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Effect of Transcutaneous Cervical Spinal Cord Stimulation on Trunk Function in Subjects with Cervical Spinal Cord Injury

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Abstract

This study aimed to examine how cervical transcutaneous spinal cord stimulation (tSCS) influences trunk muscle activity and movement patterns while individuals with SCI perform a reaching task. Trunk stability is crucial for daily activities, and spinal cord injury (SCI) often impairs this stability. By evaluating muscle activity and movement patterns during a specific task, the researchers seek to understand whether tSCS has an impact on enhancing trunk muscle control and movement.

Methods: Nineteen subjects with cervical or high thoracic SCI participated in the randomized mix of parallel group and crossover clinical trial, consisting of an intervention group (n=13; tSCS) and control group (n=10), and four of them participated in both groups.

We used the American Spinal Injury Association Impairment Scale (AIS) scale to evaluate clinical motor and sensory deficits, and the clinical trunk impairment control test (static and dynamic equilibrium and static equilibrium with upper limbs). In addition, data from electromyography (EMG) and smartphone accelerometers were recorded during a reaching task that required trunk tilting. Outcome measures included response time (RespT) until pressing a target button, EMG onset latencies and amplitudes, and trunk tilt, lateral deviation, and other movement features from accelerometry. Patients were evaluated before and after eight sessions of tSCS applied at C3-4 and C6-7 at 30 Hz during upper extremity rehabilitation.

Result: The results showed in tSCS group significant improvement in total motor strength, while trunk control evaluated by clinical scales did not show significant changes in any group. Additionally, there were no significant changes in any EMG or smartphone variables, except response time (RespT), which was faster in the controls after last session. Changes as absolute or percentage values were similar in both groups in all parameters.

Significance: tSCS applied at two cervical segments showed significant improvement in total motor score but not in trunk control in SCI individuals. This is a crucial finding, suggesting that while tSCS at cervical segments positively affected certain aspects of motor function, this did not translate into improvements in trunk stability.

Keywords: Transcutaneous spinal cord stimulation; cervical spinal cord injury; trunk stability; EMG; Smartphone accelerometer

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Introduction

Spinal cord injury (SCI) is a catastrophic event that culminates in a deficiency of sensorimotor and/or autonomic functions. Trunk instability is a major concern for people with SCI [13]. Particularly, lesions in the cervical to the thoracic region can paralyze trunk muscles, leading to a partial or complete loss of trunk stability [5]. The trunk plays a critical role in maintaining balance and stability during activities of daily living (ADLs). Therefore such impairments adversely affect an individual's ability to carry out everyday activities including bed movements, unsupported sitting, and self-care duties [16] and their capacity to perform transfers, and reach for objects [20].

Actually, postural rehabilitation to improve trunk function has been identified as one of the highest priorities for optimizing the recovery of SCI individuals. While transcutaneous spinal cord stimulation (tSCS) shows promise as a treatment for trunk stability in subjects with cervical spinal cord injuries, it is important to note that this technique is still in the early stages of development [19,17,8]. When tSCS was applied at Th11-12 and/or L1-L2, there was an improvement in trunk and sitting functions with increased static and dynamic balance [19]. The application of tSCS also increased trunk extension, enabled upright sitting posture and improved ability to perform transfers [8], and increased unilateral reaching [17].

Previous reports emphasize the potential of tSCS at cervical level to affect not only the adjacent spinal cord, but also provide opportunities for remote neuromodulation [1,2,10,11]. It was previously reported that tSCS applied to cervical segments could increase cortical excitability, affecting the responsiveness of the cerebral cortex. This effect has been observed both in healthy individuals [10,11] and in individuals with spinal cord injuries [2]. In addition, modulation of the H-reflex in the lower limb has been reported when tSCS is applied to the cervical segments [1]. The H-reflex is a measure of spinal cord excitability, and its modulation can affect muscle and nerve responses in the lower extremities. This highlights the versatility of tSCS as a neuromodulation technique with applications, offering opportunities for remote therapeutic interventions.

