Improved Gait symmetry with spinal cord transcutaneous stimulation in individuals with spinal cord injury

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***Abstract*— A previous study by our group showed preliminary results showcasing the usage of optimal and individualized spinal cord transcutaneous stimulation (scTS) parameters during overground gait training to facilitate more repeatable gait kinematics profiles for one participant with an incomplete spinal cord injury (SCI). The goal of this study was to use the combined targeted scTS and training to improve spatial and temporal parameters to achieve a symmetrical gait profile after completing activity-based training (ABT) (stepping and stand training) and exoskeleton training with and without scTS. Our data indicates that stimulation with optimal and individualized parameters can lead to more effective, stable and symmetric gait patterns in participants with varied levels of SCI.**

***Clinical Relevance*— This analysis will enable us to better understand the combined effect of exercise based training and tonic scTS on improving the quality and symmetry of gait pattern in participants with incomplete SCI.**

I. INTRODUCTION

Spinal cord Injury (SCI) leads to a disrupted transmission of motor and sensory information through the spinal cord. Spinal cord transcutaneous stimulation (scTS) has shown improvements in gait kinematics in subjects with complete or incomplete SCI [1]. scTS at targeted sites has been shown to evoke spinal sensorimotor outputs enabling targeted rehabilitation therapy to provide functional gains to participants with SCI [2]. Powered exoskeleton training has been shown to have enabled increased mobility and independence while walking overground [3].

A previous study by our group showed preliminary results showcasing the usage of these targeted parameters during overground gait training to facilitate more consistent gait kinematics profiles for one participant with an incomplete SCI. Our approach now focuses on using the combination of targeted scTS parameters along with activity-based training (ABT) (stepping, stand training) and exoskeleton training to achieve the consistency in gait pattern for all the recruited participants. The purpose of this study was to use the targeted scTS and training to achieve a symmetrical kinematic gait profile.

II. PROCEDURE

An individual with incomplete spinal cord injury underwent activity-based training (ABT) along with Exoskeleton training in EksoNR (Ekso Bionics, San Rafael, CA). The participant provided [1]written informed consent to the study procedures, approved by Kessler Foundation's Institutional Review Board.

Table I SUBJECT DEMOGRAPHICS

Gender	***TSI*** [a] ***(yrs.)***	***AIS*** [b]	***NLI*** [c]
M	8	D	T12

a. Time since Injury.

b. American Spinal Injury Association Impairment Scale,

c. Neurological Level of Injury (NLI) according to International Standards for Neurological Classification of SCI (ISNCSCI)

Multiple, targeted cohorts of scTS (NeoStim, Cosyma, Russia), decided through series of spinal mapping sessions, were delivered as part of the integrated neuromodulation at the lumbosacral and thoracic spinal sites for cathodes and bilateral iliac crest for anodes. The stimulation waveforms consisted of a monophasic rectangular pulse (width of 1ms) with 5kHz carrier frequency.

A. Training protocol

After initial amplitude and frequency mapping, participants were enrolled in targeted training based on their functional needs. ABT included tasks like standing, hip hiking while kneeling, arm reaching exercises, weighted leg rises etc. This was accompanied with progressive EksoNR training. The participants start with "Max" mode wherein the robot guides the gait. Once the participant gets used to/comfortable with walking in the exosuit the support from the robot is reduced to "fixed" mode where certain percent of support is given to either of legs or "Pro-step plus" mode where steps are initiated by participants' weight-shifts. Based on the progress thus far, the participants switched to the '2Free' mode, walking without any assistance from the robot. Training was also provided overground for incomplete SCI participants in addition to ABT and Ekso training while using assistive devices like walker and crutches.

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B. Data collection

Kinematic data was collected at baseline and post training during 10meter gait trials with and without ekso. Reflective markers were placed on the bony landmarks of the subjects adhering to Halen-Hayes marker set. Full body kinematics were collected using CORTEX motion capture system (Motion Analysis Corporation, Santa Rosa, CA) at 120 Hz.

