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ARTICLE

The robotic Trunk-Support-Trainer (TruST) to measure and increase postural workspace during sitting in people with spinal cord injury

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Abstract

Study design Cross-sectional study.
Objectives To measure and expand the sitting workspace of participants with spinal cord injury (SCI) with the Trunk-Support-Trainer (TruST).
Setting Columbia University.
Methods TruST is a motorized-cable belt placed around the torso. Participants performed maximal trunk excursions along eight directions, radiating in a star-shape, to define their seated postural limits and workspace area (cm^2). TruST was configured to apply *"assist-as-needed"* forces when the trunk moved beyond these postural limits. Kinematics were collected to examine trunk control. The clinical features of the sample ($n = 5$) were documented by neurological injury, dynamometry, the American Spinal Injury Association Impairment Scale, and Spinal Cord Independence Measure-III.
Results Statistical significance was examined with paired *t*-tests. TruST successfully recreated the postural limits of participants and expanded their active sitting workspace (Mean: $123.3 \pm$ SE: $42.8\ cm^2$, $p < 0.05$). Furthermore, participants improved their trunk excursions to posterior (Mean: $5.1 \pm$ SE: 0.8 cm, $p < 0.01$), right (Mean: $3.1 \pm$ SE: 1.1 cm, $p < 0.05$), and left (Mean: $5.0 \pm$ SE: 1.7 cm, $p = 0.05$) directions with TruST-force field.
Conclusions TruST can accurately define and expand the active seated workspace of people with SCI during volitional trunk movements. The capacity of TruST to deliver continuous force-feedback at the user's postural limits opens new frontiers to implement motor learning-based paradigms to retrain functional sitting in people with SCI.

Introduction

Spinal cord injury (SCI) is a multi-systemic condition characterized by muscle paralysis and deficits in the cardiopulmonary, integumentary, gastrointestinal, genitourinary, and sensory systems. This conglomerate of problems in people with SCI alters mobility and limits self-care and participation in society [1]. SCI incidence just in the US is greater than in most regions of the world with an average age onset of 37.1 years. An increase in the SCI incidence is expected in people 65 years or older, from 13.0% in 2010 to 16.1% by 2020. The survival rate for 60-year-olds with SCI is predicted to be 59.2% in people with C1-4 injuries, 67.9% in people with C5-8 lesions and 78.0% in people with paraplegia [2]. Altogether, these epidemiological data indicate that there is a high survival rate of people with SCI who need to function in the community despite their impaired sitting control. Thus, new objective measurements and evidence-based motor treatments are needed for people with SCI to address their trunk control deficits and workspace limitations during independent sitting.

Sitting balance is impaired in people with SCI due to abnormal neuromuscular control of postural muscles and disrupted processing of sensory inputs [3, 4]. In some cases, the synergistic control of key torso muscles is absent; and as a result, people with SCI compensate with non-postural muscles such as latissimus dorsi and trapezius during sitting [3]. The residual sitting ability in these individuals may be clinically examined with tests such as the Sitting Balance

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Measure, the Trunk Control Test, or the Set of Assessment Tools for Measuring Unsupported Sitting [5, 6]. Another way to characterize sitting balance is via kinematic-related instrumentation. For instance, force plates have been widely applied in SCI to estimate postural stability limits through center of pressure measures (COP) [7, 8]. Even though COP is widely used as a measure of sitting balance control in SCI, it is not a direct evaluation of volitional trunk control; which should be prioritized in individuals with SCI [9]. From a functional standpoint, addressing the limitations in sitting workspace of individuals with SCI based on direction-specific trunk movements can bring a new perspective for the dual purposes of evaluation and training seated postural control in this population.

In the present work, we introduce the robotic Trunk-Support-Trainer (TruST). TruST is a motorized-cable driven belt placed on the user's torso to determine the postural control limits and sitting workspace area in people with SCI. It also delivers forces—TruST-force field—on the torso during upper body movements when users move the trunk beyond their postural stability limits in sitting. Research has shown that force fields modulate and improve motor performance in individuals with and without neuromotor impairments [10–12].