Here, our hypothesis was that tSCS applied at the cervical level could positively impact trunk-related parameters in individuals with cervical or high thoracic SCI indicating a comprehensive understanding of the potential effects of neuromodulation beyond the targeted area. Therefore, the application of tSCS during upper extremity therapy with a robotic exoskeleton in SCI individuals with cervical or high thoracic SCI [6], our focus was to explore a potential improvements in trunk stability and the impact on trunk muscle activity, movement patterns, and trunk response to disrupting effect of startling acoustic stimuli (SAS).

Materials and Methods

Participants

The inclusion criteria were: i) clinical diagnosis of cervical or high thoracic SCI, either traumatic or non-traumatic in origin; ii) including complete and incomplete injuries; iii) classified as AIS A, B, C, or D according to the American Spinal Injury Association Impairment Scale (AIS) [9].

Exclusion criteria were: (i) unstable medical condition (cancer, acute infections, or other health issues that could potentially impact their participation); (ii) dependent on mechanical ventilation; (iii) severe spasticity (≥ 3 score on the Modified Ashworth scale – MAS); (iv) peripheral nerve injury; (v) intolerance of tSCS; peacemakers electronic implants, episodes of epilepsy; (vi) participating in another investigation.

The protocol was approved by the Ethics Committee of the Institute Guttmann and was carried out in accordance with the standards of the Declaration of Helsinki. All subjects were informed of all experimental procedures, after which each subject completed a signed informed consent. The study was conducted between December 2019 and January 2023.

Experimental Design

The experimental design at the beginning was a randomized, controlled clinical trial, which consisted of two groups: (i) intervention group: tSCS which realized during robotic exoskeleton for upper extremity and (ii) control group: the subjects realized their routine rehabilitation program including robotic exoskeleton for upper extremity. We used a computer-generated list as randomization strategy. Assignment of the subjects to the treatment interventions was random. If the subjects wanted to participate in tSCS following control condition, we gave them this possibility. Finally we realizaed a randomized mix of parallel group and crossover clinical trial. The duration of both interventions was 4 sessions per week during 2 weeks. All patients from each group were evaluated at baseline condition and after the last session. Total duration of clinical and neurophysiological assessments was around 3-4 hours. The study was carried out in the installations of the Guttmann Institute from January 2020 until December 2022.

Neurological assessment

AIS scale was used to evaluate the clinical motor and sensory deficit according to American Spinal Injury Association (ASIA) Impairment Scale [9]. AIS-A is sensory and motor complete SCI; B: sensory incomplete and motor complete SCI; C and D: sensory and motor incomplete SCI and AIS-E: normal sensory and motor function. The sensory and motor score assessment was carried out with the participant in a supine position.

To evaluate trunk stability, we used the clinical trunk impairment control test (static and dynamic equilibrium and static equilibrium with upper limbs) [15].

Neurophysiological assessment during simple reaction time of body displacement to evaluate trunk function

Participants were instructed to perform a simple reaction time task to reach a switch on the wall [3,4]. In the initial position, subjects were sitting in a wheelchair, with the hip flexed at 90°, the knees flexed at 90°, the arms resting on their legs or the armrests. The target switch button was placed in front of them, aligned with the subject's midline, at a distance of 15 cm of the index fingertip with the arm extended.

The participants had to raise their arm and flex the trunk forward to reach the button as fast as possible but trying not to lose balance to the imperative signal (IS). The IS was a low-intensity electrical signal (between 3.6-8.1 mA, 0.2 ms duration) applied to the right little finger. If participant did not feel IS, it was delivered on the right shoulder. Participants performed 20 trials, in 5 (25%) of which a startle auditory stimulus (SAS) was presented simultaneously with the IS. The SAS was obtained by discharging a magnetic coil on top of a metallic platform, reaching a sound intensity of 125 dB for 250 ms [3,4].

Electromyographic (EMG) and smartphone recordings during body displacement

EMG data were collected from 8 muscles on the left side of the body: sternocleidomastoid (SCM), middle deltoid (DEL), trapezius (TRA), pectoralis major (PECT), upper abdominal Th6 (ABD), and paraspinal muscles at cervical C3 (PC), thoracic T6 (PT), and lumbar L2 (PL) levels. We asked the patients to use their left hand to press the button. If the left hand was more affected, the patient reached with the right hand. EMG signals were recorded at a sampling rate of 10 kHz by means of a ten-channel EMG system (Synergy, VIASYS Healthcare UK Ltd., 2005), using disposable adhesive surface electrodes (outer diameter 20 mm; Technomed) that were attached over the muscle belly. The remaining two channels of the EMG system were used to record 1) the activity of the orbicularis oculi muscle (OOc) and thus measure the blink reflex, and 2) the electrical artefact generated when pressing the wired switch button. Each trial was recorded for 3 seconds, starting 500 ms prior to the IS to evaluate the basal activity [3,4].

