Effects of Trunk Impairments on Manual Wheelchair Propulsion Among Individuals with a Spinal Cord Injury: A Brief Overview and Future Challenges

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The majority of individuals with a spinal cord injury experience sensory and motor trunk impairments. The severity of these impairments, along with their side effects on postural stability and upper limb strength-generating capability, may reduce these individuals' capacity to efficiently propel their manual wheelchair and perform other wheelchair-related activities. This article presents a brief overview of the relevant literature focusing on potential effects of trunk impairments on manual wheelchair propulsion and explores a few future research challenges. There is a need to develop quantitative sensorimotor trunk assessment and to develop innovative therapeutic approaches. **Key words:** *biomechanics, movement, paraplegia, postural balance, rehabilitation, spinal cord injuries, task performance and analysis, tetraplegia, upper extremity, wheelchair*

There is a growing consensus among rehabilitation specialists that sensorimotor trunk impairments in individuals who have sustained a spinal cord injury (SCI) deserve additional attention. It is surprising to realize that assessment of sensorimotor trunk impairments in clinical practice relies almost exclusively on observational and qualitative measures and that those impairments have received

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insufficient and unspecific attention over the years. Sensorimotor trunk impairments have classically been inferred from the level of lesion when investigating manual wheelchair propulsion. The lack of specific measurement instruments with known psychometric properties, along with the paucity of precise rehabilitation interventions targeting those impairments, may explain this situation. Additional research is required to gain insight into both sensory and motor trunk impairments and on their combined effects on the synergies needed to control the trunk.

The severity of sensorimotor trunk impairments, along with their side effects on postural stability, are believed to reduce capacity for individuals with an SCI to manually propel their wheelchair and perform other wheelchair-related activities.[1] During manual wheelchair propulsion, the cyclical acceleration and deceleration to which the head, neck, and trunk segments are exposed generate substantial inertial forces because these segments represent approximately 60% of the total body weight.[2] In addition, the wheelchair further contributes to these moments of inertia. Sensorimotor trunk impairments reduce the ability to control these disturbances among individuals with an SCI and can have deleterious consequences on manual wheelchair performance. Many also suggest that the sensorimotor trunk impairments may exacerbate the development of secondary upper limb (UL) impairments, found to be particularly prevalent at the shoulder joint, among individuals with an SCI. Moreover, these individuals have been found to be exposed to an increased risk of falls out of the wheelchair given their trunk impairments, which are perceived to be a key contributor.[3]

The main objective of this article is to highlight the potential association between sensorimotor trunk impairments and manual wheelchair capacity among individuals with an SCI. The trunk impairments observed following an SCI will be addressed first. Then their potential effects on manual wheelchair propulsion capacity will be discussed. Finally, future research challenges will be presented. Despite the importance of proper wheelchair/cushion ergonomics and body alignment/positioning, these two topics will not be covered in this brief overview.

Overview

Sensorimotor trunk impairments

The severity and symmetry of sensorimotor trunk impairments primarily relates to the level, degree of completeness, and location of the injury sustained to the spinal cord along with postinjury medical and surgical care and rehabilitative efforts. As a result of these impairments, individuals with an SCI will experience motor paresis (partial denervation) or paralysis (complete denervation) at and below the level of injury affecting their abdominal/back and lower extremity muscles in the majority of cases. These motor impairments often cause individuals with SCI to passively rotate their pelvis posteriorly and to accentuate their thoracolumbar kyphosis in order to maintain a sitting position.[4] Such postures are generally accompanied by an increase in scapular internal rotation and anterior tilting and humeral internal rotation.[5] These combined movements augment the risk of an impingement of the musculoskeletal structures in the subacromial space with the consequence of increasing the likelihood of developing secondary shoulder impairments.[5] A sensory loss at and below the level of injury is also expected following SCI. This sensory loss will generally perturb, to various extents, the perception of different sensory modalities such as light touch (tactile), pain, or temperature sensation. The presence of spared sensations at or below the level of SCI when part of the spinothalamic tract is preserved has been found to be a good prognostic indicator of motor recovery.[6] In clinical practice, the American Spinal Injury Association Impairment Scale (AIS) is typically used to classify sensorimotor impairments after SCI.[7] Hence, this scale neglects to assess the motor function of the trunk, even if manual muscle testing of key trunk muscle is feasible,[8] as it only incorporates the sensory assessment.

