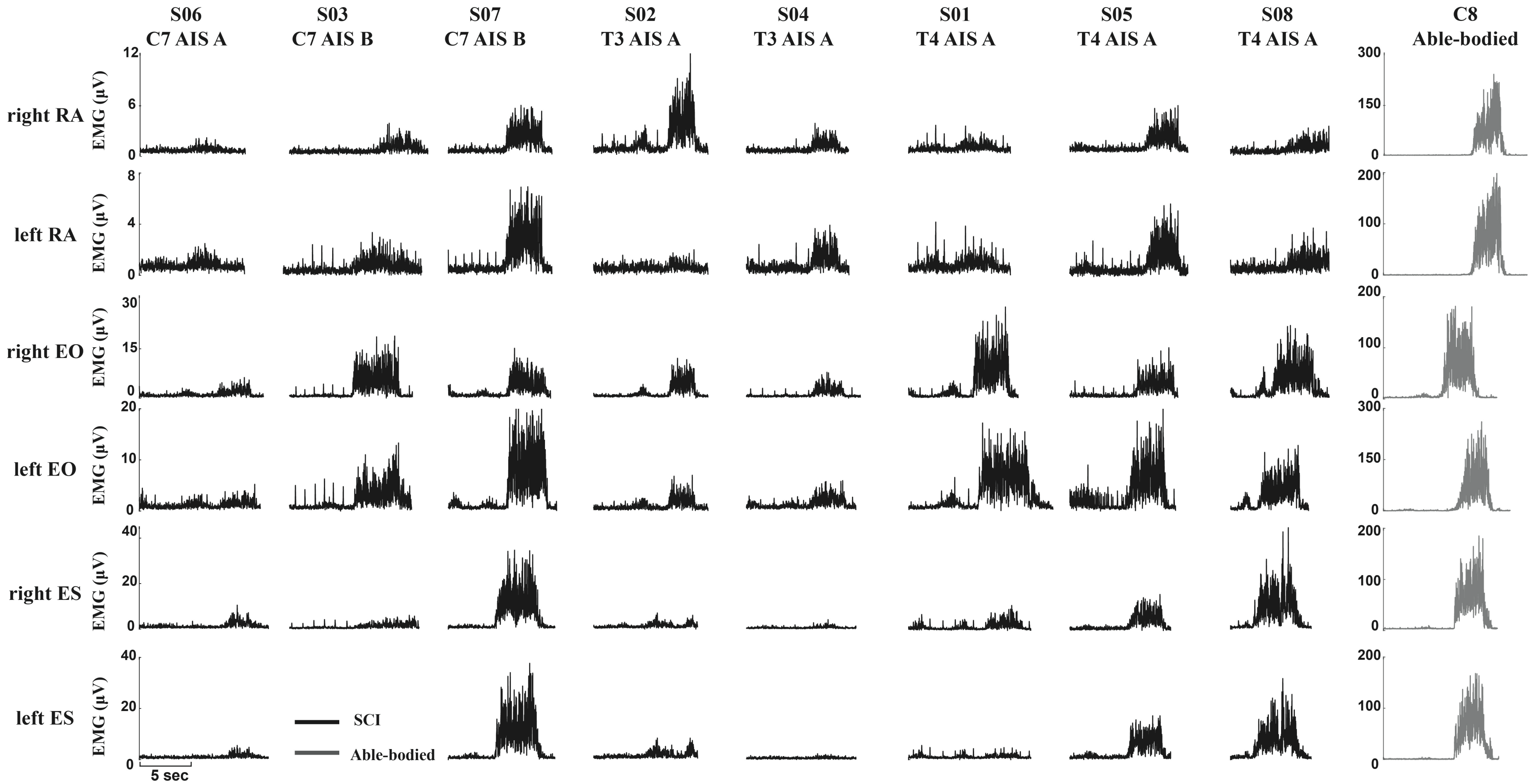

Figure 1: Trunk muscle filtered and rectified EMG activity during maximum voluntary contraction (MVC) trials in all SCI subjects (black) and a sample of able-bodied subjects (C8) (grey). Each EMG plot shows baseline and MVC activity. Subjects were arranged according to their injury level from highest to lowest, left representing the highest. RA = Rectus Abdominis, EO = External Oblique and ES = Erector Spinae.

3.3 Trunk muscle activation patterns during robotic-assisted walking

Figure 2 shows ensemble EMG gait patterns during normal treadmill walking (Fig. 2A) and robotic-assisted walking (Fig. 2B) from able-bodied subjects compared to ensemble SCI subjects EMG data during robotic-assisted walking (Fig. 2C). The trunk muscles showed higher muscle activity during the Ekso walking conditions (Ekso-OG and Ekso-TM) compared to Loko-TM in both the SCI and the able-bodied subjects. Moreover, trunk muscle activation patterns during robotic-assisted walking were comparable in timing to EMG patterns during regular treadmill walking in able-bodied individuals at similar speeds, however they showed generally higher activation. Figure 3 shows individual EMG patterns from each of the SCI subjects.

Figure 2 Trunk muscle activation patterns during robotic-assisted walking in able-bodied and SCI subjects

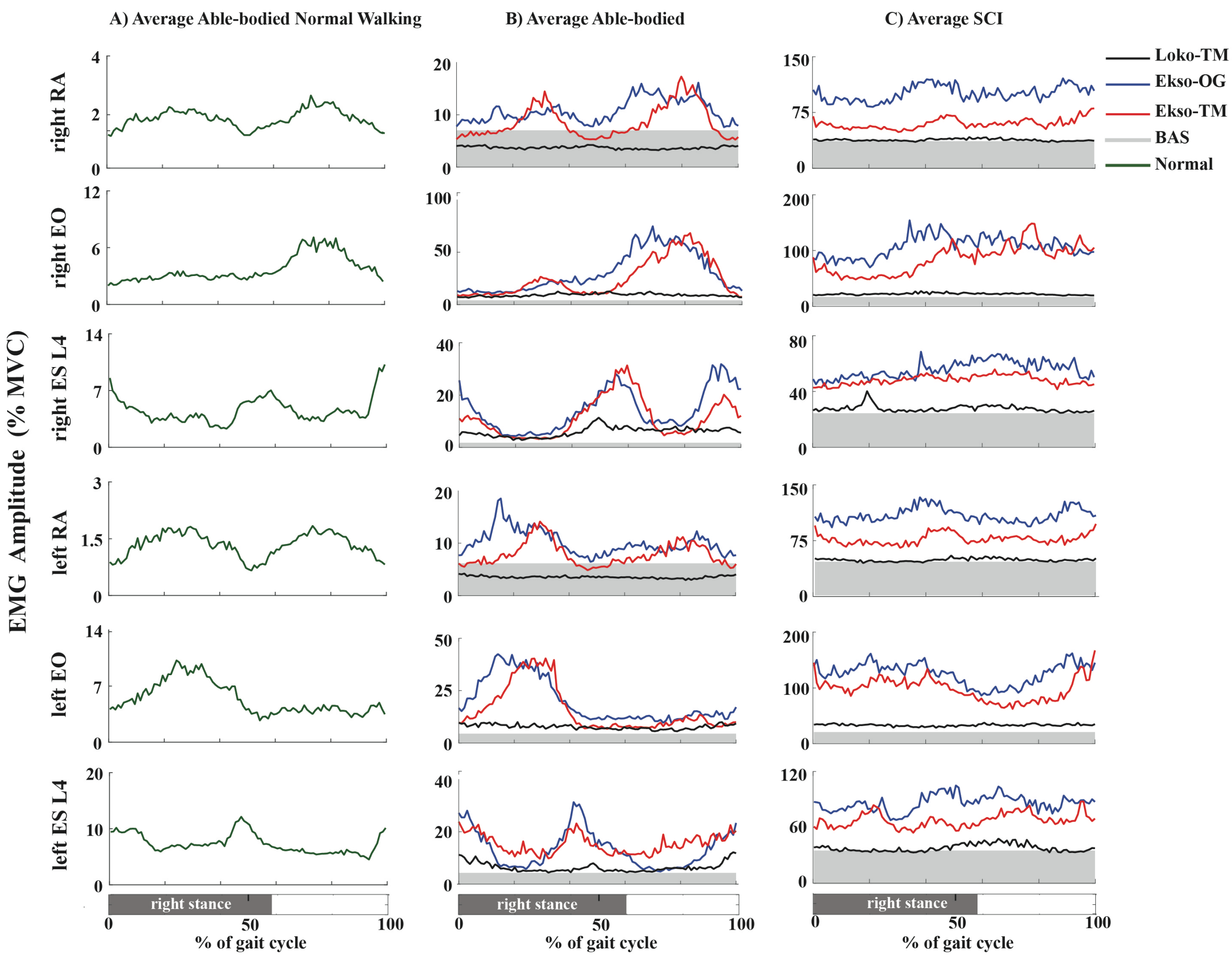

Figure 2: A) Mean trunk muscle activity patterns averaged across 5-able-bodied participants during walking on treadmill with an average speed of 1.2 km/h. **B)** Mean trunk muscle activity patterns averaged across 5 able-bodied participants during walking in the Lokomat (Loko-TM), Ekso on treadmill (Ekso-TM) and Ekso overground (Ekso-OG) with an average matched speed across conditions of 1.26 km/h. All plots represent the mean trunk muscle activity normalized to 100% of the gait cycle (n>20 steps each plot for each subject). Grey shaded areas in each plot represent baseline EMG activity recorded in supine position (BAS). **C)** Mean trunk muscle activity patterns averaged across all SCI subjects (n=8) during the same walking conditions with an average matched speed across conditions of 1.16 km/h. RA = Rectus Abdominis, EO = External Oblique and ES = Erector Spinae.

Figure 3 Trunk activation patterns in all SCI subjects

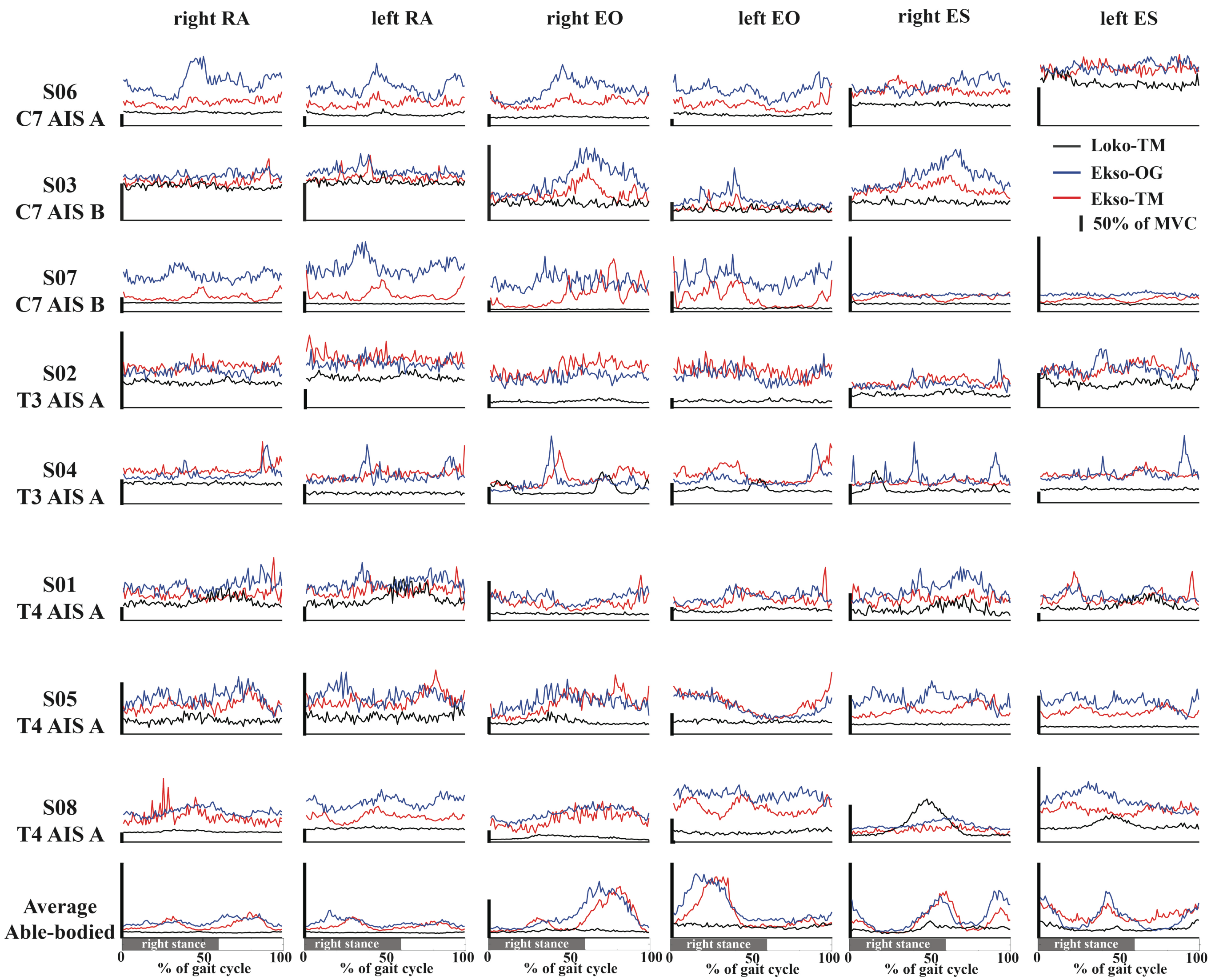

Figure 3: Activation patterns recorded from the rectus abdominis (RA), external oblique (EO) and erector spinae (ES) muscles in each SCI subject are plotted separately (individual rows, ordered top to bottom by lesion level), in addition to the ensemble EMG activity in these muscles averaged across able-bodied subjects (n =5, bottom row) and compared across the three walking conditions: Lokomat on treadmill (Loko-TM, black lines), Ekso on treadmill (Ekso-TM, red lines) and Ekso overground (Ekso-OG, blue lines). All data are normalized to 100% of the gait cycle and aligned to right heel contact. Thick vertical bars in each plot represent 50% of the MVC for that muscle.