In addition, a smartphone (Samsung Galaxy S5) was placed on the subjects' chest, over the sternum, using an elastic band, to collect triaxial accelerometer data for motion analysis with the smartphone built-in sensor (MPU-6500 three-axis MEMS accelerometer with 16-bits ADCs, TDK InvenSense, San Jose, CA, United States). The smartphone accelerometer x-axis was in the transverse (left-to-right) direction, the y-axis in the longitudinal (superior-to-inferior) direction, and the z-axis in the anteroposterior direction. Accelerometer data were sampled at 200 Hz and stored as a text file.

From the tilt angle signal, we calculated the maximum trunk inclination angle PeakAng., the duration and angular velocity of the forward movement (from the beginning of the movement to the time of the maximum tilt angle), and the maximum peak-to-peak distance in the first 200 ms, [3,4]. Data processing and analysis was performed with custom written Matlab code (r2018a, Mathworks Inc.).

Interventions

Transcutaneous electrical spinal cord stimulation

Electric stimulation was delivered using the transcutaneous electrical stimulator BioStim-5 (Cosyma Inc., Moscow, Russia). tSCS was delivered simultaneously at two sites of cervical spinal cord along the midline between spinous processes C3-C4 and C6-C7, through 2 cm diameter hydrogel adhesive electrodes (axion GmbH, Hamburg, Germany) as cathodes and two 5×12 cm rectangular electrodes placed symmetrically over the iliac crests as anodes [6]. The intensity of stimulation at each spinal level was set at 90% of rest motor threshold induced by single-pulse tSCS at Abductor Pollicis Brevis (APB) muscle [4] of the less affected hand or of the right hand if both hand were similarly affected. tSCS consisted of biphasic rectangular 1-ms pulses, each one filled with a carrier frequency of 10 kHz (i.e., each 1-ms pulse was composed of ten 0.1-ms biphasic rectangular pulses), at a frequency of 30 Hz. tSCS was delivered with time patterns of 30s of stimulation followed by 60 s resting for 1 h. during robotic exoskeleton for upper extremity.

All assessments were carried out before (pre) and after last session (post) except the clinical trunk impairment control test (static and dynamic equilibrium and static equilibrium with upper limbs) was done after 2 weeks of last session also for follow-up assessment.

Data Processing and Statistical Analysis

EMG traces contaminated by artefacts were removed by visual inspection. The response time (RespT) was calculated as the time from the IS to the button press.

EMG onset latencies from IS were calculated for each muscle and trial. To calculate the EMG envelopes, EMG signals were full-wave rectified and low-pass filtered at 20 Hz. The baseline activity was calculated over the 600 ms prior to the IS and subtracted from all signals. Then, for each muscle and trial, the mean absolute value (MAV) of the EMG envelope from the onset of the muscle to the RespT was calculated, as a measure of the EMG amplitude.