Decreased seated postural stability

Intricately related to sensorimotor trunk impairments, multidirectional seated postural stability/instability, commonly referred to as sitting balance, is also highly relevant for individuals with SCI, especially in the context of manual wheelchair propulsion.[9] Though "true'" physiological or neurological restoration is possible over time, individuals with an SCI have been found to develop compensatory sensorimotor strategies to reach an optimal level of seated postural stability.[10] From a motor perspective, these compensatory strategies rely in part on the increased use of the erector spinae and the solicitation of large nonpostural thoracohumeral muscles (e.g., latissimus dorsi, pectoralis major) to provide additional stability to the trunk segment, particularly in terms of appropriate muscle recruitment and timing (co-contraction).[11,12] These strategies correspond with the results of functional magnetic resonance imaging (fMRI) studies suggesting that motor activity can be displaced in the direction of the disconnected motor cortex region and expanded outside the typical somatotopic representation early after SCI.[13–16] It has also been proposed that the contraction of the diaphragm contributes to enhance postural stability during UL repetitive movements.[17–20] From a sensory perspective, afferent information via the visual and vestibular sensory organs also becomes vital to the multisensory integration mechanisms contributing to seated postural stability. To this effect, the cortical receptive fields with intact inputs have been found to have the possibility to expand into deprived territory in primary somatosensory cortex rapidly after an SCI (deafferentation).[15] Sublesional bone mineral density loss and UL muscle hypertrophy that develop following an SCI further increase the postural stability challenges, because the center of mass is shifted upwards within the trunk segment.[21,22] Additionally, it is important to take into consideration whether conservative approaches (e.g., thoracic brace) or surgical approaches (e.g., segmental spinal stabilization) have been used to fix the vertebrae shortly after the SCI.[23] Although intuitive to date, there is no clear evidence that supports a strong relationship between seated postural stability and manual wheelchair propulsion performance.

Reduced UL force-generating capability

An optimal level of force-generating capability of the UL is essential for manual wheelchair propulsion among individuals with an SCI. Peak shoulder strength values have been found to be strongly associated with the force imparted to the pushrim during manual wheelchair propulsion (e.g., resultant force, tangential force).[24] The reduced stability of the trunk, commonly referred to as *core stability*, resulting from the sensorimotor trunk impairments briefly discussed above, may lessen the capability of the ULs to generate propulsive forces.[25,26] No more force can be exerted on a distal segment (i.e., UL) than the amount that can be counteracted proximally (i.e., trunk) to ensure the stability of a system.[25,26] Following an SCI, some large thoracohumeral muscles become engaged in maintaining trunk stability.[10–12] This can potentially limit their contribution to the force production that contributes to the overall force generated at the ULs. Indeed, it has been confirmed that the neurological level of injury is a strong predictor of the weight-normalized isokinetic strength developed at the shoulder joint in the sagittal, frontal, and horizontal planes among individuals with SCI.[27] Individuals with low-level thoracic SCI have been found to be generally stronger at the UL than those with a high-level thoracic SCI in most planes.[27,28] In addition, the decreased force-generating capability of key scapulothoracic muscles, ensuring scapular stability (serratus anterior, rhomboids, upper trapezius, levator scapula), is known to modify the biomechanics of the scapulothoracic functional articulation in all individuals.[29,30] This can further limit UL force-generating capability, especially at the shoulder joint (scapulohumeral joint) in individuals with SCI.[29,30] Finally, the large muscles that originate from the trunk and directly insert into the humerus, referred to as *thoracohumeral muscles* (pectoralis major, latissimus dorsi), have also been found to be weaker among individuals with a high-level SCI in comparison to those with a low-level SCI.[27,28] Such a reduction in static strength among these muscles that functionally bypass the shoulder joint may reduce or change the direction of the resultant force applied to the humerus to counteract the superiorly and posteriorly directed excessive loading of the glenohumeral joint during manual wheelchair propulsion. All of these elements provide indirect evidence that sensory and motor trunk impairments may increase the likelihood of the development of secondary UL impairments reported among individuals with an SCI.[29,30]