C. Data analysis

Collected data was filtered using a 2nd order low pass Butterworth filter with a cutoff frequency of 6Hz.

Temporal spatial parameters such as Initial Double Support, Single Stance, Terminal Double Support, Swing, Stride Length, Step Length, Step Height, Step Width, and Range of Motion were also calculated. These parameters were normalized to 100% of gait cycle using the corresponding heel strikes. Intralimb (Comparing ipsilateral joint angle kinematics for consecutive gait cycles) coefficient of variation, interlimb (comparing contralateral joint angle kinematics) coefficient of variation (CV), standard error for joint kinematics during swing and stance phase, and mean walking velocity were calculated. CV was calculated as the ratio of standard deviation over the mean.

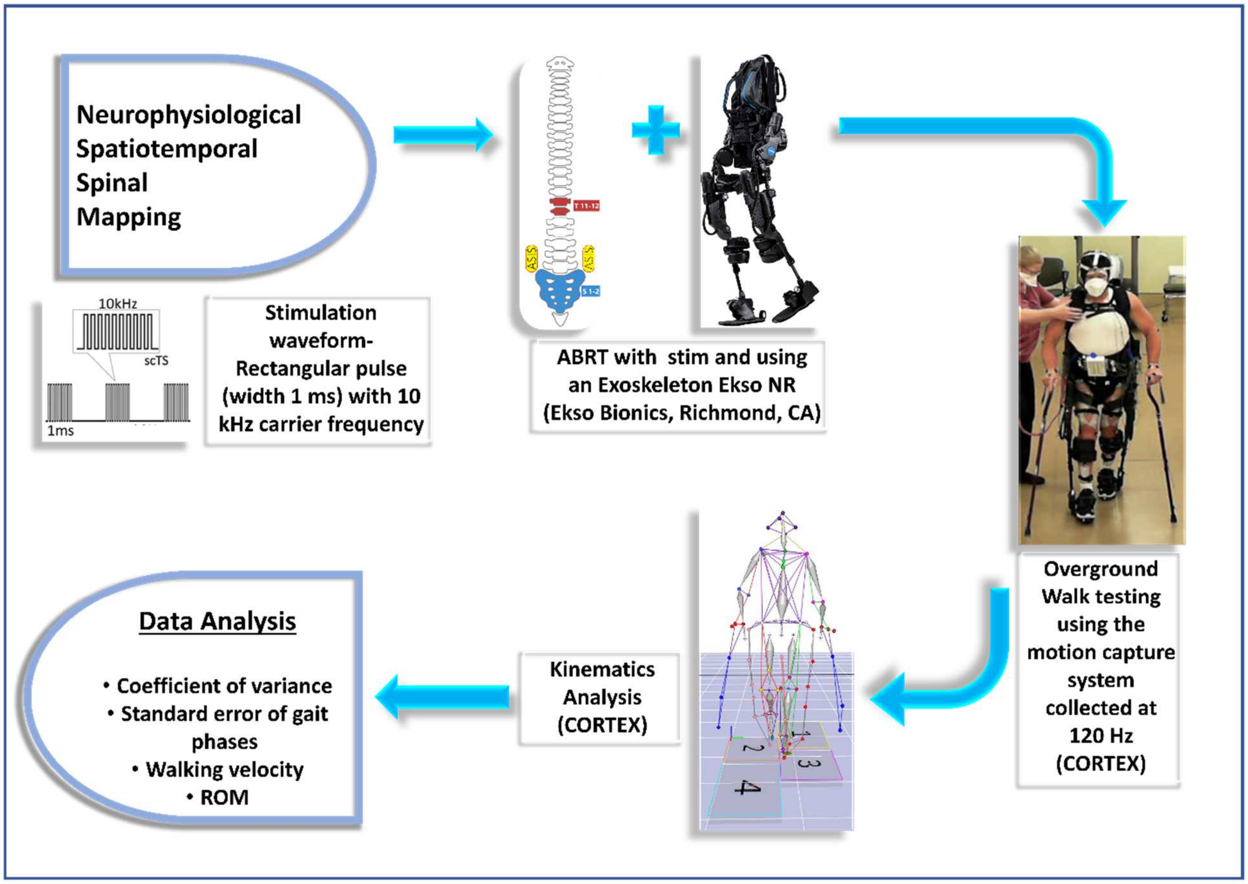

Figure 1 Experimental Workflow

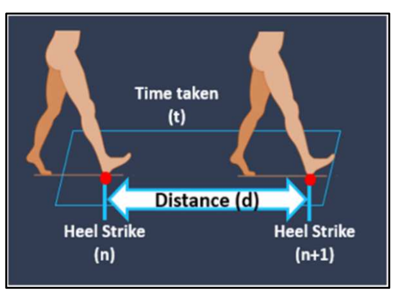

Figure 2 Walking Velocity calculation.

III. RESULTS

Overground gait data, without the Ekso-suit, were analyzed for this study to better understand the effect of the exoskeleton training.

A. Kinematics - Post training compared to pre-training.