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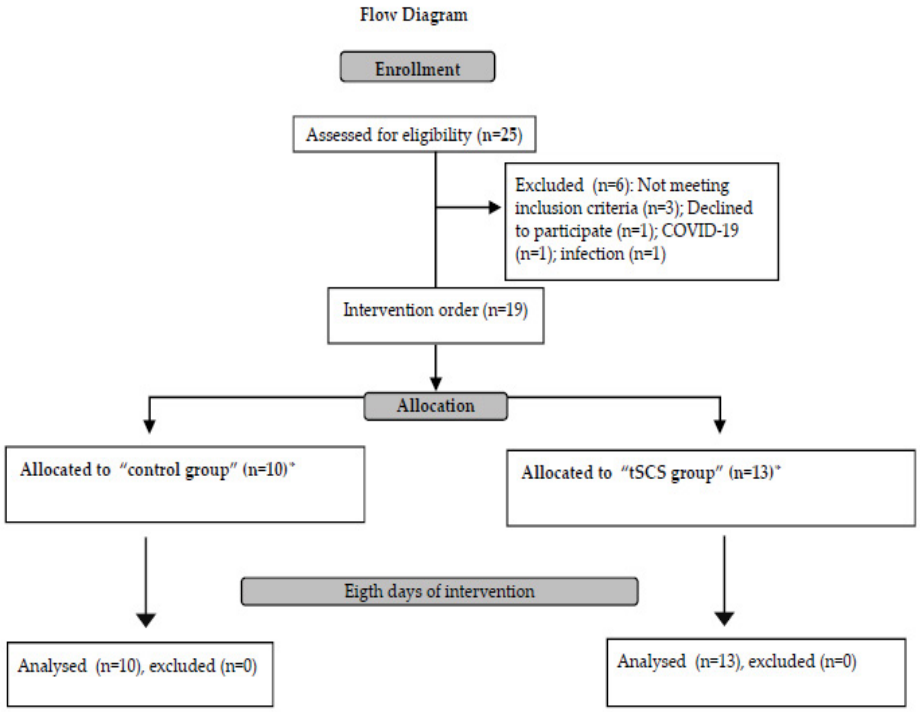

Figure 1: Flow Diagram

Flow Diagram. tSCS: transcutaneous spinal cord stimulation; *:4 individuals first were included in control group and at least one week later in tSCS group

The smartphone accelerometer data was used to monitor the trunk tilt and lateral angle signals, which are the angles calculated in the ZY plane, and the XY plane, respectively. These angles were estimated based on the projection of the gravity acceleration on the axes of the accelerometer [3,4].

For each feature, clinical, neurophysiological and smartphone data were averaged across trials to obtain a single measure for each subject and condition (non-SAS vs. SAS pre and post tSCS vs. control). Then, descriptive statistics, i.e., means and standard deviations (SD), were calculated for each group (tSCS and control).

Normality was assessed using the Shapiro-Wilk test. Since the assumptions for parametric analyses were not met, Wilcoxon signed-rank tests were conducted to compare pre and post non-SAS and after than pre and post SAS trials in each group except the total motor score for so we used the parametric test: Student's t test. While Mann-Whitney U tests were performed to determine differences in absolute value or percentage (%) changes following intervention or during follow-up between tSCS vs. control group. The alpha level was set at 0.05 for all comparisons.

Results

Twenty-five people were selected for this study, but six of them were excluded due to not meeting inclusion criteria (n=3); declined to participate (n=1); COVID-19 (n=1); infection (n=1) (Figure 1).

Nineteen individuals with cervical (n=18) or high thoracic(n=1) SCI participated in this study: 13 in tSCS and 10 in control group. Four of them participated in both groups at least one week after the follow-up period (Figure 1).

All subjects were able to complete the experiment. Two patients could not realize following assessment because of living in the other city. All subjects had cervical SCI except one with high thoracic lesion. The clinical and demographical characteristics of all the subjects with SCI were given in Table 1.

The age was similar between both groups (39.9±12.4 years in tSCS and 38.7±14.0 years in control groups; p. 0.83). Duration of SCI was 5.9±3.2 months in tSCS and 5.3±2.1 months in control group (p. 0.58). Total motor score were similar between control vs. tSCS group at baseline condition (pre intervention) (39.3±21.8 vs. 49.2±24.8 respectively; p. 0.34).

Neurological assessments

After the last session of tSCS, total motor score improved significantly (from 49.2±24.8 to 52.8±26.1; p=0.015), but in control group it did not reach a significant level (from 39.3±21.8 to 41.7±23.6; p=0.11). There were not significant changes in the absolute value of the total motor score in tSCS and in control group (p. 0.23; Table 1).

Clinical trunk impairment control test was similar between

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tSCS (17.2±9.0) and control group (13.7±6.5) at baseline condition (p=0.20). Table 2 shows the pre, post and follow-up values of clinical trunk impairment control test, static and dynamic equilibrium, and static equilibrium with upper limbs for each SCI subject.

There were no significant changes in static or dynamic equilibrium, static equilibrium with upper limbs, or in total clinical trunk impairment control test in tSCS, neither in control group, after last session (p>0.05), neither during follow-up period (p>0.05; Table 2).