Effects on manual wheelchair propulsion

Sensorimotor trunk impairments, along with their side effects on postural stability and UL force- generating capability, can have deleterious effects on manual wheelchair propulsion performance.

Altered propulsion technique

Dallmeijer et al[31] documented that individuals with tetraplegia (C5 to C7) positioned their hands further back on the pushrim at the start of the push phase in comparison to individuals with paraplegia (T5 to L4). They suggested that this difference may be due to the more pronounced trunk stability reduction observed among individuals with tetraplegia.[31] Schantz et al[32] have found that individuals with high-level SCI (tetraplegia; level of SCI = C5 to C7) relied on a shorter push phase relative to the pull phase and on a reduced forward trunk flexion at the start of the push phase in comparison to individuals with low-level SCI (paraplegia; level of SCI = T9 to T12) when propelling at self-selected normal and maximum speeds. These distinct movement strategies observed in the two groups may clarify why individuals with a high-level SCI (self-selected = 1.1 m/s;

maximum = 2.4 m/s) were found to propel at approximately 50% of the speed reached by individuals with low-level SCI (self-selected = 2.0 m/s; maximum = 4.3 m/s).[32] The difference in voluntary control of the trunk muscles between the two groups may explain these results.[32] Newsam et al[33,34] assessed spatiotemporal characteristics as well as UL and trunk kinematics during manual wheelchair propulsion in individuals with low paraplegia, high paraplegia, C7-8 tetraplegia, and C6 tetraplegia. They revealed that individuals with C6 tetraplegia had about twice the amount of trunk flexion excursion in the sagittal plane as that observed among the other participants, even though they were propelling about 50% slower (0.78 m/s) than their counterparts.[33,34] Though reduced sensory and motor trunk impairments have been found to affect manual wheelchair propulsion technique, no clear consensus on these effects exists in the literature.

Increased UL muscular demand

Harburn et al have pioneered the assessment of shoulder muscle activity (EMG) in an attempt to estimate relative muscular demand during manual wheelchair propulsion among a small sample of healthy individuals (n = 3) and individuals who recently sustained an SCI (n = 6).[35] They have reported that participants with high-level SCI (tetraplegia; level of SCI = C5 and C6) reached the highest EMG magnitudes, expressed as a percentage of the peak EMG value recorded during maximal voluntary contraction, during manual wheelchair propulsion (0.4 m/s) for all muscles studied.[35] Moreover, individuals with low-level SCI (paraplegia; level of SCI = T8 to T12) relied on a higher muscular demand than their healthy counterparts for all muscles studied during manual wheelchair propulsion at a similar speed.[35] In addition to the reduced elbow extensor muscle strength and hand grip abilities, the reduced capability to properly stabilize the trunk is also highlighted as a potential contributor to these differences.[35] More recently, Mulroy et al[36] have scrutinized the effects of SCI level on muscle activity during manual wheelchair propulsion in individuals with low paraplegia, high paraplegia, C7-8 tetraplegia, and C6 tetraplegia. They showed that individuals with tetraplegia were found to experience a prolonged activation of the pectoralis major muscle and needed similar electromyographic activity levels (%EMG max) as individuals with paraplegia to propel about 50% slower velocities.[36] Other research has also reported that individuals with sensorimotor trunk impairments primarily rely on the use of large nonpostural thoracohumeral muscles (e.g., latissimus dorsi, pectoralis major) to develop additional stability at the trunk segment,[11,12] which may also increase muscular demand and precipitate the development of trunk and UL muscle fatigue.