In the present study, we use TruST to define the seated postural control limits and sitting workspace of participants diagnosed with SCI at thoracic-lumbar level. Moreover, we investigate the applicability of TruST-force field to expand their active sitting workspace beyond the postural control limits of each participant during sitting.

Materials and methods

Participants

The demographic and clinical information of our sample (Males = 2, Females = 3, Average age: 60 ± SE: 6 years) is included in Table 1. A group of seven participants with SCI were recruited and five complied with the inclusion/exclusion criteria. As inclusion criteria, all participants (1) were diagnosed with SCI, (2) had a traumatic etiology, and (3) had chronic SCI (>1 year). Participants were excluded if they (1) underwent surgery within 6mos prior to the study, and (2) were unable to sit independently (i.e. sitting unsupported without external assistance during at least 30s on a bench with ankles, knees, and hips flexed 90°).

Diverse SCI assessments and tests were used for clinical characterization of our group. The American Spinal Injury Association Impairment Scale (AIS) was used to define the severity of the SCI: motor complete (AIS A-B) or incomplete (AIS C-D) [13]. This AIS score was obtained through medical records. The Spinal Cord Independence Measure-III (SCIM-III) was used to score the level of functional independence during relevant daily tasks [14]. Table 2 shows the results of our digital dynamometry to measure the force-generation

Table 1 Demographic and clinical characteristics of participants.

Participant code	Age (yrs)	Gender	Neurological SCI level	Time since SCI (yrs)	AIS (A-D)	SCIM-III
01	59	Female	T_9	2.6	C	60
02	73	Female	T_{10}	4.5	C	68
03	74	Male	T_4	5.2	B	55
04	41	Male	T_8	3.8	C	67
05	54	Female	T_{11}	2.6	C	52

Yrs years, *SCI* spinal cord Injury, *AIS* The American Spinal Injury Association Impairment Scale, *SCIM-III* Spinal Cord Independent Measure III, *SE* standard error

Table 2 Force measurement of direction-specific torso muscle groups.

Muscle dynamometry (kg) ± SE						
Participant	Flexion	Extension	Right lateral flexion	Left lateral flexion	Right rotation	Left rotation
01	4 ± 1.55	4 ± 1.75	5 ± 1.10	4 ± 0.25	4 ± 0.15	3 ± 0.05
02	13 ± 0.50	10 ± 1.20	9 ± 0.25	7 ± 0.00	7 ± 0.15	6 ± 0.15
03	8 ± 0.60	10 ± 0.61	5 ± 0.10	7 ± 0.25	2 ± 0.10	3 ± 0.20
04	13 ± 0.70	7 ± 0.35	5 ± 0.55	7 ± 1.25	5 ± 0.80	6 ± 0.80
05	2 ± 0.15	6 ± 0.60	6 ± 0.05	6 ± 0.10	5 ± 0.15	5 ± 0.07
Group average ± SE	8.0 (± 3.5)	7.4 (± 4.6)	6.0 (± 4.6)	6.2 (± 5.4)	4.6 (± 3.4)	4.6 (± 3.7)

kg kilograms, *SE* standard error

ability of each participant: strength (kg). We used a *"make test approach"* with a hand-held dynamometer (Lafayette Manual Muscle Tester), in which participants exerted maximal isometric muscle contraction while the dynamometer was held stationary by the examiner. The goal was to test the overall muscle activity of specific muscle groups of the torso: flexion (i.e. rectus abdominis), extension (i.e. bilateral erector spinae), lateral flexion (i.e. quadratus lumborum and ipsilateral erector spinae), and rotations (i.e. abdominal external and internal obliques). The position of the hand-held dynamometer was on the chest (sternum, below the sternal notch) for trunk flexion, on lateral shoulder (lateral deltoid region) for trunk lateral flexion, inter-scapular region (between the superior scapulae angles) for trunk extension, and on anterior shoulder (anterior deltoid region) for trunk rotations. Participants sat with arms crossed over the chest and were instructed to perform maximum isometric contractions during 3 s in each trunk direction. An average of three trials was collected.