Electromyographic (EMG) and smartphone accelerometer recordings during body displacement Outcome measures from EMG and smartphone accelerometer in the tSCS and control groups, are described in Table 3, both in SAS and non-SAS trials.

Table 4 shows the p-values according to Mann-Whitney U Test corresponding to the pre-intervention comparison between the two groups: tSCS vs. control group. Both groups were similar for all pre-intervention variables from EMG and smartphone accelerometry (Table 4; p>0.05 for all comparisons).

Table 5A shows statistical analysis and p-values between pre and post comparison in each group according to Wilcoxon signed rank test, while Table 5B shows the comparison between tSCS vs. control group for absolute value and percentage changes following intervention (Mann-Whitney U Test).

After the last session in the tSCS group, there were not any significant changes in EMG or smartphone variables with or without SAS condition:RespT, action duration, lateral deviation, angle velocity, peak acceleration angel, onset latencies and MAV in EMG for all muscles did not significantly change with the intervention. The same happened in the control group: none of the parameters changed after two weeks of upper limb rehabilitation (p>0.05 for each comparison between pre and post-intervention, Table 5A), except RespT, which was accelerated in the non-SAS trials after the last session (p=0.05).

There were not any significant changes in absolute value or in the % changes between tSCS vs. control group (p>0.05; Table 5B).

Table 1: The clinical and demographical characteristics of all the subjects with SCI

Intervention	Age	Sex	SCI level	AIS	Etiology	Time since SCI (months)	total motor score	total motor score	tSCS intensities at C3-C4/ C6-C7 (mA)
							pre	post	
tSCS*	25	M	C4	A	Trauma	4	11	15	67/86
tSCS	46	M	C4	C	Trauma	4	21	23	80/80
tSCS*	36	M	C5	B	Trauma	14	14	15	74/86
tSCS	36	M	C7	D	Trauma	6	74	74	63/85
tSCS	28	M	C4	C	Trauma	6	52	56	63/85
tSCS	28	M	C5	A	Trauma	4	28	28	86/86
tSCS	38	M	C4	B	Trauma	5	48	48	54/77
tSCS*	56	M	C4	C	Trauma	9	47	50	86/86
tSCS	60	M	C5	D	Trauma	3	88	90	86/86
tSCS*	22	F	C7	C	Trauma	5	44	51	85/86
tSCS	55	M	C3	D	Trauma	4	87	91	86/86
tSCS	47	M	C6	C	Trauma	10	57	59	86/86
tSCS	42	M	C4	D	Trauma	3	69	86	80/76
control*	25	M	C4	A	Trauma	8	15	15	-
control	46	M	C4	C	Trauma	6	23	23	-
control*	36	M	C4	B	Trauma	5	12	14	-
control	38	M	C7	C	Trauma	3	48	48	-
control*	56	M	C4	C	Medical	6	46	46	-
control	58	M	C6	A	Trauma	6	44	46	-
control	21	M	C6	B	Trauma	9	22	22	-
control	53	M	T1	D	Medical	3	51	65	-
control	32	M	C5	D	Trauma	3	90	94	-
control*	22	F	C7	C	Trauma	4	42	44	-

*Individual with SCI participated first in control group and than at least one week of wash-out, in tSCS group.

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Table 2: Clinical trunk impairment control test (static and dynamic equilibrium and static equilibrium with upper limbs)