Elevated trunk muscle co-contraction around transition period

Yang et al have specifically focused on the assessment of trunk muscle activity during manual wheelchair propulsion at various speeds among 14 healthy individuals.[9] They established that trunk muscle recruitment increased as speed increased and that the back muscles were always more engaged than the abdominal muscles during manual wheelchair propulsion.[9] For the back muscles, the longissimus thoracis, the iliocostalis lumborum, and multifidus showed a high level of activity during the push phase across the three speeds investigated.[9] For the abdominal muscles, only the external oblique reached a high level of activity at a slow speed during the same period, whereas the rectus abdominus and internal oblique also became highly solicited as the speed was increased.[9] Overall, the multifidus displayed the highest muscle activity level during the push and recovery phase (median = 17.2% and 14.6% EMGmax, respectively).[9] They also revealed that the highest level of activation of the back and abdominal muscles occurred during the late recovery and early push phase of the propulsion cycle.[9] They suggest that such a high level of trunk muscle co-contraction around this transition period of the propulsion cycle may optimize trunk stability before generating propulsive forces (preparatory trunk response).[9] However, sensorimotor trunk impairments (reduced trunk stabilization capability) associated with an SCI, combined with the elevated dynamic reaction forces recorded when the hands contact the handrims during manual wheelchair propulsion, could explain the backward motion of the trunk previously reported when initiating the push phase among individuals with SCI.[37] Yang et al also highlighted that the forward trunk flexion with respect to an initial upright position increased with propulsion speed and reached a mean peak value of 20.8°.[9] It has been suggested that a forward trunk flexion, facilitated by the effect of gravity, increases the ability to efficiently shift power and apply forces to the pushrim.[38] Although the study completed by Yang et al provides valuable information,[9] there is a need to extend this work among experienced manual wheelchair users, especially among individuals who have sustained an SCI. One must also take the inertial properties of the axial skeleton (head and trunk segments) into consideration during testing.

Greater fatigability

Rodgers et al[39] studied changes observed during fatiguing wheelchair propulsion among individuals with paraplegia. They suggested that the increased forward trunk flexion observed with fatigue, accompanied by an increased peak handrim force, may have occurred to aid the application of force to the handrim.[39] More recently, Rogers et al[40] have stratified manual wheelchair users with SCI into two distinct groups based on the magnitude of trunk flexion observed during propulsion: a forward trunk flexion propulsion style and a nontrunk flexion style. The forward trunk flexion style was also characterized by greater shoulder flexion and elbow extension when compared to the nontrunk flexion style during propulsion.[40] As a state of fatigue developed, the peak forward trunk flexion was found to significantly progress among individuals relying on the trunk flexion style for manual wheelchair propulsion.[40] Such a compensatory strategy may facilitate the application of force to the handrim and the generation of the propulsive moments. In fact, this strategy is believed to compensate for peripheral muscle fatigue, rather than for aerobic economy, because the biceps and pectoralis major muscles were also found to reduce their contribution as fatigue developed.[40] Moreover, the contact time on the handrim was also slightly reduced among these individuals, which may translate into faster application of forces at the handrim (increased rate of rise of force). This may exacerbate the development of secondary impairment at the shoulder joint.[40] In contrast, among manual wheelchair users who used a nontrunk flexion style, only the contact time on the handrim was found to increase as fatigue developed.[40]

Higher joint forces at the shoulder joint

Kulig et al[41] investigated the effects of SCI level on shoulder kinetics during manual wheelchair propulsion. They confirmed that superiorly directed joint reaction force, which neglects to compute the active forces generated by the muscles in individuals with tetraplegia (C7 = 21.4 N; C6 = 9.3 N), was significantly higher than in persons with high paraplegia (7.3 N) after considering the wheelchair velocity as a co-variable.[41] This may increase susceptibility of subacromial structure compression in individuals with a tetraplegia, especially since the sternal pectoralis major muscle (humeral depressor) is generally weakened.[41]

Future Challenges

This section will highlight a few research opportunities that are crucial for a better understanding of the interactions between trunk impairments and manual wheelchair propulsion capacity among individuals with an SCI.