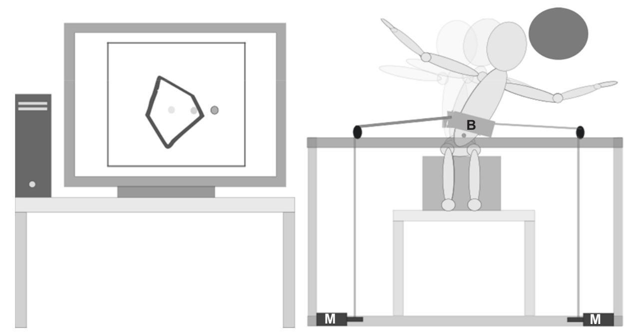

Fig. 1 To the right, the robotic trunk-support-trainer (TruST) device with cables attached to the belt (B) and routed through the pulleys down to the motors (M) on the frame. Participants were instructed to perform the postural star-sitting test. During the test, the evaluator uses a large ball (gray circle) to make the test goal-oriented. The ball is displaced along each of the 8 directions to instruct the participant on how to perform the trunk movements. The monitor on the left displays in real-time the participant's trunk location (TruST-belt) with respect to the postural stability limits (asymmetrical black boundaries). When the participant moves the trunk outside the sitting workspace (solid gray dot), TruST delivers force-feedback to assist the participant in performing active trunk movements beyond the pre-defined postural limits and recover posture during sitting.

Study design

This research was carried in the RObotics and Rehabilitation (ROAR) laboratory, Mechanical Engineering department at Columbia University. All study protocols were approved by the IRB at Columbia University. Participants were recruited from New Jersey and New York areas.

This is a confirmatory quasi-experimental cross-sectional study to investigate the applicability of TruST to measure the maximal volitional trunk control of people with SCI and to expand their sitting workspace. We tested if the use of the TruST-force field tailored to the seated postural stability limits of each participant can significantly increase their active trunk excursion across planes of motion and expand their sitting workspace.

Experimental setup and procedure

The robotic Trunk-Support-Trainer (TruST)

The robotic TruST (Fig. 1) is a motorized-cable driven device that can apply a force in any direction on the user. There are four cables that are connected to a belt placed at the participant's torso. In previous studies with able-bodied participants [11, 15], we configured TruST to apply a force field that corresponded to a point of sitting stability failure —maximum trunk displacement during a reaching task at which the participant loses sitting balance. In this setting, the force field boundary was a uniform circle surrounding the person's torso, and the radius of this circular boundary equaled the maximal trunk excursion. Therefore, this force field assumed symmetric seated postural control limits across participants. In SCI, however, there is a need for a force field that is both individualized and designed around their irregular and asymmetric seated postural control limits. For this purpose, the TruST-force field was designed based on postural limits obtained with a customized sitting test, the postural star-sitting test.

The postural star-sitting test and TruST-force field configuration

The TruST-belt was placed on the lower ribs (thoracic region: T9-12) of participants. Performance of trunk control was examined with the postural star-sitting test, a customized trunk control assessment with TruST that measures the area of independent sitting control and workspace of participants with SCI. It is based on the Star Excursion Balance Test to measure standing balance, in which a person displaces the foot along eight directions that radiate like the shape of a star during one-leg stance [16]. Similarly, in the postural star-sitting test, participants are sitting on a bench and are instructed to perform maximal active trunk excursions. For this purpose, the evaluator uses a large ball that is shown and displaced along the direction the participant is instructed to displace the trunk—the person tries to touch it while performing each one of the 8 direction-specific trunk movements. Once the participant achieves the maximum trunk excursion, the participant needs to recover neutral sitting position without hand assistance. Three trunk movements per direction were collected in each experimental condition—a total of six movements per direction with and without TruST-force field. The maximal trunk excursion was used for further analysis.