		Total score			Static equilibrium			Dynamic equilibrium			Static equilibrium with upper limbs		
Group	Age	Pre	Post	Follow-up	Pre	Post	Follow-up	Pre	Post	Follow	Pre	Post	Follow-up
tSCS	25	0	8	18	0	6	6	0	0	0	0	2	12
tSCS	46	0	0	0	0	0	0	0	0	0	0	0	0
tSCS	36	12	12	12	6	6	6	0	0	0	0	0	0
tSCS	36	24	24	24	6	6	6	6	6	6	12	12	12
tSCS	28	9	15	NA	6	6	NA	3	3	NA	0	6	NA
tSCS	28	24	24	24	6	6	6	6	6	6	12	12	12
tSCS	38	19	19	22	6	6	6	4	4	4	9	9	12
tSCS	56	19	21	21	6	6	6	2	3	3	11	12	12
tSCS	60	24	24	NA	6	6	NA	6	6	NA	12	12	NA
tSCS	22	22	22	22	6	6	6	4	4	4	12	12	12
tSCS	55	24	24	24	6	6	6	6	6	6	12	12	12
tSCS	47	23	23	23	6	6	6	5	5	5	12	12	12
tSCS	45	24	24	24	6	6	6	6	6	6	12	12	12
mean (SD)		17.2 (9.0)	18.5 (7.6)	19.5 (7.4)	5.1 (2.3)	5.5 (1.7)	5.5(1.8)	3.7 (2.5)	3.8 (2.4)	3.6 (2.5)	8.7 (5.3)	9.3 (4.7)	9.6 (5.1)
p. value			0.109	0.893		0.317	0.564		0.317	0.285		0.109	0.581
control	25	6	6	6	6	6	6	0	0	0	0	0	0
control	46	20	20	20	6	6	6	2	2	2	12	12	12
control	36	2	2	2	2	2	2	0	0	0	0	0	0
control	38	16	16	19	6	6	6	4	4	4	6	6	9
control	56	19	19	19	6	6	6	2	2	2	11	11	11
control	58	13	15	15	6	6	6	3	4	4	4	5	5
control	21	11	11	11	6	6	6	3	3	3	2	2	2
control	53	13	15	15	4	6	6	3	3	3	6	6	6
control	32	24	24	24	6	6	6	6	6	6	12	12	12
control	22	13	22	22	3	6	6	4	4	4	6	12	12
mean (SD)		13.7 (6.5)	15.0 (7.0)	15.3(7.1)	5.1 (1.5)	5.6 (1.3)	5.6(1.3)	2.7 (1.8)	2.8 (1.9)	2.8 (1.9)	6.5 (4.3)	7.3 (4.6)	7.7 (4.6)
p. value			0.102	0.066		0.18	0.18		0.317	0.317		0.18	0.109

SD: standard deviation; NA: not available; pvalue according to Wilcoxon-test {comparison between pre vs. post, and pre vs. follow-up)

Table 3: Outcome measures from EMG and smartphone accelerometer in the tSCS and control groups, both in SAS and non-SAS trials.

Means per tSCS and control Groups pre and post intervention																						
			Accelerometer Parameters					EMG Onset Latencies (ms)								EMG Mean Absolute Value (MAV) (μV)							
	Group	RespT (ms)	ActDur (s)	TiltAngle (deg)	LateralDev (deg)	AngVel (deg/s)	PeakAcc_ Ang (deg)	SCM	DEL	TRA	PECT	ABD	PC	PT	PL	SCM	DEL	TRA	PECT	ABD	PC	PT	PL
non-SAS	tSCS Pre	978.9	0.9	29.6	8.6	36.7	12.3	267	356.2	268.8	281.7	390.2	327.4	405.3	496.1	79.3	429.6	301	122.8	42.1	30.5	108.4	107.6
	tSCS Post	972.7	0.9	32.8	8.6	40.2	14.4	310.4	399	301.3	320.8	356	335.9	396.3	510.1	66	533.8	346	146.2	50.2	46.2	129.7	81.9
	Control Pre	1210.6	1.1	33	8.3	36.9	8.9	320.6	472.4	407.7	344.4	405.5	416.7	475.4	649.9	53	397.1	326.8	59.5	36.2	34.4	110.4	39.2
	Control Post	1053.2	1	29.7	8.5	33	8.9	333.9	414.6	318.7	341.8	421.3	384.1	475.2	571.6	64.1	416.4	314.6	118.1	37.8	31.7	114.3	81.5
SAS	tSCS Pre	866.6	0.8	30.7	8.1	39.8	20.4	192.3	274.8	205.9	196	300.7	219.3	319.7	436.1	85	448	320.4	137.5	46.6	34.1	125.8	110.5
	tSCS Post	897.5	0.9	33.5	10	40.7	16.9	234.9	335.3	215.2	253	310.1	225.1	305.7	416.8	71	576.7	373.9	156.2	69.7	66.8	147.2	86.6
	Control Pre	1060.2	1.1	33	8	36.8	14.7	240.7	352.1	268.9	245.2	340.2	275.5	328.7	541	62.4	415.4	360.7	69.5	38.7	38	117.9	52.1
	Control Post	952	1	30.9	8.6	35.3	18.7	263.2	251.8	221.9	235.9	309.2	234.2	362.7	492.7	67.7	529.7	356.9	134.6	40.6	37.3	141.3	92.5

The columns show the Mean for each group and condition. RespT: response time; ActDur: Action duration; LateralDev: lateral deviation, AngVel: angle velocity, PeakAccAng: peak acceleration angle. SCM: sternocleidomastoid muscle; DEL: deltoid; TRA: trapezius; PECT:pectoralis, ABD: abdominal muscle; paraspinal muscles at cervical C3 (PC), thoracic T6 (PT), and lumbar L2 (PL) levels .