Refining trunk impairment measures

Better outcome measures are needed to characterize trunk impairments before the strength of the relationship between these impairments and manual wheelchair propulsion outcome measures (e.g., peak resultant shoulder force) can be confirmed. Refining the AIS motor assessment to include muscles of the trunk in the future may be relevant. However, motor assessment of the trunk using manual muscle testing remains problematic. Given the limits of manual muscle testing and of its grading system,[42] measuring the static or dynamic strength-generating capability of the trunk muscles using an instrumented dynamometer represents a valuable alternative to manual muscle testing to precisely quantify motor impairment. Moreover, monitoring muscle strength over time to better understand how neural factors and muscle volume may affect the strength-generating capability at the trunk also appears to be a point of interest. To this effect, quantitative ultrasound imaging of the back and abdominal muscles has the potential to measure cross-sectional area and property changes at the muscles (e.g., cross-sectional area and secondary pixel analysis of the region of interest using grey scale values). Ultrasound imaging could also allow one to assess muscle synergies in clinical practice. Much like the approach used for dynamic standing, the assessment of "anticipatory" multidirectional dynamic seated postural stability using instrumented surfaces, which would allow one to extract quantitative measures of dynamic balance capability (e.g., center of pressure excursion), may also serve as a surrogate measure to evaluate sensorimotor trunk impairment. The distance traveled by the center of pressure (COP), the surface area fitting most of the COP data points, and the distance between the COP and center of mass (COM) during a specific period of time could be used to quantify quasi-static postural stability in sitting. As for dynamic postural stability, the comprehensive biomechanical approaches recently proposed by Popovic et al[43] and Duclos et al[44] now allow objective measurement. Popovic et al[43] propose the margin of stability to quantify dynamic postural stability during dynamic tasks. This margin of stability reflects the smallest distance between the position of the COP and the predefined limits of stability that reflects the largest possible multidirectional excursion range of the COP within the base of support. More recently, Duclos et al[44] have suggested a biomechanical model to assess postural stability that documents both the equilibrium associated with the body position over the base of support (*destabilizing forces*) and the energy required for the subject to keep his/her COM inside the base of support (*stabilizing forces*) in mediolateral and anteroposterior directions. In both of these approaches, a loss of balance is technically anticipated in the event that the COP would travel outside the boundaries of the base of support (BOS). Alternatively, a portable and automated postural perturbation system,[45] recently developed, will allow one to compute "reactive" multidirectional dynamic seated postural stability. As there is a need for additional reliable and valid measures of sensorimotor trunk impairment among individuals with SCI, these new approaches should be explored.

Advanced electrodiagnostic and neuroimaging techniques also offer exciting fundamental research opportunities, because the specific changes in sensory and motor processing of trunk-related information following an SCI still require clarification.[46] For example, knowing whether the spinal networks of neurons (commonly referred to as the central pattern generator in gait studies) can possibly control basic trunk motor responses despite the absence of descending or afferent inputs also appears to be a point of interest. Moreover, an insight into the role of the sensory afferent information in the adaptation and modulation of trunk motor response during the performance of functional tasks would complement research efforts focusing on motor dimension. In fact, it is highly probable that dynamic interaction exists between these two distinct dimensions in order to generate coherent trunk movements in response to internal (self-induced) or external perturbations.