The participant's controllable siting workspace was measured during the postural star-sitting test with the help of an infrared camera-based system and the TruST-belt (Fig. 1). The participant's sitting control limits correspond to the boundaries of the TruST-force field. These boundaries are defined by TruST and correspond with the participant's seated postural control deficits. When the trunk is inside the postural control boundaries, TruST is inactive and does not provide postural assistive forces. However, as the participant approaches the sitting boundaries—the trunk moves beyond 75% of the maximum trunk excursion from the center—TruST applies a small assistive-force equivalent to 2% of the participant's body weight. This assistive force increases exponentially as the trunk moves closer and beyond the predefined postural control limits to equal a constant force of 5% body weight. Once the force field was configured to the participant's postural control limits, the postural-star-sitting test was performed again with TruST delivering force-based postural feedback (*"assist-as-needed force"*) at the postural control limits. As a result, the participant could perform maximal active trunk movements beyond these predefined postural limits and recover sitting position.

Data reduction

MATLAB (R2017b, Mathworks, 2017) was used for data processing off-line. To examine postural trunk control, we applied kinematics (100 Hz) and a motion capture system (VICON, Oxford Metrics). Kinematic data from the TruST-belt was smoothed with a zero time-lag 4th order Butterworth filter and 4Hz-cutoff. An in-built MATLAB function (*boundary (x, y, z)*) was used to compute the area of the active sitting workspace with and without TruST-force field. This function returns a set of points (the postural boundary) that envelopes the maximum x and y points and the area encompassed by these x and y points. These data points were obtained via the TruST-belt and corresponded to the maximum trunk excursion point of each direction during the postural star-sitting test.

We measured maximal trunk excursions across sagittal and frontal planes during flexion, extension, and right and left lateral flexions of the trunk with and without TruST-force field. Additionally, we examine the motor capability of the participant to perform straight trunk excursions without deviation from the sitting origin (i.e. trunk paths that followed a linear vector during maximal anterior, posterior, right, and left directions). In a 2D scenario, this was computed from the vector generated by the trunk movements along the anterior-posterior directions with respect to the horizontal (i.e. a lateral vector that creates a 90° angle to this anterior-posterior trunk path) and trunk movements along the right-left directions with respect to the vertical (i.e. an upward/downward vector that creates a 90° angle to this lateral trunk path).

Statistical analysis

The statistical package SPSS (IBM, version 25) was used. Data normality was examined with the *Shapiro–Wilk* test and visually with normality Q–Q plots. The area of stable sitting control and trunk excursion data followed a Gaussian distribution. Thus, a paired-*t-test* was used to examine statistical significance. An alpha rate <0.05 was set as significance level and a two tailed-*p* value was considered. *Cohen's d* was used to compute the magnitude of the mean differences.

Results

Postural star-sitting test with robotic TruST: area of stable sitting control

The postural stability limits during sitting for each participant are depicted in Fig. 2a. As hypothesized, the robotic TruST significantly expanded the active sitting workspace (Fig. 2b). The use of the TruST-force field, tailored to the participant's seated postural control limits, significantly increased the sitting workspace area (Mean difference: $123.3 \pm$ SE: $42.8\ \text{cm}^2$) with a moderate effect size ($t(4) = 2.88$, $p = 0.04$, *Cohen's d*: 0.45).

Maximal trunk excursions and unidirectional trunk control with TruST

With the use of TruST, participants showed greater ability to increase their active seated trunk excursions (Fig. 2c). The application of TruST-force field had a large effect size to increase the maximal trunk excursion towards right (Mean: $3.1 \pm$ SE: 1.1 cm, $t(4) = 2.92$, $p = 0.04$, *Cohen's d*: 0.90), left (Mean: $5.0 \pm$ SE: 1.7 cm, $t(4) = 2.75$, $p = 0.05$, *Cohen's d*: 1.5), and posterior (Mean: $5.1 \pm$ SE: 0.8 cm, $t(4) = 2.92$, $p < 0.01$, *Cohen's d*: 0.72) directions. This significant increase in active trunk excursion with TruST-force field was not observed in the anterior direction (Mean: $0.9 \pm$ SE: 2.0 cm, $t(4) = 0.46$, $p = 0.67$).