In trials without stimulation, mean intralimb CV decreased by 51% and 64% (Table II) for the knee and hip joint respectively, whereas at the ankle we saw limited changes with 2% increase in CV post-training. Interlimb CV decreased by 55% average around all joint without stimulation post-training. In trials with stimulation, the mean intralimb CV decreased by 17%, 56%, and 49% at the ankle, knee and hip joint respectively. Interlimb CV decreased by 32%, 35%, 19% at the ankle, knee and hip joint respectively (Table II).

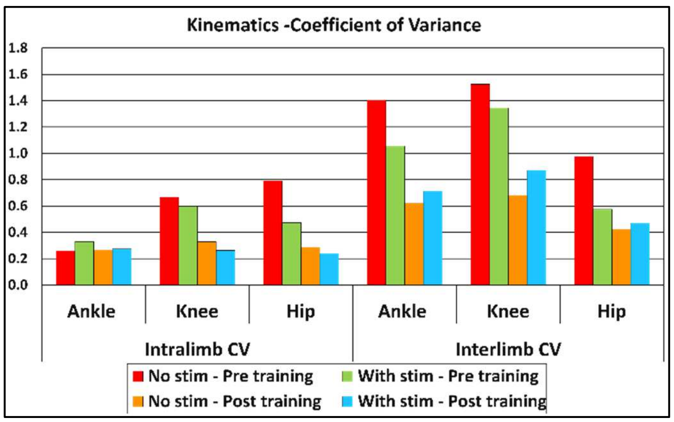

Figure 3 Interlimb and Intralimb Coefficient of Variation

Table II PERCENTAGE CHANGE IN CV

		Percentage change	
		No-STIM Pretraining vs Post training	With STIM Pre training vs Post training
Mean Intralimb CV	Ankle	2	-17
	Knee	-51	-56
	Hip	-64	-49
Interlimb CV	Ankle	-56	-32
	Knee	-55	-35
	Hip	-57	-19

B. Kinematics - Stance and swing phase

As seen in Fig 3 the mean intralimb CV for ankle joint without stimulation increased by 2% post-training for the entire gait cycle, but looking at the stance phase standard error reveals 46% decrease without stimulation post-training.