Optimizing biomechanical assessments

To date, biomechanical assessment of manual wheelchair propulsion has been primarily performed on instrumented wheelchair ergometers or on treadmills (artificial environments). Though these methodological approaches have generated a highly relevant body of knowledge on manual wheelchair propulsion, one should consider that the cyclical acceleration and deceleration of the axial skeleton (head, trunk, and UL segments) and the wheelchair during manual propulsion in an artificial environment may be reduced in comparison to propulsion in a natural environment. Because the axial skeleton represents a large proportion of the body weight and the capability of the active and passive properties of the trunk to counteract the cyclical momentum is often drastically reduced among individuals with an SCI, some of the evidence currently available possibly underestimates the side effects of these accelerations and decelerations. It would be highly relevant to compare the biomechanical requirements of manual wheelchair propulsion across various experimental set-ups (i.e., ergometers vs. treadmill vs. natural surface) for a select group of individuals to rapidly answer this question to ensure that the design of future studies is optimized. At a minimum, additional efforts should be made to model the trunk using three separate segments: the thorax, abdomen, and pelvis. Modeling the trunk as a unique rigid segment, as has frequently been done during biomechanical assessment of manual wheelchair propulsion, prevents a full understanding of the interactions between the trunk and manual wheelchair propulsion outcomes among individuals with an SCI, particularly for those individuals with an incomplete SCI who have the capability to use these segments differentially. The development of an instrumented wheelchair frame, on which instrumented wheels (e.g., SmartWheels®) could be attached, would also facilitate the assessment of the multidirectional seated postural stability demand during manual wheelchair propulsion using biomechanical models recently developed.[44] This would allow for better understanding of the biomechanical coupling/damping between the wheelchair and the user (e.g., individuals with an SCI).

Enhancing trunk stability

The development of therapeutic interventions aimed at optimizing trunk stability among individuals with an SCI has received little attention over the past few years. Preliminary research activities have targeted the use of functional electrical stimulation (FES) to generate the sequence of muscle activation and force generation needed to stabilize the trunk and improve sitting postural stability.[47,48] Despite the fact that the use of FES represents a promising alternative, it remains essential to gain additional insights into the sensorimotor strategies governing trunk stability among individuals with SCI before designing more sophisticated transcutaneous or intramuscular FES trunk neuroprosthesis prototypes. Such neuroprostheses would ideally stimulate abdominal and trunk muscles as well as use a combination of open-loop and closed-loop controllers to accommodate, as an example, manual wheelchair propulsion requirements. The open-loop controller would provide tonic stimulation of trunk musculature at levels below those likely to cause fatigue but sufficient to stabilize the upright posture of the trunk. The closed-loop controller would provide phasic, task-specific, feedback-driven stimulation of the trunk musculature in response to voluntary trunk and/or arm movement and perturbations. Features allowing the continuous recording COP displacement, velocity, and acceleration underneath the cushion with an instrumented mat or to monitor the wheelchair surrounding physical environment with captors attached to it could be included as a potential controller of a trunk neuroprosthesis during propulsion. Technically, these approaches are feasible; however more data on sensorimotor trunk control would improve their development. The portable and automated postural perturbation system[45] developed to assess trunk impairment (see section, Refining trunk impairment measures) can also be useful in clinical practice to train trunk stability. This device could allow therapists to harmonize the training protocol along with some basic motor learning principles used in neurorehabilitation, especially the task-specific and massed-practice aspects. Future research is required to ascertain the potential beneficial effects of specific therapy programs targeting trunk stability coupled with manual wheelchair propulsion using increased understanding of biomechanics and assessment of efficiency. Wheelchair propulsion is a relatively new field of study for restorative motor control. As wheelchair propulsion is a new skill, learned after SCI, there are additional motor learning challenges coupled with suboptimal motor control in the subacute phase. This area of research requires a carefully thought out multidisciplinary research program to advance our understanding of an activity that a large proportion of individuals with an SCI perform routinely in their everyday lives.

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