Participants did not demonstrate improvements in the ability to perform unidirectional trunk movements with TruST—defined as the ability of the participant to move the trunk following a rectilinear path across the sagittal and frontal planes (Fig. 2c). These trunk paths generated similar angles with and without TruST-force field across all directions: anterior (mean difference: 3°, $p > 0.05$), right (mean

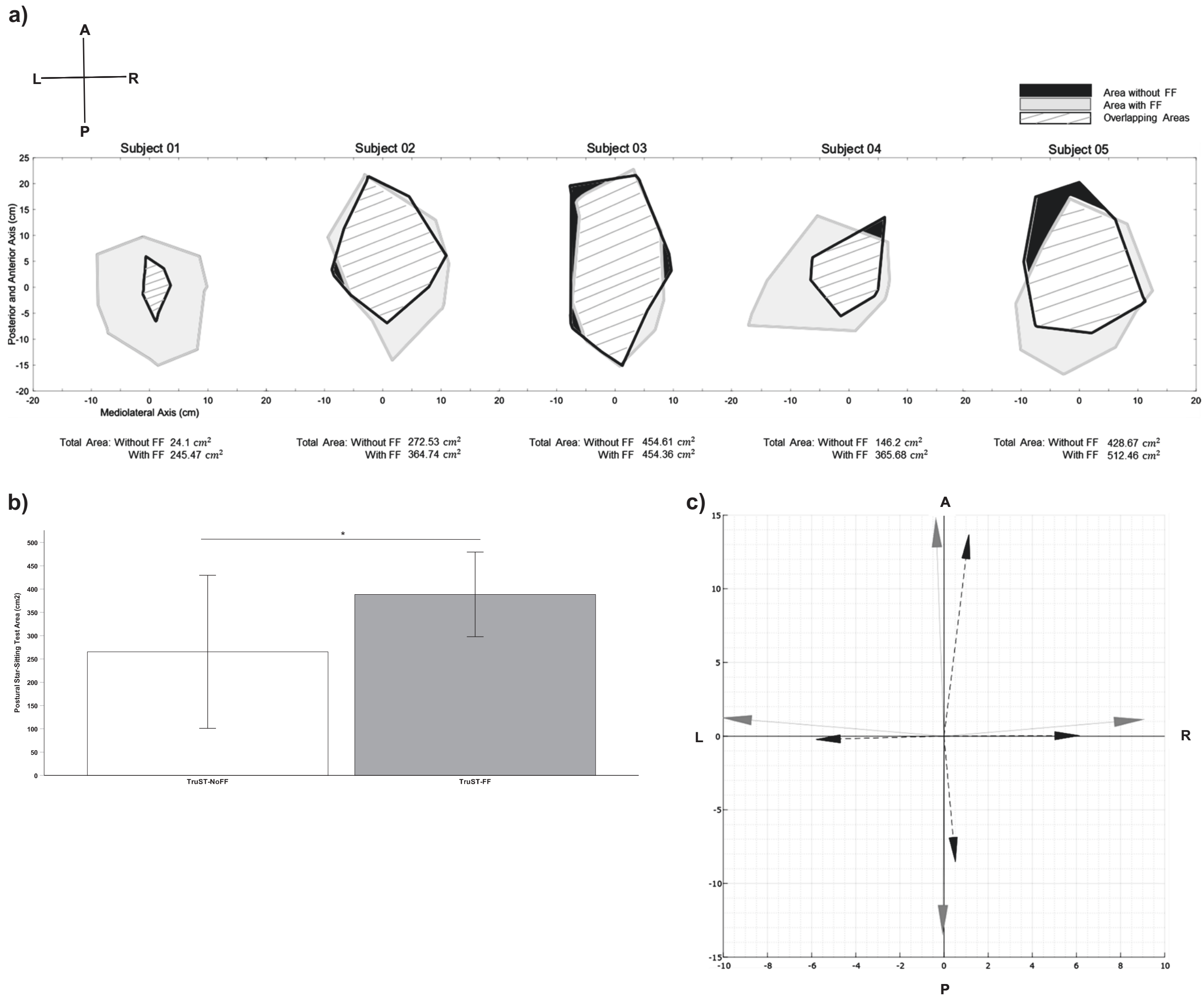

Fig. 2 Area of active seated postural control in sitting measured with the postural star-sitting test via the Trunk-Support-Trainer (TruST). The graphs (**a**) depict the area of active seated workspace for each participant with and without TruST-force field (gray and black, respectively). The diagram on the upper left corner indicates the direction of the trunk movements. A = Anterior, R = Right, P = Posterior, L = Left. The bar graph (**b**) displays the averaged area of active seated workspace (cm^2) during the postural star-sitting test (±SE). There was a significant increase in the workspace when participants received TruST-force field (TruST-FF) compared to inactive TruST-force field (TruST-noFF). $^*p < 0.05$, *SE* standard error. The vectors depicted in (**c**) represent the group average (cm) of maximum trunk excursions in the sagittal and frontal planes, with and without TruST-force field (solid gray and dotted black lines, respectively). Participants performed greater trunk excursions during right, left, and posterior directions with TruST-force field. As represented in the figure, trunk movements followed similar unidirectional directions—displacement vectors from origin—with and without TruST-force field. A = Anterior, R = Right, P = Posterior, L = Left.

difference: 4°, $p > 0.05$), posterior (mean difference: 1.5°, $p > 0.05$), and left (mean difference: 4°, $p > 0.05$).

Discussion

In this study, we report for the first time the use of the robotic Trunk-Support-Trainer (TruST) to assess and enhance the active sitting workspace of people with thoracic-lumbar SCI. In summary, our outcomes demonstrate that TruST is a valuable tool to measure objectively seated trunk control and to define the sitting workspace of individuals with SCI. Furthermore, TruST can substantially expand the sitting workspace area and increase the active seated trunk excursions of people with SCI.