3.4 EMG amplitude

There was a main effect of walking condition in all muscles (RA: $F(1.085, 7.597) = 8.566$, $p = 0.019$, partial $\eta^2 = 0.550$, observed power = 0.739; EO: $F(1.677, 11.736) = 24.723$, $p < 0.001$, partial $\eta^2 = 0.779$, observed power = 1.000; ES: $F(1.248, 8.737) = 18.170$, $p = 0.002$, partial $\eta^2 = 0.722$, observed power = 0.980; (Fig. 4).

Pairwise post-hoc comparisons using Bonferroni correction revealed significant differences between BAS and Loko-TM only in EO ($p = 0.008$), but not in RA ($p = 0.112$), nor in ES ($p =0.062$). There were significant differences between BAS and Ekso-TM in RA ($p = 0.006$), EO ($p = 0.001$), and ES ($p = 0.005$).

Pairwise post-hoc comparisons between Loko-TM and Ekso-TM also revealed significance difference in all muscles (RA: $p = 0.006$; EO: $p = 0.001$; ES: $p = 0.009$).

There was a significant difference between Ekso-TM and Ekso-OG in ES ($p =0.007$), but not in RA ($p = 0.072$), or EO ($p = 0.192$), showing no walking aid effect on EMG amplitude for RA and EO.

Figure 4 Trunk muscle EMG amplitudes across baseline and walking conditions

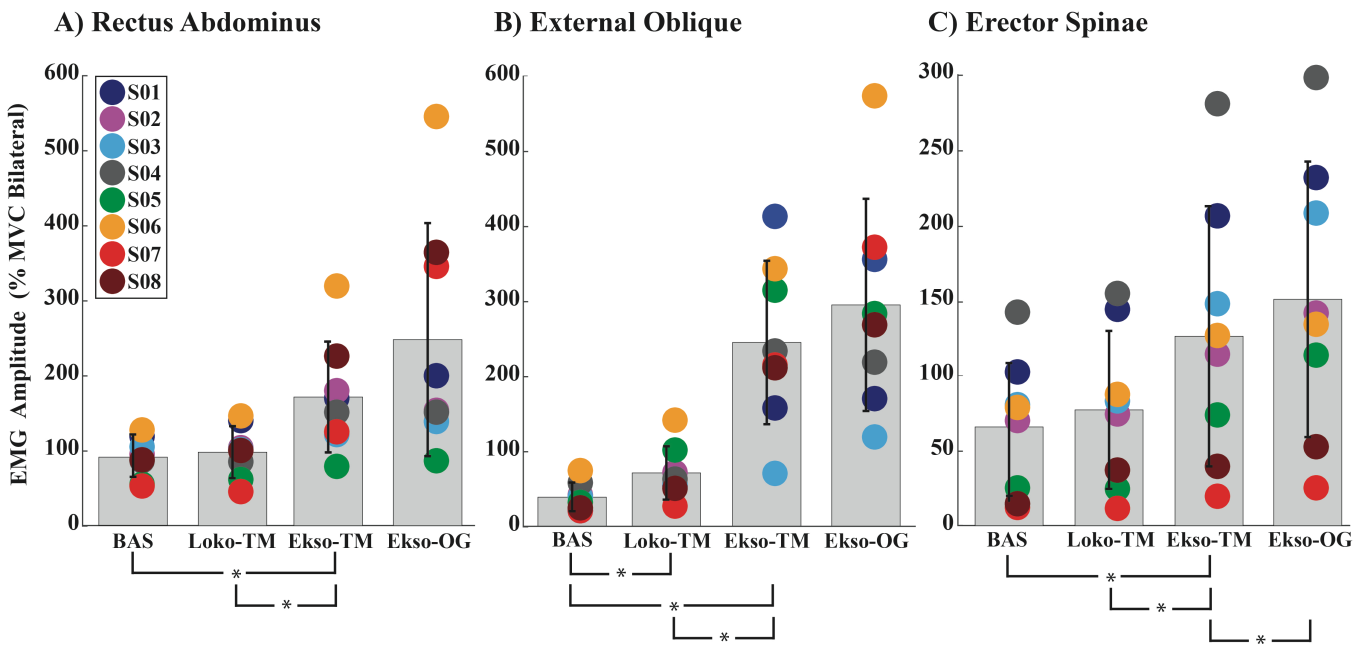

Figure 4: Comparison of EMG amplitude across quiet supine lying and robot-assisted walking conditions. The average RMS EMG amplitude in **A)** Rectus Abdominis, **B)** External Oblique, and **C)** Erector Spinae during quiet supine lying (BAS), Lokomat-assisted walking (Loko-TM), Ekso on the treadmill (Ekso-TM) and Ekso overground walking (Ekso-OG) are plotted for each SCI participant (represented by different coloured circles). Grey bars represent the average RMS EMG amplitude across all SCI participants and error bars represent the standard deviation. * = $p < 0.0125$.

3.4.1 EMG timing

Figure 5 shows trunk muscle EMG timings during walking with the Ekso and the Lokomat in SCI subjects and regular treadmill walking in able-bodied subjects. Trunk muscles onset time did not show main effect of the walking condition (Loko-TM, Ekso-TM and Ekso-OG) (Table 3). Similar to the onset time, the total activity time of the trunk muscles also did not show significant main effect of the walking conditions except for the left EO. However, pairwise post-hoc comparisons on left EO total activity time revealed no significant difference between

Loko-TM and Ekso-TM (p = 0.029) or Ekso-TM and Ekso-OG (p = 0.029) (Table 4). There was no main effect of walking condition in the number of bursts for each trunk muscle except for right EO and right ES. Pairwise post-hoc comparisons showed significant differences between Loko-TM and Ekso-TM for EO (p = 0.008), but not between Ekso-TM and Ekso-OG (p = 0.03). For ES, pairwise post-hoc comparisons did not reveal any significant differences between Loko-TM and Ekso-TM (p = 0.047) or Ekso-TM and Ekso-OG (p = 1.000).

Figure 5 Trunk muscle EMG timings during robotic-assisted and regular treadmill walking

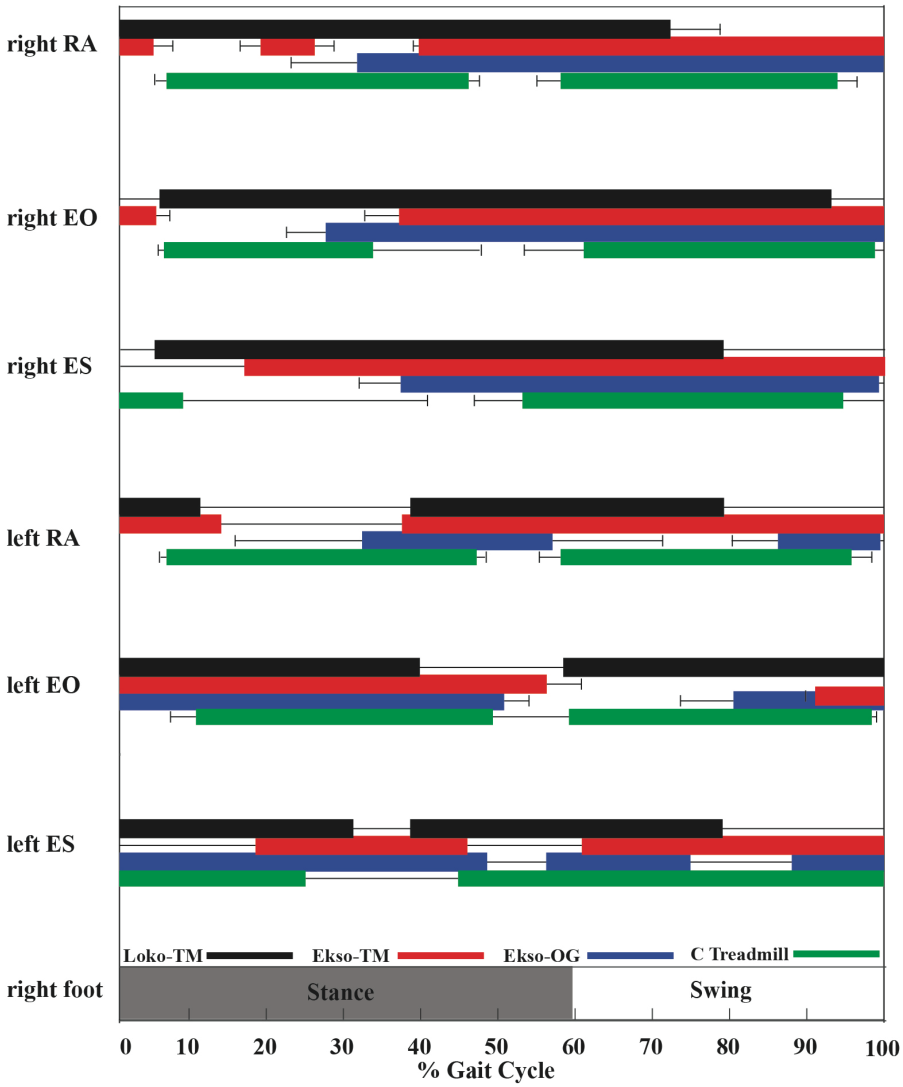

Figure 5: Average trunk muscles onset and total activity times (normalized to the gait cycle) during walking in the Lokomat (black), Ekso on treadmill (red) and Ekso overground (blue) in SCI subjects and regular treadmill walking (C Treadmill) in able-bodied subjects (n=5) (green). Thin horizontal lines represent the standard deviation. RA = Rectus Abdominis, EO = External Oblique and ES = Erector Spinae.

Table 3 Trunk muscle EMG onsets during robotic-assisted walking

Muscle	Loko-TM	Ekso-TM	Ekso-OG	Condition Effect
Right RA	10.72 (18.11)	5.12 (8.79)	14.09 (17.08)	F(2, 12) = 1.637, p = 0.235
Right EO	19.32 (17.82)	14.13 (25.26)	21.87 (15.23)	F(2, 12) =0.255, p = 0.779
Right ES	11.51 (12.39)	8.85 (8.40)	22.01 (20.29)	F(2, 12) = 1.904, p = 0.191
Left RA	11.50 (18.66)	6.37 (16.86)	9.24 (15.84)	F(2, 12) = 0.430, p = 0.660
Left EO	2.69 (5.81)	5.43 (14.36)	4.53 (11.99)	F(1.005, 6.028) = 0.168, p = 0.697
Left ES	20.74 (27.36)	2.35 (6.24)	10.78 (17.32)	F(2, 12) = 1.375, p = 0.290

Abbreviations: RA = Rectus Abdominis, EO = External Oblique, ES = Erector Spinae, Loko-TM = Lokomat-assisted walking, Ekso-TM = Ekso-assisted walking on treadmill, Ekso-OG = Ekso-assisted walking overground.

Table 4 Trunk muscle EMG total activity times during robotic-assisted walking

Muscle	Loko-TM	Ekso-TM	Ekso-OG	Condition Effect
Right RA	63.54 (27.41)	46.90 (30.64)	56.41 (25.96)	F(2, 12) = 1.324, p = 0.302
Right EO	59.40 (32.68)	48.53 (20.63)	63.83 (27.63)	F(2, 12) = 0.622, p = 0.553
Right ES	61.63 (31.54)	64.62 (20.32)	53.48 (20.55)	F(2, 12) = 0.301, p = 0.746
Left RA	54.27 (25.72)	45.80 (23.09)	56.28 (19.60)	F(2, 12) = 0.397, p = 0.681
Left EO	74.84 (17.56)	45.12 (21.17)	65.32 (19.30)	F(2, 12) = 4.542, p = 0.034*
Left ES	49.59 (24.83)	64.16 (28.25)	69.03 (25.82)	F(2, 12) = 1.360, p = 0.294

Abbreviations: RA = Rectus Abdominis, EO = External Oblique, ES = Erector Spinae, Loko-TM = Lokomat-assisted walking, Ekso-TM = Ekso-assisted walking on treadmill, Ekso-OG = Ekso-assisted walking overground.

