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ELECTRICAL NEUROMODULATION DURING ROBOT-ASSISTED STEPPING IN HUMANS WITH SPINAL CORD INJURY

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Abstract— *Electrical neuromodulation using transcutaneous spinal stimulation can modify the spinal motor output. In recent years, proof-of-principal studies have shown the benefits of this intervention to recover locomotor functions. Here, we assess changes of joint torques during stimulation over a wide range of stimulation frequencies (1 – 100 Hz). The presented example shows high susceptibility to the external input by modifying stepping patterns during robot-assisted treadmill training.*

Keywords—*Transcutaneous spinal stimulation, neuromodulation, sensorimotor integration, spinal cord injury, robot-assisted gait training*

Introduction

Spinal cord injury (SCI) is a devastating neurological condition that affects the interactions between supraspinal structures and the spinal cord below the lesion. It results in partial or complete loss of volitional and postural control of movements associated with impaired sensorimotor integration. The ensuing muscle weakness is often accompanied by spastic motor behaviors, such as increased muscle tone (hypertonia), hyperactive reflexes (hyperreflexia), and clonus, as well as involuntary muscle contractions (spasms) and improper muscle coordination (dyssynergia) [1, 2].

New developments in electrical neuromodulation with transcutaneous (TSS) spinal stimulation show promise for improving walking in people with SCI [3–5]. The underlying premise of TSS interventions is that the generated afferent input modifies the excitability of the lumbosacral network to either augment appropriate or suppress pathophysiologic spinal motor output [4, 6].

Here, we address the impact of TSS frequency from 1 up to 100 Hz on locomotor pattern in people with incomplete SCI.

Methods

Robot-assisted treadmill stepping

The participant was first instrumented for EMG recording and TSS stimulation (see below). After determining the stimulation thresholds, the subject was placed in the bodyweight support harness and fitted into the robotic gait orthosis (Lokomat Pro V4, Hocoma AG, Volketswil, CH). The Lokomat (Fig. 1A) was used in a research mode, which provided real-time analog data output. This device controls leg movement towards a predefined trajectory of a physiological gait pattern by controlling the hip and knee joint torques of the exoskeleton. A cascaded control system (Fig. 1B) integrates a first-order impedance controller (proportional-

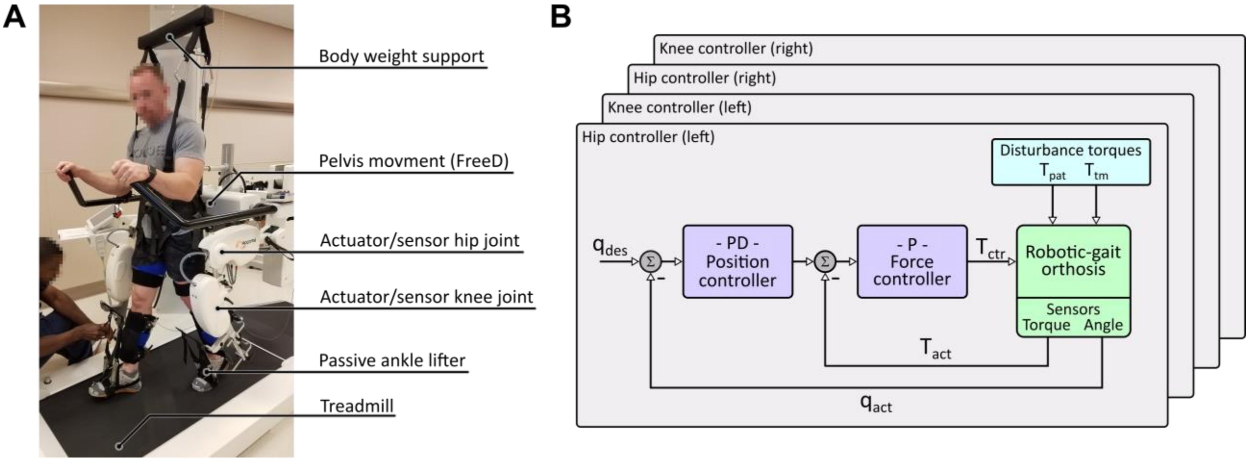

Figure 1. (A) Components of the robot-assisted gait exoskeleton, Lokomat Pro. (B) Cascaded control structure. Primary angle controller based on desired (q_{des}) and measured actual (q_{act}) angles; secondary torque control loop based generates the actuating torque (T_{ctr}) of the exoskeleton; actual torque (T_{act}) measured at the actuators. The disturbance torques by a participant (T_{pat}) and treadmill (T_{tm}). Modified from Jezernik et al. (2003) [7].