A survey study in SCI investigated their level of community participation based on transportation, accessibility and physical activity. The authors concluded that people with SCI are happy, involved in society, and are physically active [17]. However, most of patients with SCI, who are wheelchair users, live with impaired trunk control that limits their full participation in diverse community activities

[3, 4, 8]. Therefore, rehab sciences in SCI should focus on developing new objective measurements that involve active trunk movements and trainings that maximize seated postural control in this population. This has been particularly true in the last years in which new restorative-rehab approaches are emerging to substitute compensatory-rehab strategies [18].

Optimal sitting control in people with SCI is an arduous task to achieve due to its multi-systemic nature. Testing techniques, such as magnetic resonance imaging, allow clinicians to determine the anatomical level of injury [19], electrodiagnosis (i.e. nerve conduction and electromyographic studies) are used to examine the sensorimotor status after the SCI [20], and transcranial magnetic stimulation can be used to define the integrity of the corticospinal system (brain-spinal cord connectivity) [21]. In addition, new clinical assessments, such as the Segmental Assessment of Trunk Control (SATCo), are being validated in SCI to evaluate trunk control deficits in the static, active and reactive postural dimensions with the use of segmental trunk support [22]. However, this population has severe difficulties shifting their body weight and completing daily tasks such as dressing or undressing their upper body while sitting [8], in which a multidirectional control of the trunk is critical. To the best of our knowledge, there are no measurements to define the sitting workspace of people with SCI based on their active trunk control. Force plates are often used to measure sitting balance. Research applying COP and COP-related variables has shown that people with paraplegia after SCI demonstrate reduced stability limits during trunk movements in sitting [23]. This finding is in line with our trunk control measurement obtained with the postural star-sitting test via TruST, in which we can compute the sitting workspace and maximal trunk excursions of people with SCI during sitting. While sitting on force plates, people with SCI are instructed to move their body as far as possible to test balance. During this testing, trunk control is a key element. However, in contrast to force plates, TruST offers a direct measurement of volitional trunk control in sitting whereas COP-related variables are an indirect approximation of upper body control in SCI.