* = Statistically significant ($p < 0.05$), partial $\eta^2 = 0.431$, observed power = 0.564.

Table 5 Trunk muscle EMG number of bursts during robotic-assisted walking

Muscle	Loko-TM	Ekso-TM	Ekso-OG	Condition Effect
Right RA	1.86 (0.9)	2 (0.58)	2 (0.816)	$F(2, 12) = 0.072$, $p = 0.931$
Right EO	1.14 (0.38)	1.86 (0.38)	1.29 (0.49)	$F(2, 12) = 9.000$, $p = 0.004$*
Right ES	1.29 (0.49)	2 (0.58)	2 (0.58)	$F(2, 12) = 6.250$, $p = 0.014$*
Left RA	1.57 (0.79)	1.57 (0.53)	2.29 (0.49)	$F(2, 12) = 2.885$, $p = 0.095$
Left EO	1.71 (0.49)	2.43 (0.79)	2 (0.58)	$F(2, 12) = 3.081$, $p = 0.083$
Left ES	1.43 (0.79)	2 (0)	1.86 (0.69)	$F(2, 12) = 1.814$, $p = 0.205$

Abbreviations: RA = Rectus Abdominis, EO = External Oblique, ES = Erector Spinae, Loko-TM = Lokomat-assisted walking, Ekso-TM = Ekso-assisted walking on treadmill, Ekso-OG = Ekso-assisted walking overground.

* = Statistically significant ($p < 0.05$), right EO: partial $\eta^2 = 0.6$, observed power = 0.924. Right ES: partial $\eta^2 = 0.51$, observed power = 0.8.

3.5 Breathing

Normalizing the trunk muscle EMG to breathing cycles did not show any observable pattern of rhythmic activity in any of the muscles. Sample data from an individual SCI subject is shown in Figure 6 and data from each of the SCI subjects comparing EMG patterns normalized to inhalation vs. right foot contact times are plotted in Appendix B.

Figure 6 Trunk muscle activity normalized to gait cycle and breathing cycle

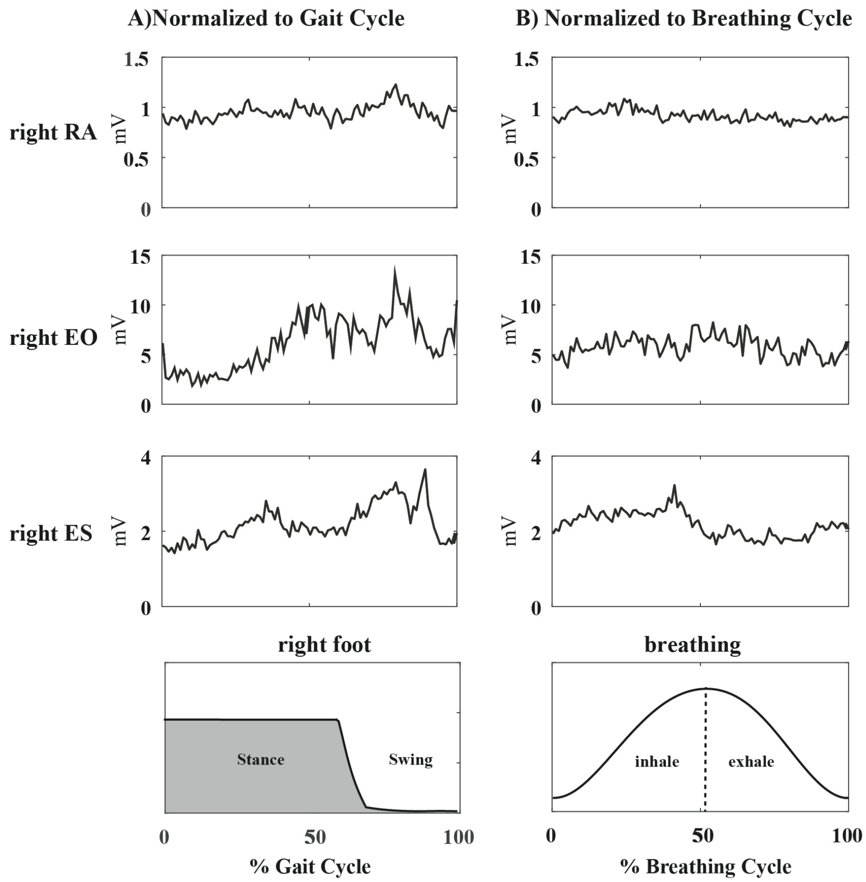

Figure 6: SCI subject (S05) average trunk muscles activity (Rectus Abdominis (RA), external oblique (EO) and erector spinae (ES)) when **A)** Normalized to the gait cycle and **B)** Normalized to the breathing cycle during walking in the Ekso on treadmill.

A comparison of breath-to-gait cycle rate and respiration rate between SCI and able-bodied subjects is described in Figure 7. Breath-to-gait cycle rate was observably higher during Ekso-assisted walking compared to Loko-TM and only higher in Ekso-OG in able-bodied subjects. Moreover, breathing-to-gait cycle rate was generally higher in SCI subjects in all conditions compared to able-bodied.

Respiration rate was also observably higher in Ekso-assisted walking for both SCI and able-bodied subjects compared to Lokomat. However, SCI subjects had observably higher respiration rate compared to able-bodied.

Figure 7 Breath-to-gait cycle ratio and respiration rate during robotic-assisted walking

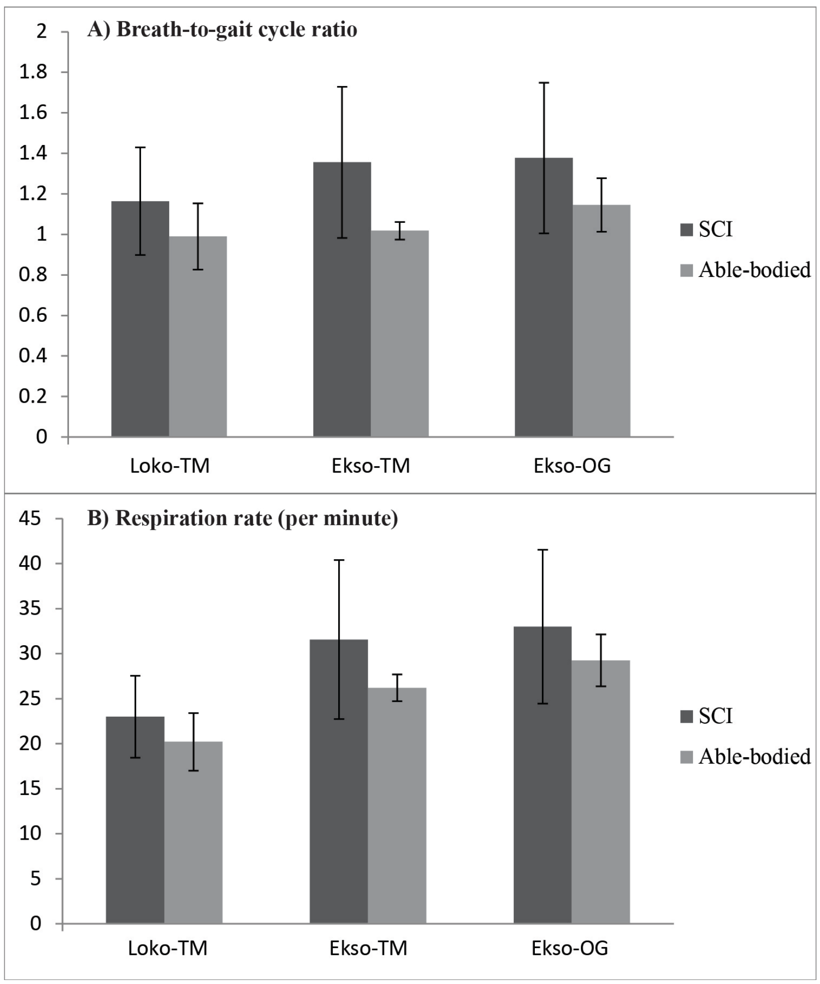

Figure 7: A) Breath-to-gait cycle ratio and B) Respiration ratio compared between SCI and able-bodied subjects across the three walking conditions: Lokomat (Loko-TM), Ekso on treadmill (Ekso-TM) and Ekso overground (Ekso-OG).

3.6 Trunk acceleration

Figure 8 shows average anterior-posterior and medial-lateral acceleration of SCI subjects during the 3 walking conditions and average able-bodied subjects during regular treadmill walking.

There was a main effect of the walking condition on the trunk acceleration in both anterior-posterior ($F(2, 14) = 15.025$, $p < 0.001$, partial $\eta^2 = 0.682$, observed power = 0.99) and medial-lateral directions ($F(2, 14) = 17.003$, $p < 0.001$, partial $\eta^2 = 0.708$, observed power = 0.998). Post-hoc analysis showed statistically significant differences in both directions between the Ekso walking conditions compared to Lokomat. For the anterior-posterior direction, Loko-TM compared to Ekso-TM ($p = 0.002$) and Loko-TM compared to Ekso-OG ($p = 0.002$). for the medial-lateral direction, Loko-TM compared to Ekso-TM ($p = 0.001$), and Loko-TM compared to Ekso-OG ($p = 0.001$). However, there were no statistically significant differences between Ekso-TM and Ekso-OG in either direction (anterior-posterior: $p = 0.33$; medial-lateral: $p = 0.33$) (Figure 9).

Figure 8 Anterior-posterior and medial-lateral acceleration during robotic-assisted and regular treadmill walking

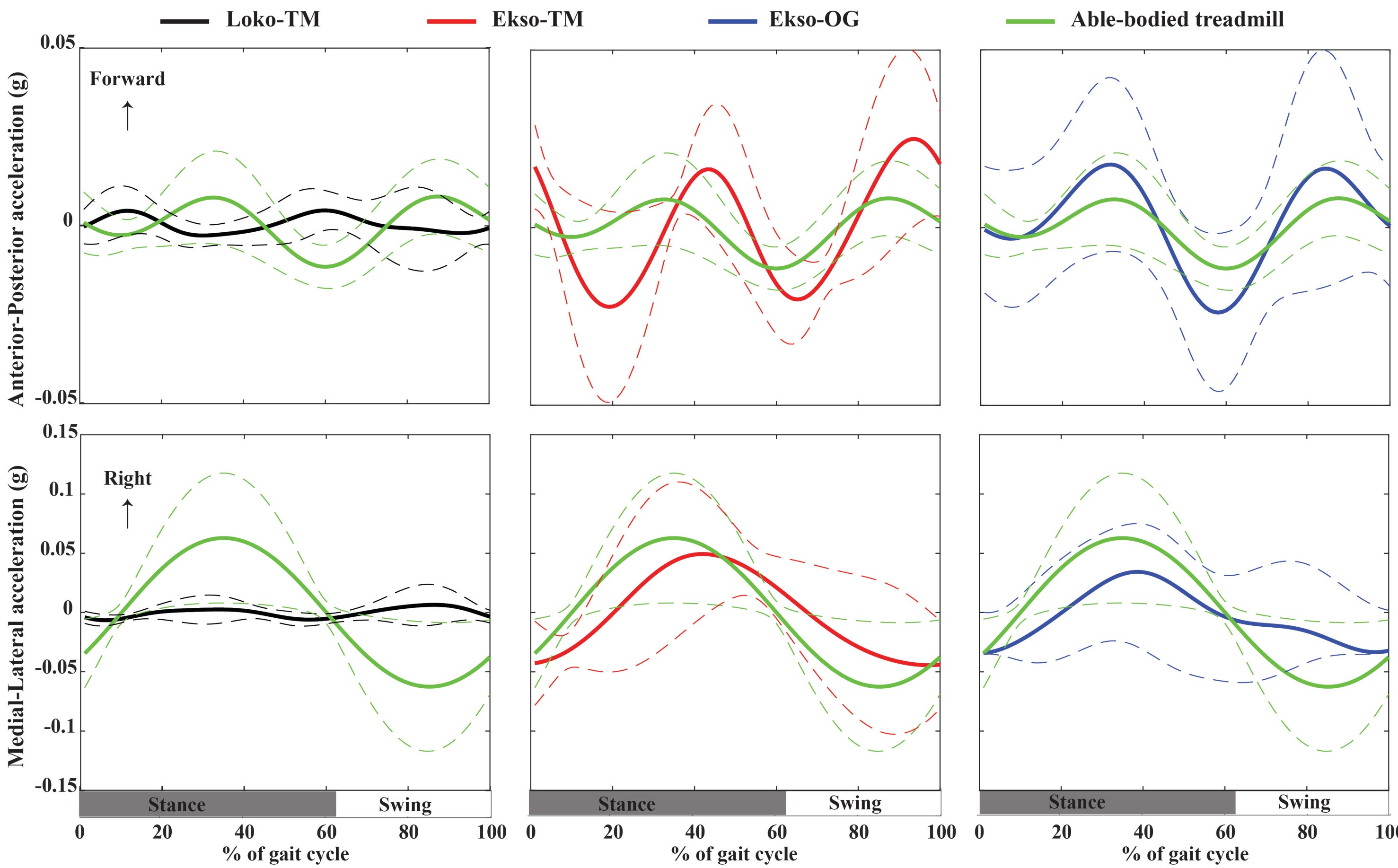

Figure 8: Average anterior-posterior (upper graphs) and medial-lateral acceleration (lower graphs) of SCI subjects during walking in the Lokomat (Loko-TM), the Ekso on treadmill (Ekso-TM) and Ekso overground (Ekso-OG) and able-bodied subjects normalized to the gait cycle. Dashed lines show the standard deviation.