Table 4: The homogeneity of two groups pre-intervention (pre-tSCS vs. pre-control group) (p-value according to Mann-Whitney U Test)

p-values to compare the homogeneity of two groups pre-intervention (pre-tSCS vs pre-control) (Mann-Whitney U Test)																						
			Accelerometer Parameters					EMG Onset Latencies								EMG Mean Absolute Value (MAV)							
Condition	Group	RespT	ActDur	TiltAngle	LateralDev	AngVel	PeakAcc_Ang	SCM	DEL	TRA	PECT	ABD	PC	PT	PL	SCM	DEL	TRA	PECT	ABD	PC	PT	PL
non-SAS	Pre	0.22	0.48	0.5	0.95	0.66	0.8	0.4	0.4	0.1	0.5	0.4	0.7	0.9	0.2	0.9	0.3	0.8	0.7	0.9	0.3	0.8	0.5
SAS	Pre	0.34	0.2	0.5	0.61	0.64	0.93	0.6	0.9	0.7	0.9	0.7	0.8	0.9	0.4	0.3	0.6	0.6	0.9	0.6	0.8	0.6	0.3

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Table 5A: Statistical analysis and p-values between pre and post comparison in each group according to Wilcoxon signed rank test

p-values Pre vs Post for each group (Wilcoxon signed-rank test for paired samples)																						
			Accelerometer Parameters					EMG Onset Latencies							EMG Mean Absolute Value (MAV)							
Condition	Group	RespT	ActDur	TiltAngle	LateralDev	AngVel	PeakAcc_Ang	SCM	DEL	TRA	PECT	ABD	PC	PT	PL	SCM	DEL	TRA	PECT	ABD	PC	PT	PL
non-SAS	tSCS	1	0.41	0.45	1	0.27	0.95	0.3	1	0.7	0.5	0.5	0.5	1	1	0.9	0.1	0.7	0.7	0.8	0.2	0.3	0.9
	Control	0.05	0.28	0.56	1	0.85	1	0.9	0.2	0.1	0.8	0.6	1	0.9	0.2	0.8	0.8	0.8	0.1	0.4	1	0.7	0.3
SAS	tSCS	0.89	0.34	0.54	0.19	0.59	0.89	0.5	0.7	1	0.2	0.6	1	0.8	0.8	0.5	0.1	0.6	1	1	0.1	1	1
	Control	0.38	0.38	0.85	0.56	1	0.32	0.8	0.2	0.4	1	0.9	0.6	0.9	0.4	0.4	0.9	0.9	0.2	0.6	0.5	0.3	0.2

Table 5B: Groups comparison (tSCS vs control group) for absolute value and percentage (%) changes following each intervention (Mann-Whitney U Test)

p-values between two groups (Mann-Whitney U Test)																							
			Accelerometer Parameters					EMG Onset Latencies								EMG Mean Absolute Value (MAV)							
Condition	Difference	RespT	ActDur	Tilt Angle	LateralDev	AngVel	PeakAcc_Ang	SCM	DEL	TRA	PECT	ABD	PC	PT	PL	SCM	DEL	TRA	PECT	ABD	PC	PT	PL
non-SAS	Absolute	0.22	0.48	0.5	0.95	0.66	0.8	0.4	0.4	0.1	0.5	0.4	0.7	0.9	0.2	0.9	0.3	0.8	0.7	0.9	0.3	0.8	0.5
	%	0.17	0.53	0.2	0.44	0.4	0.44	0.6	0.8	0.2	0.9	0.2	0.8	0.2	0.3	0.8	0.5	0.2	0.5	0.7	0.4	0.9	0.3
SAS	Absolute	0.35	0.12	0.5	0.42	0.85	0.42	0.5	0.1	0.3	0.4	0.7	0.5	0.7	0.8	0.9	0.4	0.6	0.5	0.8	0.1	0.4	0.4
	%	0.26	0.11	0.5	0.42	0.8	0.42	0.8	0.2	0.4	0.4	0.6	1	0.5	0.6	0.9	0.8	0.7	0.7	1	0.1	0.5	0.3