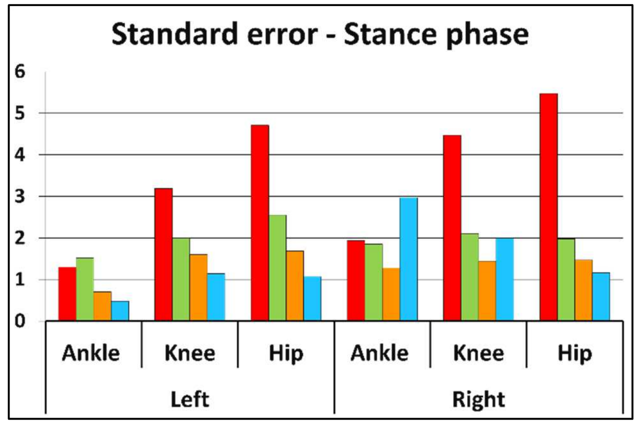

Figure 4 Standard error of joint kinematics in the stance phase

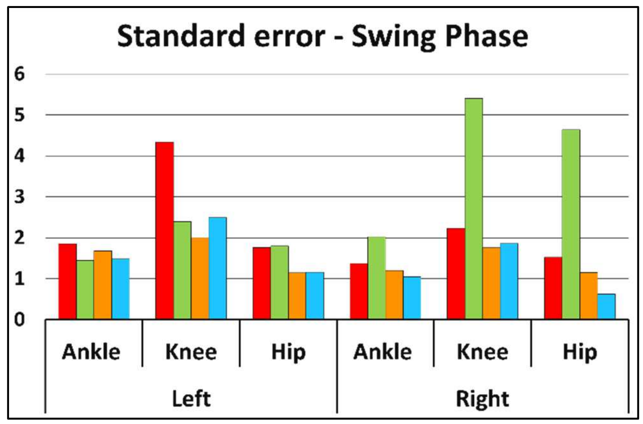

Figure 5 Standard error of joint kinematics in the swing phase

Walking velocity, which was calculated by tracking the heel marker, also increased post training with and without stim 3% and 40% on the left leg and by 20% and 30% on the right respectively. (Fig 6)

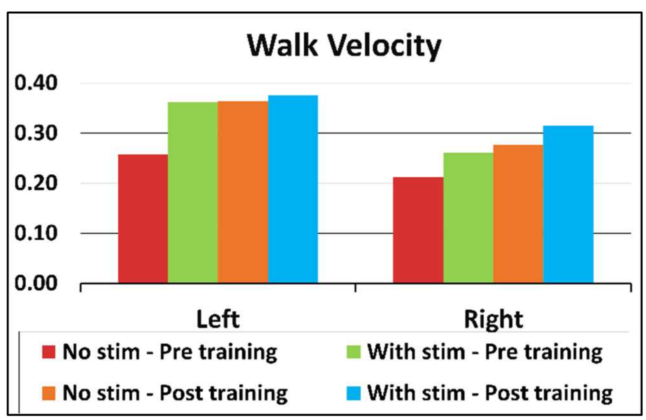

Figure 6 Improvements in the walking velocity with stimulation and ABT

IV. DISCUSSION

Overall, the significant decrease in the interlimb CV and intralimb CV, reflects a more homogeneous kinematic gait profile during the 10m gait as a result of scTS+ABT. This affected the quality of gait. Even without training we observed an immediate effect of stimulation on the intra/inter limb kinematic symmetry of gait with decrease in the coefficient of variation (data not shown). During the stance and swing phases of overground gait, there was a large decrease in the intralimb standard error. More importantly, these large decreases in intra/interlimb kinematic CVs were maintained in the gait trials where there was no spinal stimulation.

Clinically the immediate and training effect of the scTS+ABT intervention determined a more consistent and controlled ipsilateral limb and interlimb joint kinematics than pre-intervention.

These gait changes persisted in the trials without stimulation, demonstrating the effectiveness of targeted scTS+ ABRT and exoskeleton training, and its sustenance post-training, across the participant population. The subject was tested 6 months post training to ascertain these findings. The kinematic CV changes indicated the potential cortical spinal and reticular spinal changes. However, the mechanism for these changes and the overall limitation of a small sample size study needs to be studied further. Future research will focus on expanding on these results for a larger sample size.

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