Figure 9 Total acceleration of the trunk across robotic-assisted walking conditions

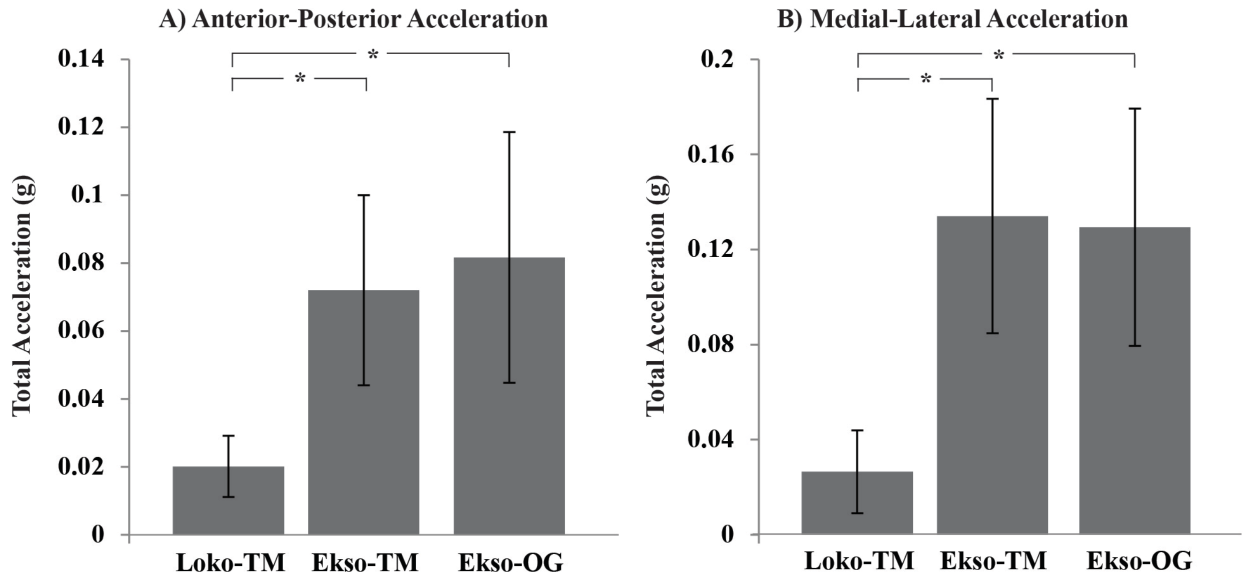

Figure 9: A) Mean total acceleration of the trunk for all SCI subjects across the 3 robotic-assisted walking conditions: Lokomat (Loko-TM), Ekso on treadmill (Ekso-TM) and Ekso overground (Ekso-OG). **B)** Total medial-lateral trunk acceleration during the same walking conditions. * = $p < 0.001$

3.7 Effect of body weight support

Figure 10 shows average trunk muscle activity averaged across 3 able-bodied subjects walking in the Lokomat with 50% BWS compared to 5kg BWS. RA activity was similar between 50% BWS and 5kg BWS. EO activity seemed slightly higher and ES EMG seemed to be lower at the lower BWS level, but the differences do not seem to be appreciable as the 95% confidence interval overlapped between the 2 conditions.

Figure 10 Trunk muscle EMG activity during walking in Lokomat with varying body weight support

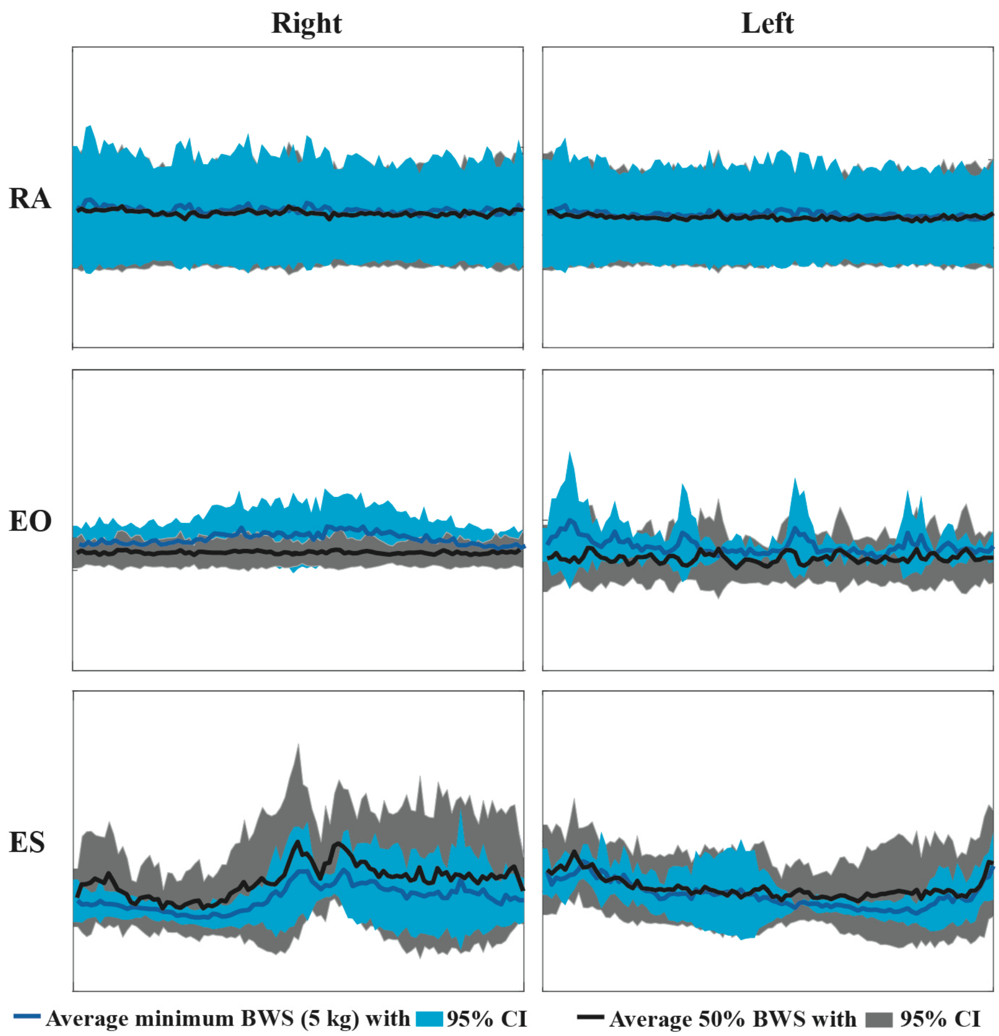

Figure 10: Average trunk muscle activation patterns from 3 able-bodied subjects normalized to the maximum voluntary contraction (MVC) during walking with the Lokmoat with 50% body weight support (BWS) (black) and 5kg BWS (red) in an able-bodied

3.8 Varying speeds

Only 2 SCI subjects (S02 and S03) were able to walk in Ekso-TM and Loko-TM with varying speeds. There was an observable increase in trunk muscle EMG amplitudes with increasing speeds. Figure 11 shows a sample of SCI subject (S02).

Figure 11 Trunk muscle EMG activity with varying speeds

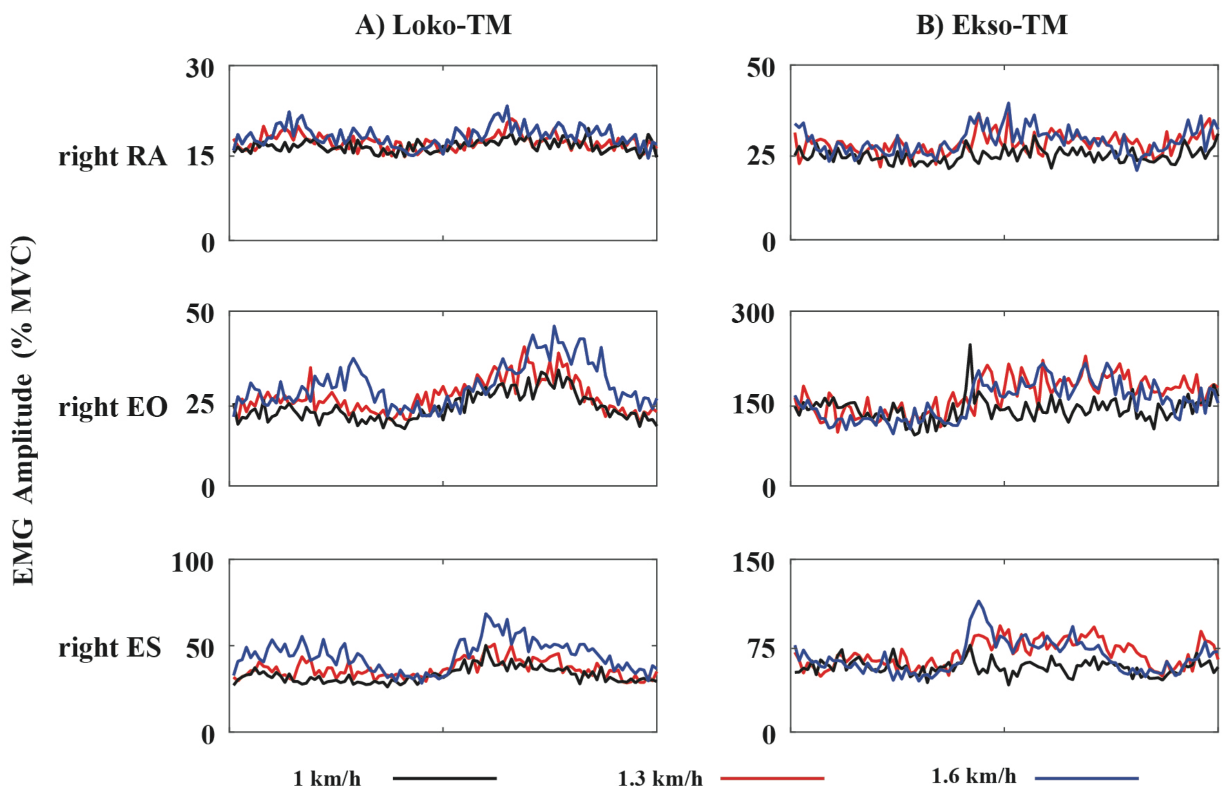

Figure 11: Trunk muscle, Rectus Abdominis (RA), External Oblique (EO) and Erector Spinae (ES), EMG amplitudes normalized to the maximum voluntary contraction (MVC) of a subject with SCI (S02) during walking with the Lokomat on treadmill (Loko-TM) and Ekso on treadmill (Ekso-TM) in three different speeds: 1 km/h (black), 1.3 km/h (red) and 1.6 km/h (blue).

3.9 Erector Spinae muscle timing

Inspection of ES EMG activity across multiple spinal levels revealed a unique observation reminiscent of the metachronal propagation of motor activity reported by others (de Sèze et al., 2007; Falgairolle et al., 2006; Falgairolle & Cazalets, 2007). Figure 12 shows ES EMG recordings at T3, T12 and L4 levels during Ekso-TM walking from an individual with SCI in whom we observed a clear example of this. ES showed a rostro-caudal activation pattern during walking in Ekso-TM, although this was not observed during Loko-TM (Fig. 13).