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Discussion

Despite the observed total motor score improvement following tSCS, we did not find any significant changes in trunk control in these individuals. This is a crucial finding, suggesting that while tSCS at two cervical segments positively affected certain aspects of motor function as published previously [6], but this did not translate into improvements in trunk stability and its EMG and smartphone accelerometer measurements.

We have methodological differences with the previous studies: (i) Our study was randomized mix of parallel group and crossover clinical trial and we applied tSCS during upper limb therapy in 13 cervical SCI individuals during 8 days; (ii) we used the clinical trunk impairment control test (static and dynamic equilibrium and static equilibrium with upper limbs; (iii) EMG and smartphone assessments to evaluate the trunk stability [3,4]. However, Rath et al. (2018) [17] studied 8 chronic cervical or thoracic SCI subjects following one session of tSCS. They used monophasic rectangular 1ms pulses, frequency at 30 Hz at T11 level, and 15 Hz at L1, carrier frequency 10 kHz, and intensity 10 to 150mA. Reported an elevated activity of the trunk muscles contributing to improved trunk control, and increased multi-directional seated stability. Keller et al (2021) [8] applied tSCS at intensity of 20-200 mA at T11 at 30 Hz, L1 at 15 Hz, and C5 at 30 Hz during 22 experiments in 8 children with cervical or thoracic SCI ages 3–14 years old. It was non-randomized, non-blinded pilot clinical trial. They reported increased trunk extension, enabled upright sitting posture. Tharu et al. (2022) [19] included just five subjects with chronic complete cervical SCI participated in 24-week therapy that combined tSCS and conventional task-specific rehabilitation (TSR) in the first 12 weeks, followed by TSR alone for another 12 weeks. tSCS was delivered simultaneously at T11 and L1 spinal levels, at a frequency ranging from 20–30 Hz with 0.1–1.0 ms biphasic pulse width. They reported improved trunk and sitting functions with increased static and dynamic balance.

The principal mechanism of tSCS is a non-invasive activation of neuronal networks of the spinal cord likely including the recruitment of afferent fibers in the posterior root in order to elevate spinal network excitability [18,14]. The excitability of spinal interneuronal networks without directly producing action potentials can be readily modulated by changing the networks' physiological state [7]. For that reason, the placement of tSCS electrodes is an important consideration in order to target specific segments of the spinal cord and promote desired functional outcomes. The previous studies, tSCS applied at thoracic and lumber segments, [17,19] in addition to one cervical segment [8]. In our study, tSCS was applied to two cervical segments (C3-4 and C6-7).

Other important differences in the application duration of tSCS between our study and previous three studies highlight an important aspect of study design. We applied tSCS over eight days in adult SCI individuals, which contrast with studies that utilized a single session [17,8] and involved children [8]. Tharu et al. (2022) [19] applied tSCS and conventional task-specific rehabilitation during 12 weeks. Al those three studies were done in chronic SCI individuals [17,8,19]. Additionally, our study exclusively focused on individuals with cervical or one with upper thoracic SCI, emphasizing the severity of the condition compared to thoracic SCI.

Our study acknowledges the limitations: (i) using only two cervical segments for stimulation. Consideration of thoracic and lumbar segments might offer a broader perspective on the effects of tSCS on trunk stability; ii) the study notes the absence of a specific trunk exercise combined with tSCS. Incorporating such exercises, as demonstrated in previous research [19], might potentially enhance neuromodulation.

In conclusion, while our study demonstrates robustness through its control group and diverse assessment methods, the limitations suggest areas for improvement and avenues for future research. Consideration of tSCS at thoracic and lumbar segments and exploration of combined trunk interventions may provide a more comprehensive understanding of the potential benefits of tSCS on trunk stability following SCI.

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Conflicts of Interest

The authors declares no conflicts of interest.

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