The outcomes of the present study are compelling and confirm that the robotic TruST can be a promising rehab tool in SCI. With the application of TruST-force field, which is tailored to the person's postural stability limits in sitting during direction-specific trunk movements, TruST can not only prevent falling but also maximize trunk movements beyond the postural control limits. In this vein, we did a *proof-of-concept* study with TruST in able-bodied participants. We showed that the use of postural force-feedback at the point of sitting stability failure, the participants significantly increased their excursion and rotation of the lumbar region while practicing a fine-motor task during unbalanced sitting conditions, and after a single 30 min session [11].

Researchers have shown that intensive goal-oriented practice of seated postural and reaching tasks may have a positive functional impact in people with SCI [24]. TruST can potentially be a powerful robotic tool to maximize the outcomes of motor learning-based programs by allowing clinicians to include greater flexibility and variability of motor tasks beyond the seated postural stability limits of the person. In addition, the system allows clinicans to modulate the training parameters (i.e. number of repetitions and intensity) and provide functional muscle strengthening of the torso. In this sense, TruST may modulate sensory-dependent signals associated with volitional trunk and upper limb goal-oriented movements practiced beyond postural control limits and during sitting recovery. However, the future applicability of robotic-mediated seated postural interventions with TruST in SCI should contemplate the particularities in trunk control performance of this population.

A study investigating sitting control in people with thoracic SCI in the stability limit test showed that patients displayed reduced sitting balance in the posterior direction compared to anterior and lateral directions [23]. In line with these results, four out of five participants increased their sitting workspace in the posterior region with TruST-force field. In anterior trunk excursions with TruST-force field however, the results were more variable: two participants improved (01 and 04), two participants showed overlapping sitting control boundaries compared to inactive TruST-force field (02 and 03), and one (05) was not able to overcome the assistive forces generated by TruST. In this regard, participant 05 was only capable of generating 2 kg of muscle force during isometric trunk flexion, as indicated by our trunk dynamometry in sitting position. Furthermore, people with SCI generally show asymmetrical impaired neuromuscular coordination and reduced muscle-force generation of trunk muscles [3, 23]. In our sample for instance, participant 03 (Neurological SCI level: T_4 and AIS: B) improved the posterior-right sitting workspace with the application of TruST-force field. However, this participant demonstrated difficulties in overcoming the assistive forces on the left side. Seelen et al. [3] already showed that some people with SCI recruit supplementary muscles (latissimus dorsi, trapezius pars ascendens, pectoralis major, serratus anterior and the thoracic segment of the erector spinae muscle group) to control sitting balance. Therefore, the simultaneous application of surface electromyography while performing direction-specific trunk movements during the postural star-sitting test could assist in determining if the activity of primary muscles such as abdominals and the lumbo-thoracic region of the erector spinae group is insufficient to move the trunk beyond the TruST-force field (i.e. sitting control boundaries).

As limitations, our sample size was small, with unbalanced male:female ratio (2:3), and characterized by heterogeneous demographics and clinical features. Also, we should note that some participants (03, 04 and 05) showed motor deficits to overcome the TruST-force field at the maximum trunk excursion point of some specific directions. In our future studies, we will consider this aspect while implementing long-term task-oriented postural interventions with TruST in individuals with SCI.

Conclusions

TruST is a robotic platform that measures the postural stability limits and the sitting workspace of people with SCI who are wheelchair users. Furthermore, TruST can deliver postural force-feedback on the trunk via force field technology that is tailored to the person's postural control limits. The TruST-force field is progressively implemented within and beyond the sitting control boundaries to assist in the active control of the trunk and expand the sitting workspace of people with SCI. Thus, TruST can be a promising rehab tool to implement efficient goal-oriented seated training interventions.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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