Figure 12 Erector spinae motor wave during Ekso-TM walking

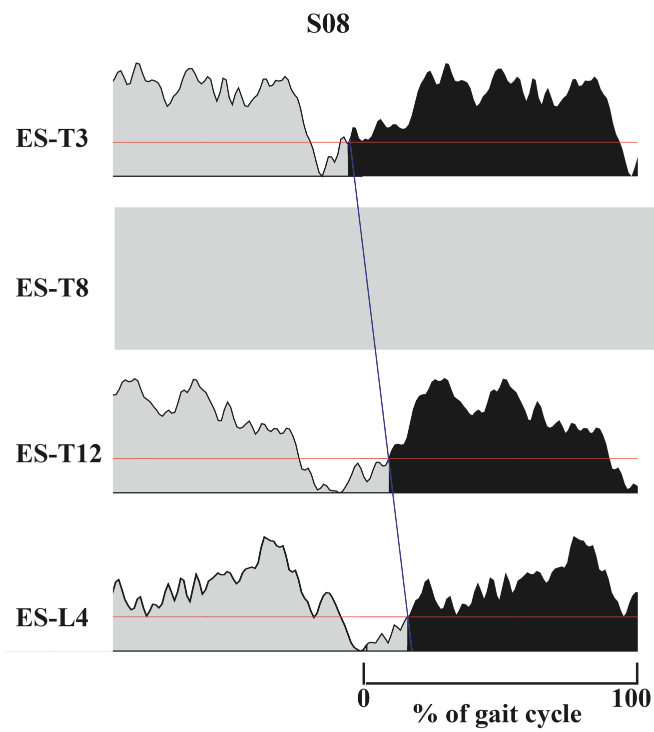

Figure 12: Erector Spinae (ES) muscle activity averaged over 60 steps at different spinal cord levels during Ekso on treadmill walking in **A)** SCI subject (S08) Horizontal red line shows onset threshold (%30 of peak contraction). Shaded black area shows activity period. Blue line shows timing sequence.

Figure 13 Average SCI erector spinae motor wave during Loko-TM and Ekso-TM walking

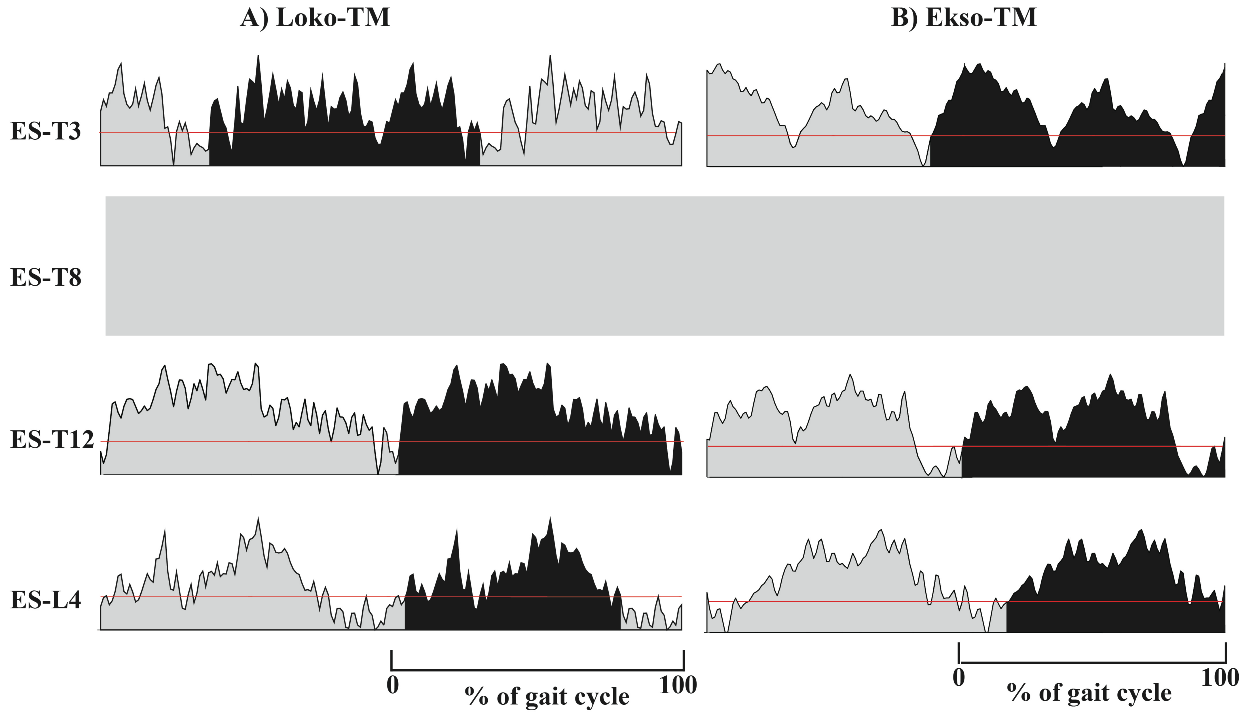

Figure 13: average SCI subjects Erector Spinae (ES) muscle activity at different spinal cord levels during **A)** Lokomat (Loko-TM) and **B)** Ekso on treadmill (Ekso-TM) walking. Horizontal red line shows onset threshold (%30 of peak contraction). Shaded black area shows activity period.

Chapter 4: Discussion

In this study trunk muscle activation patterns were compared during walking in a BWSTT device (the Lokomat) and an overground robotic exoskeleton (Ekso) in people with high thoracic motor-complete SCI. Both Lokomat and Ekso facilitate gait training in people with SCI, but it remains unknown how much they engage the trunk muscles that are normally activated during walking. Surface EMG electrodes were placed on RA, EO, and ES muscles to compare trunk muscle amplitudes and timings. Although all of the SCI participants enrolled in this study were not clinically supposed to have any trunk muscle activity (as per ISNCSCI examination), their trunk muscles showed higher EMG amplitudes in all muscles during Ekso walking conditions compared to the Lokomat.

4.1 Ekso is more effective than the Lokomat in engaging the trunk muscles

Although the Lokomat and the Ekso are both used to facilitate gait training in people with SCI, they differ in the way they provide gait training. When used with people with complete SCI, the Lokomat does not require an active participation from the user, as the trunk is passively supported by an overhead harness and the legs are moved by the device. On the contrary, gait training in the Ekso requires active participation from the user, as they have to shift their body weight from side to side and move the walker while maintaining their standing balance for taking each step. It is proposed that this alternating weight shifting movement and standing balance maintenance required by the Ekso are responsible for the higher activity in the trunk muscles during the Ekso-assisted walking conditions. Aaslund et al. (2008) have shown that walking with a weight support harness resulted in a restricted trunk acceleration in all directions (Aaslund & Moe-Nilssen, 2008b). Similarly, our acceleration data shows limited trunk movement during the

Lokomat-assisted walking trial. In fact, with such restricted trunk movement in the Loko-TM trial, trunk muscle EMG RMS amplitudes, except EO, were similar to the amplitudes recorded in supine position. In contrast, we show greater trunk acceleration during walking in the Ekso compared to the Lokomat, which is expected due to the weight shifting. Indeed, our acceleration data show that the anterior-posterior and medial-lateral weight shifting were similar to that during regular treadmill walking at the same speed. Moreover, in a study by Sylos-Labinin et al. (2014), lower limb EMG patterns during walking with a research exoskeleton (MINDWALKER), which has a similar walking mechanism to the Ekso, were compared to normal walking at similar speed in able-bodied individuals. They found that during exoskeleton-assisted walking, participants surprisingly had similar or higher activity compared to normal walking (Sylos-Labini et al., 2014). Similarly, our able-bodied data showed observably higher trunk muscle activity in the Ekso-assisted conditions compared to walking at similar speed.

4.1.1 Could walking aids have an effect?

In this study, there were two Ekso-assisted walking conditions: Ekso-OG in which the participants walked overground and used a front-wheeled walker, and Ekso-TM in which they walked over a treadmill and used the handrails. Although there were no significant differences in abdominal muscle activity between Ekso-OG and Ekso-TM trials, it could be noted that the EMG RMS amplitudes of all muscles were slightly higher in Ekso-OG trial than the Ekso-TM but not statistically significant except for ES. In the Ekso-OG condition, in addition to weight shifting, the participants had to push the wheeled walker with each step, which may also have contributed to the higher trunk muscle activity. However, as previously mentioned, Ekso users have to achieve lateral and forward targets by shifting their body weight in order to initiate the stepping mechanism. But in the Ekso-TM trial, it has been noted that less forward shifting is required. Although not statistically significant, it is observable that the trunk anterior-posterior acceleration had higher total acceleration in the Ekso-OG trial compared to the Ekso-TM. This could be because forward body-weight shifting is provided by the movement of the treadmill belt. This lack of forward shifting may have contributed to the lesser ES activation noted in the Ekso-TM trial.

4.1.2 Could Ekso be used to increase trunk muscle strength?

The trunk muscles play a major role in maintaining sitting postural stability in people with SCI. The ability to maintain sitting balance is important for people with complete SCI, as they perform the majority of daily functional activities in a seated position. Postural stability in people with SCI can be improved with intensive and appropriate training. Task-specific training programs, in which SCI subjects are intensively and repetitively trained on purposeful activities, are commonly used and shown to be effective (Betker, Desai, Nett, Kapadia, & Szturm, 2007; Bjerkefors, Carpenter, & Thorstensson, 2007; Boswell-Ruys, Harvey, et al., 2009a). These training programs have used training exercises that involved moving the upper body over and outside the base of support (Boswell-Ruys, Harvey, et al., 2009a), kayaking (Bjerkefors et al., 2007) as well as video game-based exercises (Betker et al., 2007). However, in task-specific training programs, people with SCI often develop new compensatory muscle activation patterns to control their posture by using non-postural muscles, such as latissimus dorsi muscle and upper part of the trapezius muscle, to compensate for the weakness in their postural muscles (Boswell-Ruys, Harvey, et al., 2009a; Seelen et al., 1998; Seelen & Vuurman, 1991). However, the use of these non-postural muscles could not fully compensate for the loss of ES function (Potten et al., 1999). In this study, the Ekso was successful in activating postural control muscles (trunk muscles) that are normally engaged during walking in both SCI and able-bodied subjects. Therefore, the Ekso could possibly be used as a training tool targeting these postural muscles to improve their function.

4.2 Timing of trunk muscle activity

The trunk muscles are normally activated during walking to provide upper body steadiness throughout the gait cycle (de Sèze et al., 2007; Tang et al., 1998). Several studies have shown certain pattern of activation for each muscle (Callaghan et al., 1999; Sheffield, 1962; Waters & Morris, 1972; White & McNair, 2002; Winter & Yack, 1987). In these studies, RA was documented to have different patterns of activity, either a low and constant muscle activity throughout the gait cycle or rhythmically active with a peak around 50% of the gait cycle (White & McNair, 2002) or at mid stance (Waters & Morris, 1972). Similar to RA, EO has been shown to have either a low and constant activity throughout the gait cycle in the majority of subjects, or a peak of EMG activity close to heel strike in other participants (Callaghan et al., 1999; White & McNair, 2002). ES activation patterns seem to be more consistent across individuals, with peak activity at heel strike (White & McNair, 2002; Winter & Yack, 1987). The data from our able-bodied control subjects are consistent with these previous reports (Callaghan et al., 1999; Sheffield, 1962; Waters & Morris, 1972; White & McNair, 2002; Winter & Yack, 1987). Moreover, when they walked in the Ekso, they had similar activation periods, albeit with higher amplitudes. In our SCI subjects, the onset and total activity time of trunk muscle were quite variable across the three walking conditions, which could be expected considering the variations in trunk activity patterns (Callaghan et al., 1999; Sheffield, 1962; Waters & Morris, 1972; White

& McNair, 2002; Winter & Yack, 1987). However, it could be observed that trunk muscle activation patterns from individual subject data were similar between Ekso-TM and Ekso-OG (Appendix B).

4.3 Source of trunk muscle activation

As aforementioned, the Ekso requires the user to consciously control their weight-shifting from one lower limb to the other in order to achieve the targets to trigger stepping. This voluntary control of shifting the body weight suggests engagement of the cortical and possibly vestibulospinal pathways. Sparing of corticospinal and vestibulospinal inputs to the trunk muscles has been revealed in recent studies (Bjerkefors et al., 2014; 2015; Squair et al., 2016). All SCI subjects showed greater activity during the MVC trials compared to the baseline activity recorded during supine lying. Moreover, the amplitude of this preserved trunk muscle activity showed an ability to modulate according to the postural demands. This is supported by the higher trunk muscle activity observed in the Ekso-TM and Ekso-OG walking trials compared to Loko-TM at matched speeds.

de Seze et al., (2007) have shown that ES muscles have double bursts of rhythmic activity with rostro-caudal motor wave during walking and this motor wave showed specificity according to the walking condition. For instance, forward walking produced rostro-caudal motor wave, while walking on hands while knees are on edge of treadmill produced a caudo-rostral motor wave. This specificity of motor wave propagation suggested CPG involvement reminiscent of patterns observed in animal models (de Sèze et al., 2007; Falgairolle & Cazalets, 2007) We observed similar rostro-caudal motor wave during Ekso-TM walking in some of our

SCI subjects. This specific timing of the ES muscle during gait, could suggest CPGs involvement.

It could be argued that the preserved muscle activity of the trunk below the level of injury is a result of the spinally mediated activation of the abdominal muscles due to the inspiratory activity of the diaphragm and changing intra-abdominal pressure (Silver, 2015). In this study, in addition to the controlled breathing protocol followed during the MVC (Bjerkefors et al., 2014), we recorded the breathing pattern during the Ekso and Lokomat assisted walking trials and investigated the patterning of trunk muscle activity with respect to the breathing rhythm. We did not observe any specific trunk muscle activity pattern in relation to the breathing cycle. In fact, trunk muscle activation patterns were specific to the gait cycle and were similar to the activation patterns observed in normal walking. Thus, it is unlikely that this observed muscle activity was elicited by breathing.

4.4 Potential clinical implications and future directions

Seated postural control in SCI is the foundation for many functional activities. Hence, developing effective training strategies is important to prevent performance in daily functional activities and enhance the quality of life for people with SCI. Impaired postural control after SCI occurs as a result of the paralysis or weakness of trunk muscles (Seelen et al., 1997). As a result, people with SCI are known to develop new postural control synergies by recruiting non-postural control muscles to compensate for the loss of the postural control muscles (Seelen et al., 1998; Seelen & Vuurman, 1991). However, these new postural control synergies do not fully compensate the function of trunk muscles that are responsible for the normal postural control synergies (Potten et al., 1999). Therefore, finding new training strategies to reactivate and train trunk muscles could possibly support normal postural control synergies and ultimately improve seated postural control in people with SCI. The data here could contribute to our understanding of the broader benefits of using robotic overground training and developing more efficient rehabilitation interventions.

4.4.1 Benefits of walking for people with complete SCI

SCI subjects who received BWSTT with the Lokomat showed improvements in standing balance, cardiovascular function, fitness level, sleep quality and overall life satisfaction (Buehner et al., 2012; Harkema, Schmidt-Read, Lorenz, Edgerton, & Behrman, 2012; Hicks & Ginis, 2008; S. Kornfeld et al., 2004; Musselman, Fouad, Misiaszek, & Yang, 2009; Wu, Landry, Schmit, Hornby, & Yen, 2012). However, these improvements were not dependent to the improvement in walking, as they occurred with persons with complete SCI who were not expected to improve in terms of walking function (S. Kornfeld et al., 2004). Similar to BWSTT, recent studies on incomplete SCI subjects who used robotic overground walking devices showed that in addition to improvements in overground walking quality, speed and distance (Mirko Aach et al., 2014; Spungen, Asselin, Fineberg, Kornfeld, & Harel, 2013b), other benefits were observed, such as improved soft tissue body composition (Spungen et al., 2013a) and reduced neuropathic pain severity (Kressler et al., 2014). However, the ability of such training to deliver other health benefits has not yet been investigated.

Training in one task may have positive effect on other tasks (Swinnen, Beckwee, Meeusen, Baeyens, & Kerckhofs, 2014b; Tamburella, Scivoletto, & Molinari, 2013). In people with stroke, training on multi-directional challenging reaching tasks have been shown to be effective in improving static and dynamic sitting balance, as well as a possible effect on standing balance (Dean, Channon, & Hall, 2007). Other studies in stroke have also shown positive effects of BWSTT on standing balance (Swinnen, Beckwee, Meeusen, Baeyens, & Kerckhofs, 2014b). Additionally, training of incomplete SCI subjects on standing balance has been shown to transfer to improvements in their walking performance (Tamburella et al., 2013). In this study we have shown that gait training with the Ekso activate and possibly train the trunk muscles as it challenges postural control. Therefore, future studies could investigate the possible transfer of improved postural control during Ekso-assisted walking to improvement sitting stability.

Additionally, secondary benefits of training may extend to cortical plasticity. Low thoracic SCI is known in animal and humans to cause an expansion of the sensory map of spared proximal areas into the deafferented cortex and a shift in the motor representation of proximal muscles in the motor cortex (Oza & Giszter, 2014). However, depending on use and skill, plastic changes in the cortex may occur (Dancause & Nudo, 2011). These changes are not exclusives to the sensory cortex, but also to the motor cortex (Oza & Giszter, 2014; 2015). Low thoracic neonatal rats who received robot rehabilitation gait training showed expansion of the caudal trunk area in the cortex, increased trunk coactivation at cortex sites, increased richness of trunk cortex motor representation, and movement of trunk motor representation in the cortex toward more normal topography (Oza & Giszter, 2015). Therefore, robot rehabilitation training could possibly reorganize the trunk motor cortex, which in turn could underpin improvements in the control of postural control muscles.

4.5 Methodological considerations

Trunk muscle activation patterns are known to alter with walking speed (Anders et al., 2007; Saunders et al., 2004). Therefore, walking speed had to be matched between the Lokomat and Ekso to allow for an accurate comparison. The lowest possible treadmill speed with the Lokomat is 1 km/h. However, this walking speed is considered high for walking with the Ekso (Kozlowski, Bryce, & Dijkers, 2015; Kressler et al., 2014), However, all the participants recruited to this study were able to achieve it. Additionally, at this walking speed swing time between the Lokomat and Ekso is different. In the Ekso most of the gait cycle time is spent shifting the body weight from one side to the other and swing time is relatively quick. In contrast, the gait cycle of the Lokomat is pre-programmed with the typical proportion of 60:40 ratio between stance and swing phases. This difference in swing time between the two devices might contribute to the EMG timing differences. Dividing the gait cycle into stance and swing and analyze the EMG timing in each could overcome this problem.

The Ekso exoskeleton has strict indications and contraindications lists, which might limit its possible benefits to a specific group of users. For instance, some potential participants were excluded from this study for their lower extremity measurements being under Ekso limits, or inability to tolerate standing for more than 30 minutes.

The Ekso provides full body weight bearing, which is not possible to achieve in the Lokomat with people with high thoracic motor-complete SCI. Trunk muscle activity could be affected by the percentage of the body weight support and the full-weight bearing provided by the Ekso could have contributed to the better engagement of trunk muscles. Swinnen et al. (2014) recorded trunk muscle activity from able-bodied subjects and individuals with multiple sclerosis while walking on a treadmill supported by a harness. They found that in both groups, EO EMG activity increased and ES decreased as BWS increased (Swinnen, Baeyens, Pintens, Van Nieuwenhoven, Ilsbroukx, Clijsen, et al., 2014a). However, the participants in that study did not use a Lokomat and were capable of walking independently without a BWS system, which may also have affected their trunk muscle activity. Due to the level and completeness of injury in our SCI subjects, it was not possible to vary the amount of BWS to such an extent. However, our able-bodied data have shown similar muscle activity during walking with the Lokomat at 50% of BWS compared to 5 kg BWS (minimum BWS). Therefore, the higher level of trunk muscle activity in the Ekso-assisted walking conditions compared to the Lokomat was most likely not due to the differences in the weight bearing requirements between the two devices, but to the different walking mechanisms.

Chapter 5: Conclusion

Recent studies have reveled sparing of trunk muscle function below the injury level (Bjerkefors et al., 2014; 2015; Squair et al., 2016). These trunk muscles are important for postural control in sitting and standing positions. They are also known to have specific patterns of activity to support the upper body during walking in able-bodied individuals (de Sèze et al., 2007; Tang et al., 1998; Winter & Yack, 1987). People with complete SCI could walk with the help of robotic exoskeletons. In this study, we demonstrated better engagement of the trunk muscles during walking in the Ekso compared to Lokomat; in fact, activity in some muscles during Lokomat walking was not different from quiescent activity recorded during supine-lying. These differences in trunk muscle EMG amplitudes between the devices could be due to the different walking mechanisms of the Ekso and Lokomat. The Ekso requires the user to voluntary weight shift from one limb to the other in order to trigger stepping. In the contrary, the Lokomat restricts the trunk by passively supporting it by a BWS harness.

Increasing trunk muscle strength leads to improved postural control and better performance of daily functional activities and quality of life of people with SCI. Future studies could investigate the possibility of using the Ekso as a training tool to increase trunk muscles strength and improve sitting postural stability.

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Appendices

Appendix A Trunk function and balance assessment

Guidelines for the Trunk test

for Para-Canoe Athletes

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Equipment

- Treatment bench with adjustable height
- Wobble cushion
- Protocol

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Manual Muscle Test

- Athlete will perform **seven** trunk muscle tasks
  - trunk flexion
  - trunk rotation to the right (R) and to the left (L)
  - trunk side bending to the R and L
  - trunk lumbar extension
  - trunk lumbar extension and hip extension

- The tests will be performed on a **0-2** scale.
- Total number of points available for this section = **14**

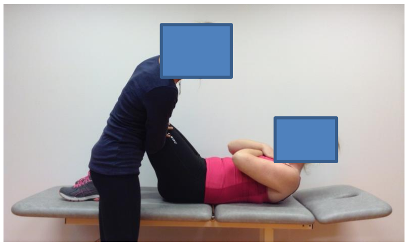
Performance of each test

- The following instruction will be given during all Manual Muscle Test
  - breathe out (2s) (athlete is still in the initial position) (instruction: out, out).
  - perform the trunk muscle task (2s) (athlete is moving to the final position) (instruction: up, up).
  - hold a maximal contraction (2s) (athlete is in the final position) (instruction: hold, hold).

- All tests will be performed during normal exhalation.

Trunk flexion Score 2

- **Position of Athlete:** Supine with arms crossed over chest.
- **Position of Classifier:** Standing at level of patient's chest to be able to ascertain whether scapulae clear table during test. If athlete has weak hip flexors, the examiner should stabilize the pelvis by leaning across the athlete on the forearms.
- **Test:** Athlete flexes trunk through range of motion. A curl-up is emphasized, and trunk is curled until scapulae clear table.
- **Instruction:** "Tuck your chin and lift your head, shoulders off the table in a sit-up."
- **Score 2:** Athlete completes range of motion and raises trunk until scapulae are off the table.



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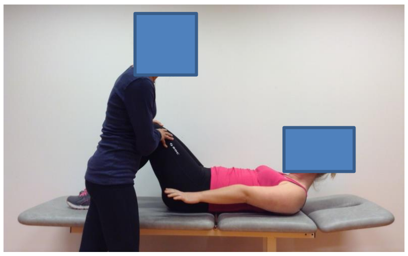
Trunk flexion Score 1

- **Position of Athlete:** Supine with arms stretched towards toes.
- **Position of Classifier:** Standing at level of patient's belly. The hand used for palpation is placed at the midline of the thorax over the linea alba, and the four fingers of both hands are used to palpate the Rectus abdominus.
- **Test:** Athlete attempts to flex trunk.
- **Instructions**: "Tuck your chin and lift your head, shoulders off the table in a sit-up."
- **Score 1:** Athlete completes partial range of motion and the examiner must be able to detect contractile activity.



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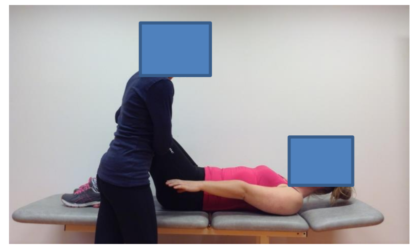
Trunk flexion Score 0

- **Position of Athlete.** Supine with arms stretched towards toes.
- **Position of Classifier:** Standing at level of patient's belly. The hand used for palpation is placed at the midline of the thorax over the linea alba, and the four fingers of both hands are used to palpate the Rectus abdominus.
- **Test:** Athlete attempts to flex trunk.
- **Instructions**: "Tuck your chin and lift your head, shoulders off the table in a sit-up."
- **Score 0:** The athlete is unable to lift the shoulders from the table, and no or very limited activity is visible or palpable during attempted contraction.



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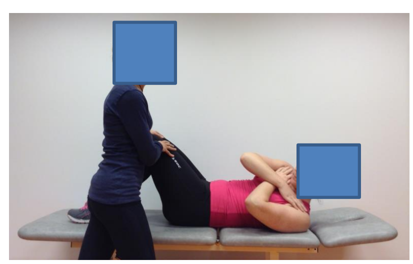
Trunk rotation Score 2

- **Position of Athlete:** Supine with arms crossed over chest.
- **Position of Classifier:** Standing at level of patient's waist.
- **Test:** Athlete flexes trunk and rotates to one side. And then the other.
- **Instruction: "**Lift your head and shoulders from the table, taking your right elbow toward your left knee." Repeat on opposite side.
- **Score 2:** The inferior angle of the scapula on the opposite side to the rotation clears the table.



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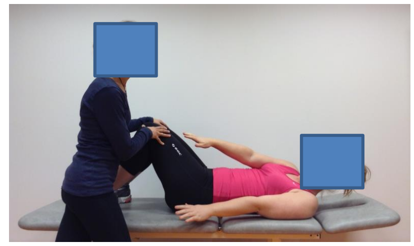
Trunk rotation Score 1

- **Position of Athlete:** Supine with arms at sides.
- **Position of Classifier:** Classifier palpates the external oblique first on one side and then on the other, with one hand placed on the lateral part of the anterior abdominal wall distal to the rib cage. Continue to palpate the muscle distally in the direction of its fibers until reaching the anterior superior iliac spine.
- **Test:** Athlete attempts to raise body and rotate to one side. And then the other.
- **Instruction:** "Lift your head and shoulders from the table, taking your right elbow toward your left knee." Repeat on opposite side.
- **Score 1.** Athlete completes partial range of motion and the classifier must be able to detect contractile activity.



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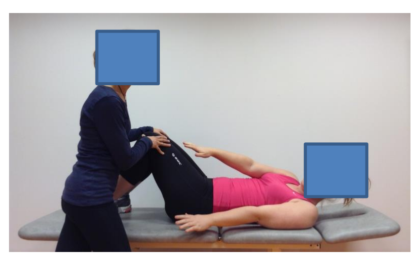
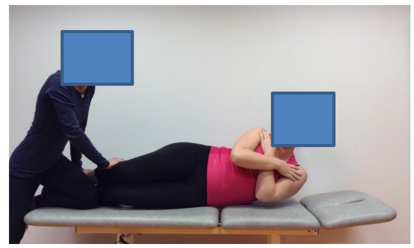
Trunk rotation Score 0

- **Position of Athlete:** Supine with arms at sides.
- **Position of Classifier:** Standing at level of athlete's waist
- **Test:** Athlete attempts to flex trunk and turn to either side.
- **Instruction:** "Try to lift your head and shoulders from the table, taking your right hand towards your left knee." Repeat on opposite side.
- **Score 0:** The athlete is unable to lift the shoulder from the table, and no or very limited activity is visible or palpable during attempted contraction.



Trunk side flexion Score 2

- **Position of Athlete:** On their side with arms crossed over chest.
- **Position of Classifier:** Standing at level of athlete's shanks to provide support.
- **Test:** Athlete laterally bends the trunk.
- **Instruction:** "Lift your trunk off the table as high as you can." Repeat on opposite side.
- **Score 2:** The inferior angle of the deltoid clears the table.



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Trunk side flexion Score 1

- **Position of Athlete:** Supine with arms at sides.
- **Position of Classifier:** Standing at level of athlete's waist. If athlete has weak hip flexors, the examiner should stabilize the pelvis by leaning across the athlete on the forearms. Classifier palpates the external oblique first on one side and then on the other, with one hand placed on the lateral part of the anterior abdominal wall distal to the rib cage.
- **Test:** Athlete laterally bends the trunk.
- **Instruction:** "Lift your head off the table and bend your trunk sideway, hand towards toes." Repeat on opposite side.
- **Score 1:** Athlete completes partial range of motion and the classifier must be able to detect contractile activity.

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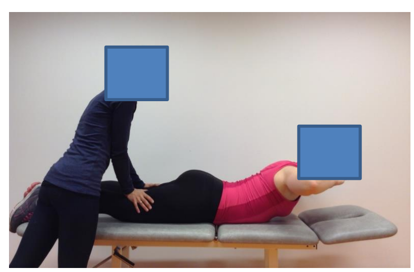
Trunk side flexion Score 0

- **Position of Athlete:** Supine with arms at sides.
- **Position of Classifier:** Standing at level of athlete's waist. If athlete has weak hip flexors, the examiner should stabilize the pelvis by leaning across the athlete on the forearms. Classifier palpates the external oblique first on one side and then on the other, with one hand placed on the lateral part of the anterior abdominal wall distal to the rib cage.
- **Test:** Athlete attempts to laterally bend the trunk.
- **Instruction: "**Lift your head off the table and bend your trunk sideway, hand towards toes." Repeat on opposite side.
- **Score 0:** The athlete is unable to bend sideways and no or very limited activity is visible or palpable during attempted contraction.

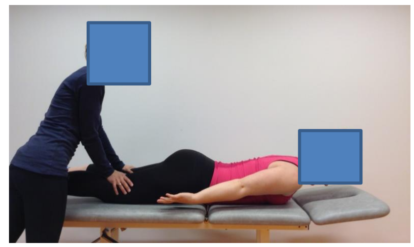
Trunk Lumbar Extension Score 2

- **Position of Athlete:** Prone with hands close to head.
- **Position of Classifier:** With hands holding the ankles.
- **Test:** Athlete extends the **lumbar** spine until the entire sternum is raised from the table .
- **Instruction:** "Raise your head, shoulders, and chest from the table as high as you can"
- **Score 2:** The athlete can achieve the end position.



Trunk Lumbar Extension Score 1

- **Position of Athlete:** Prone with their arms placed by their sides.
- **Position of Classifier:** With hands holding the ankles.
- **Test:** Athlete extend the trunk.
- **Instruction:** "Lift your head and chest as high as possible"
- **Score 1:** Athlete completes partial range of motion and the classifier must be able to detect contractile activity.



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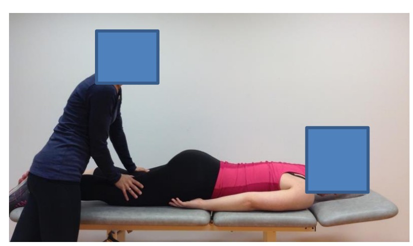
Trunk Lumbar Extension Score 0

- **Position of Athlete : P**rone with their arms placed by their sides.
- **Position of Classifier:** Standing at level of athlete's waist. Classifier palpates the lumbar extensor muscles .
- **Test:** Athlete extend the trunk.
- **Instruction:** "Lift your head and chest as high as possible"
- **Score 0**: The athlete is unable to lift the trunk of the table and no or very limited activity is visible or palpable during attempted contraction.



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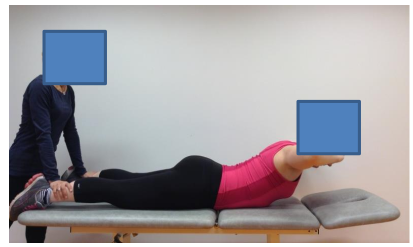
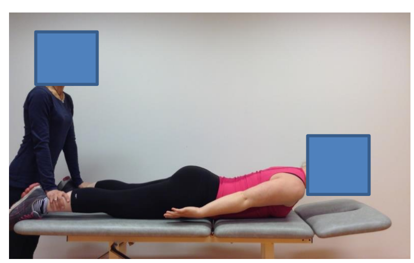
Trunk and hip extension Score 2

- **Position of Athlete:** Prone with their hands placed by the head
- **Position of Classifier:** With hands holding the ankles.
- **Test:** Athlete extend the trunk.
- **Instruction:** "Lift your head and chest as high as possible"
- **Score 2:** The sternum clears the table.



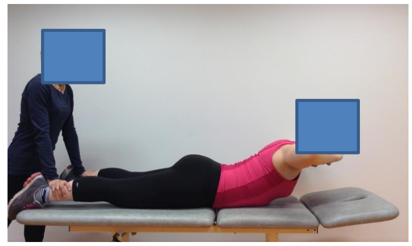
Trunk and hip extension Score 1

- **Position of athlete:** Prone with their arms placed by their sides.
- **Position of classifier:** With hands holding the ankles
- **Test:** Athlete extend the trunk.
- **Instruction:** "Lift your head and chest as high as possible"
- **Score 1:** Athlete completes partial range of motion and the classifier must be able to detect contractile activity.



Trunk and hip extension Score 2

- **Position of Athlete:** Prone with their hands placed by the head
- **Position of Classifier:** With hands holding the ankles.
- **Test:** Athlete extend the trunk.
- **Instruction:** "Lift your head and chest as high as possible"
- **Score 2:** The sternum clears the table.



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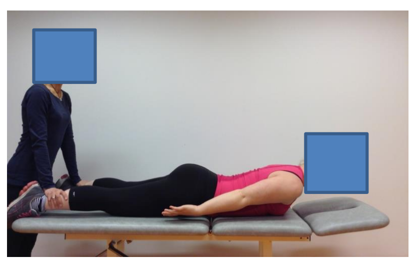
Trunk and hip extension Score 1

- **Position of athlete:** Prone with their arms placed by their sides.
- **Position of classifier:** With hands holding the ankles
- **Test:** Athlete extend the trunk.
- **Instruction:** "Lift your head and chest as high as possible"
- **Score 1:** Athlete completes partial range of motion and the classifier must be able to detect contractile activity.



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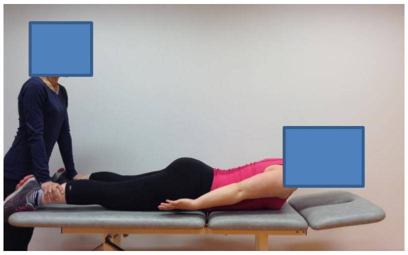
Trunk and hip extension Score 0

- **Position of athlete : P**rone with their arms placed by their sides.
- **Position of classifier:** Standing at level of athlete's waist. Classifier palpates the lumbar extensor muscles and hip extensor muscles .
- **Test:** Athlete extend the trunk.
- **Instruction:** "Lift your head and chest as high as possible"
- **Score 0**: The athlete is unable to lift the trunk of the table and no or very limited activity is visible or palpable during attempted contraction.



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Functional Assessment Score

Athlete will be asked to complete functional tasks while sitting unsupported.

The examination includes:

- static tasks (sitting upright with arms outstretched in 4 directions), scores a maximum of **10** points

- dynamic tasks (moving trunk through a range of motion), scores a maximum of **12** points

- perturbation tasks (push and recovery from 6 directions), scores a maximum of **24** points

- perturbation tasks while athlete is sitting on a wobble cushion (push and recovery from 6 directions), scores a maximum of **24** points

There are a maximum of **70** points for the Functional assessment. These are added to the Manual Muscle Test score for a maximum of **84** points

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Static test

Upright Sitting

- **Description:** Athlete sits with legs hanging over the edge with feet unsupported. Athlete crosses arms to prevent support. Classifier brings athlete into upright position, one hand on sternal bone and one hand on back, then slowly lets go of support.

- **Instruction:** "Sit up tall."

- **Evaluation:** Observe sitting position after removing the support:
  - straight/upright
  - flat belly
  - kyphotic/quad/para belly

- **Score 2:** Sits straight upright, without marked kyphosis, and with flat belly for at least 10 seconds

- **Score 1:** Can only manage upright sitting for less than 3 seconds

- **Score 0:** Sits with marked kyphosis or with quad belly

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Score 2

Score 0

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Static test

Upright Sitting with shoulder flexion/extension

- **Description:** Athlete sitting on the plinth with legs hanging over edge of plinth with the feet unsupported. The classifier may need to place his/her hands close to the hips, to fix both legs to the plinth.

  Flexion: Athlete is instructed to lift both arms to 90° shoulder flexion, hold for 2 seconds and slowly go back to the initial position.

  Extension: Athlete is instructed to lift both arms to about 30° shoulder extension, hold for 2 seconds and slowly go back to the initial position.

- **Evaluation:** Observe movement quality and range standing lateral to the Athlete.

- **Score 2:** Athlete performs shoulder **flexion** to at least 90° with a straight upright position.
- **Score 2:** Athlete performs shoulder **extension** to at least 30° with a straight upright trunk position.

- **Score 1:** Athlete attempts to **flex/extend** shoulders to **90°/30°** but can only maintain a straight upright trunk momentarily before compensating by kyphosis or lordosis

- **Score 0:** Athlete is unable to maintain an upright posture to lift the arms, either into flexion or extension.

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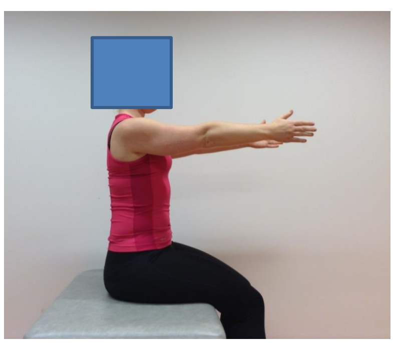
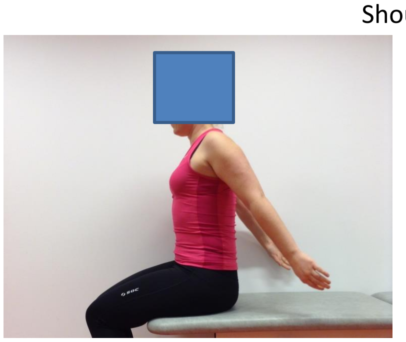
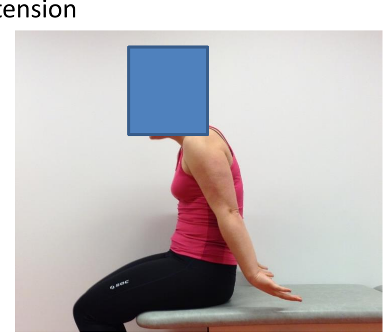
Score 2 Shoulder flexion Score 0



Shoulder extension





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Static test

Upright Sitting with abduction

- **Description:** Athlete sitting on the plinth with legs hanging over edge of plinth with the feet unsupported. The classifier may need to place his/her hands close to the hips, to fix both legs to the plinth. .

  Abduction: Athlete is instructed to lift one arm to 90° shoulder abduction, hold the position for 2 seconds and slowly go back to the initial position. The other arm is crossed over the chest.

- **Evaluation:** Observe movement quality and range standing lateral to the Athlete.

- **Score 2:** Athlete performs shoulder abduction to at least 90° with a straight upright position.

- **Score 1:** Athlete lifts shoulder to 90°, but is unable to maintain upright posture throughout the test without compensation.

- **Score 0:** Athlete is unable to lift the shoulder to 90° and compensates with kyphosis/lordosis. May need support to resume straight position

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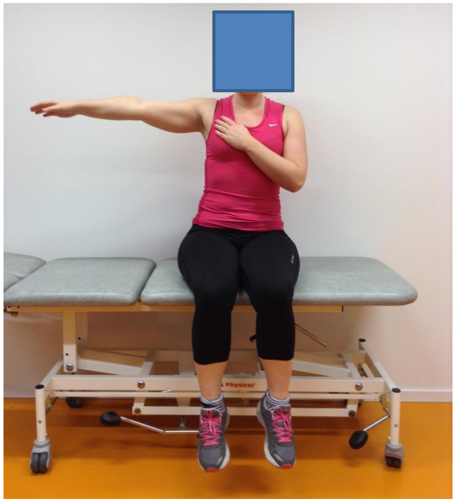
Score 2



Dynamic test

Active Trunk Flexion/Extension

- **Description:** Athlete sits on the plinth with legs hanging over the edge, with the feet unsupported. Athlete crosses the arms in front of his/her chest, to prevent support for sitting balance from the arms. The classifier may need to place his/her hands close to the hips, to fix both legs to the plinth.
- **Evaluation:** Observe movement quality and range standing lateral to the Athlete.
- **Score 2:** Athlete performs trunk flexion to at least 20° line between pelvis and C7 and vertical, and maintains position for 2 seconds before returning to upright position, **and** performs at least 15° trunk extension and maintains position for2 seconds before returning to upright position.
- **Score 1:** Athlete flexes to less than 20° and extends to less than 15°, and is unable to maintain the position for 2 seconds. May compensate to resume straight position.
- **Score 0:** Athlete cannot flex or extend without compensation by kyphosis/lordosis or cannot resume straight position without support.

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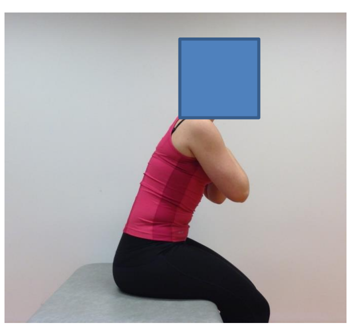
Grade 2 **Trunk flexion** Grade 0



Grade 2 **Trunk extension** Grade 0

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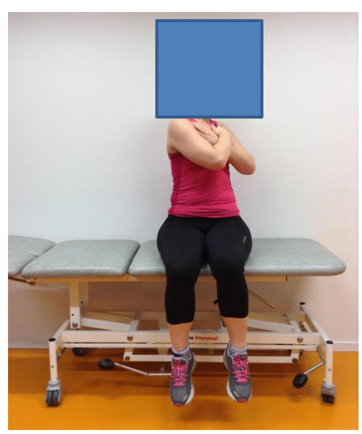
Dynamic test

Active Trunk Rotation

Grade 2

- **Description:** Athlete sits on the plinth with legs hanging over edge, with the feet unsupported. Athlete crosses the arms in front of his/her chest, to prevent support for sitting balance from the arms. The classifier may need to place his/her hands close to the hips, to fix both legs to the plinth.
- **Evaluation:** Observe movement quality and range standing lateral to the Athlete.
- **Score2:** Athlete stays in upright position and rotates 20° or more to both sides, measured in straight line between both shoulders and line between ASIS on both sides.
- **Score 1:** Athlete rotates less than 20°, or cannot remain upright whilst rotating
- **Score 0:** Athlete does not rotate, or cannot maintain upright position in sagittal plane while rotating (e.g. assumes kyphotic posture).



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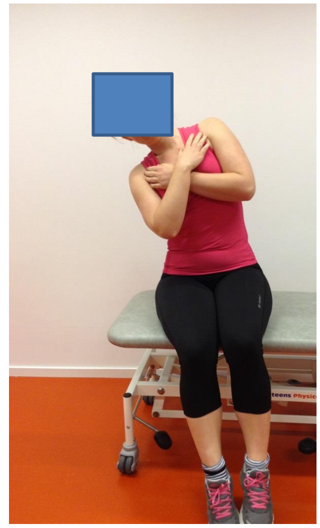
Dynamic test

Active Trunk Side Flexion

Score 2

- **Description:** Athlete sits on the plinth with legs hanging over edge, with the feet unsupported. Athlete crosses the arms in front of his/her chest, to prevent support for sitting balance from the arms. The classifier may need to place his/her hands close to the hips, to fix both legs to the plinth.
- **Evaluation:** Observe movement quality and range standing lateral to the A.
- **Score 2:** Athlete stays in upright position in the sagittal plane and performs side flexion at least with suprasternal notch in vertical line above the ASIS to both sides and can maintain this position for 2 seconds before resuming the upright position.
- **Score 1**: Athlete cannot side flex to the level of the suprasternal notch, or can only maintain position momentarily.
- **Score 0:** Athlete cannot side flex, or cannot maintain an upright position in the sagittal plane while performing side flexion (e.g. kyphotic posture).



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Trunk Resistance (Perturbation)

- Trunk Flexion, Trunk Extension, Trunk Rotation, Trunk Side Flexion

- **Description:** Athlete sits on the plinth with legs hanging over the edge, with the feet unsupported. Athlete crosses the arms in front of his/her chest, to prevent support for sitting balance from the arms.

  Classifier applies prolonged force to the trunk in six directions by placing the hand in six different locations; anterior, over the mid sternum, posterior, over the thoracic spine midway between the superior and inferior angles of the scapula, and right and left rotation, over the frontal aspect of the acromial process, and right and left side flex, over the lateral aspect of the acromial process.
- **Instruction: "**Hold, do not let me push you over!"
- **Evaluation:** Trunk flexion: RA, both sides of umbilicus, Trunk extension: ES, both sides spine, Trunk rotation to the L: OE R and OI L, Trunk rotation to the R: OE L and OI R, Trunk lat. bending to the L: QL R, Trunk lat. bending to the R: QL L.
- **Score 2:** Athlete is able to adequately resist the constant force to the trunk .
- **Score1:** Athlete resists the initial push but is unable to maintain upright posture, or can only resist a very gentle force
- **Score 0:** Athlete is not able to recover from the constant force.

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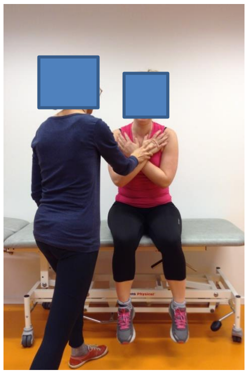
Trunk Resistance



Trunk Flexion

Trunk Extension

Trunk Rotation

Trunk Lateral Bending

Trunk Push (Perturbation)

- Trunk Flexion, Trunk Extension, Trunk Rotation, Trunk Side Flexion

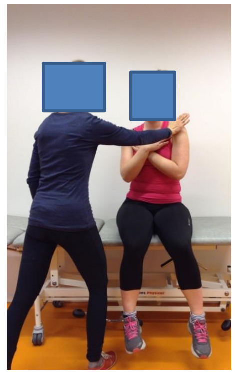
- **Description:** Athlete sitting on the plinth with legs hanging over edge of plinth with the feet unsupported. Athlete crosses the arms in front of his/her chest, to prevent support for sitting balance from the arms.

  Classifier applies an unexpected/sharp force to the trunk in six directions by placing the hand in six different locations; <u>anterior</u>, over the mid sternum, <u>posterior</u>, over the thoracic spine midway between the superior and inferior angles of the scapula, and <u>right and left rotation</u>, over the frontal aspect of the acromial process, and <u>right and left lateral</u>, over the lateral aspect of the acromial process.
- **Instruction: "**Hold, do not let me push you over!"
- **Evaluation:** Trunk flexion: RA, both sides of umbilicus, Trunk extension: ES, both sides spine, Trunk rotation to the L: OE R and OI L, Trunk rotation to the R: OE L and OI R, Trunk lat. bending to the L: QL R, Trunk lat. bending to the R: QL L.
- **Score 2:** Athlete is able to adequately resist the trunk push.
- **Score 1:** Athlete attempts to resist the push, or can only resist a very gentle push.
- **Score 0:** Athlete is not able to apply any resistance to the push.

Trunk Push

Trunk Flexion

Trunk Extension



Trunk Rotation

Trunk Lateral Bending

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All Dynamic and Perturbation tasks will be performed on the wobble cushion on a 3 graded scale.

Succeed = 2, In doubt = 1, Clearly fails = 0

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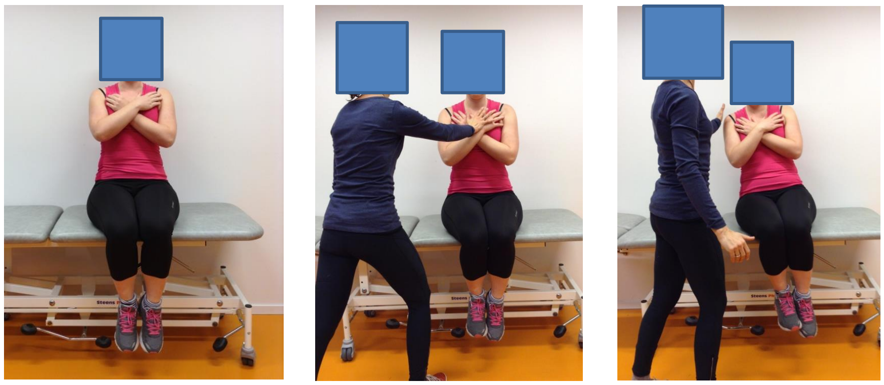
Upright sitting Trunk Resistance Trunk Push



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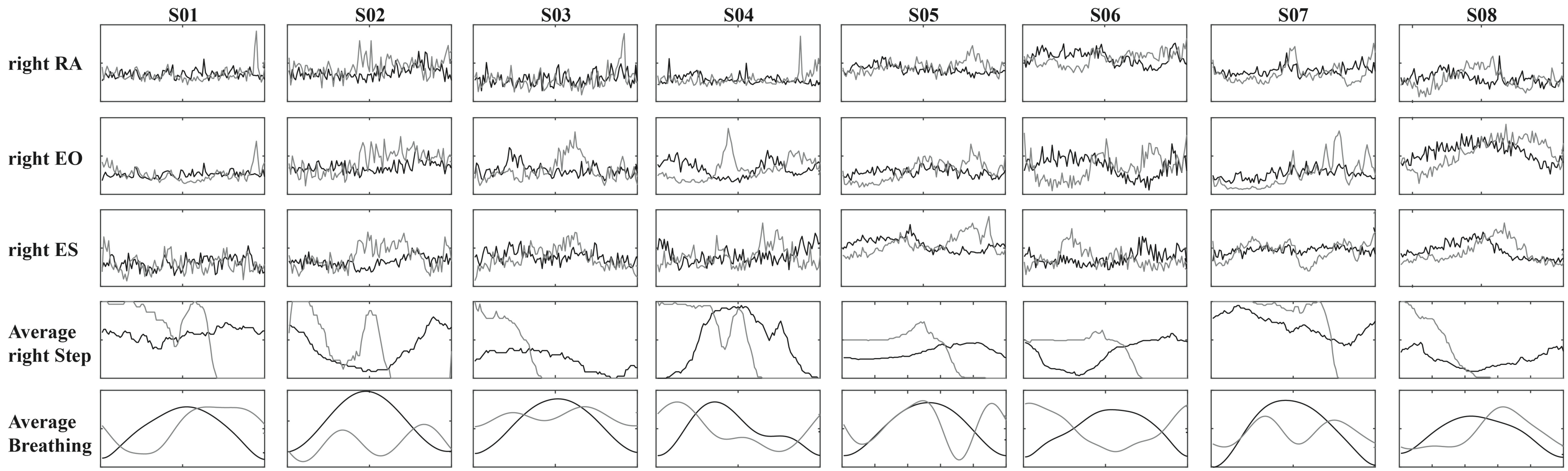
Appendix B Trunk activation patterns normalized to breathing cycle compared to gait cycle



Appendix B: Comparison of EMG recordings from the right rectus abdominis (RA), external oblique (EO) and erector spinae (ES) normalized to the breathing cycle (onset of inspiration) vs those normalized to the gait cycle (right heel contact). Each graphs shows the average of at least 50 breath cycles and steps.