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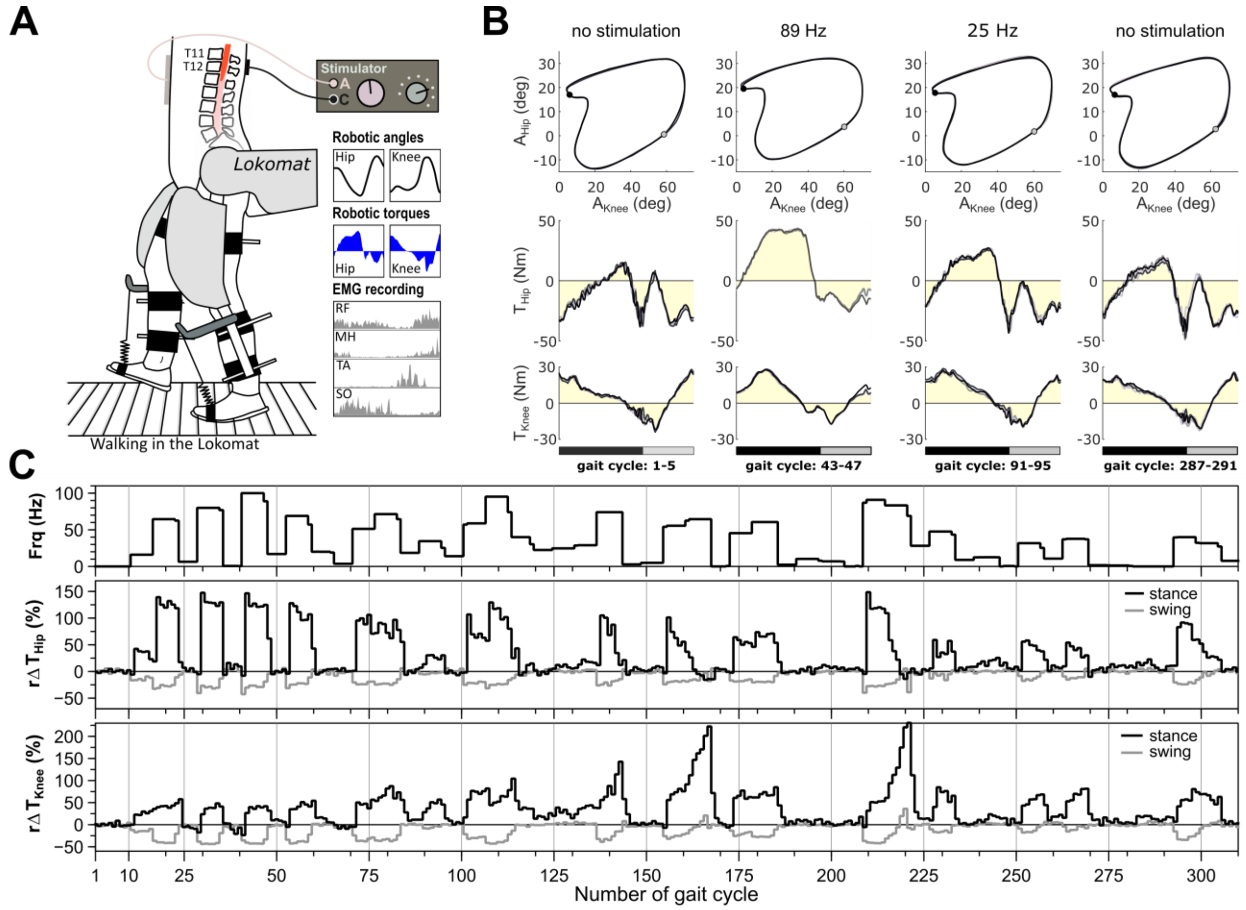

Figure 2. Recording setup and illustrative robotic torques and angles in participant S2 (left leg). A: Recording setup: The subject is placed in a robotic-assisted gait orthosis (Lokomat Pro, Hocoma, Inc.) on a treadmill with body-weight support. Robotic torques and angles in hip and knee joints were output using the Lokomat research setting. EMG signals were simultaneous recorded in the rectus femoris (RF), medial hamstrings (MH), tibialis anterior (TA), and soleus (SO) muscles. During stepping at constant treadmill speed and body weight support, continuous transcutaneous spinal stimulation was applied at various frequencies but the same intensity. B: Angle (A) and torque (T) signals for five superimposed consecutive gait cycles (duration 2.4 s) at different stimulation frequencies. Hip–knee cyclograms (top) present the gait trajectories of the robotic joints (beginning of stance, black circle; beginning of swing, grey circle). Robotic hip (middle) and knee (bottom) joint torques produced by the robotic actuators (stance phase, 62%, marked in black; swing phase, 38%, in grey). Note similar trajectories but changes in hip and knee torques at different stimulation frequency. C: Traces of stimulation frequency (top), hip (middle), and knee (bottom) robotic torques over 310 gait cycles for stance (black) and swing (gray). The stimulation frequency was randomized and kept constant for ten consecutive gait cycles. Hip and knee robotic torques are expressed relative to the first 10 gait cycles (no stimulation).

derivative, PD) for angle deviations and a second-order proportional (P) torque controller [7].

TSS intervention

Two self-adhesive hydrogel electrodes (5 cm, diameter) were placed on both sides of the T11/12 interspinous space and connected to act as a single cathode. The rectangular electrodes (7.5 x 10 cm) were placed over the lower anterior abdomen left and right of the umbilicus and connected as a single cathode [8]. The stimulation frequencies were randomized from 1 to 100 Hz, whereas the intensity was set individually to allow comfortable stepping across the applied frequency range.

Experimental procedure

After checking the proper orthosis fit and stepping pattern over ~30 gait cycles, the robotic torques and EMG were first recorded without stimulation (10 gait cycles). Then, the stimulation frequencies were randomly selected by custom-made software up to 100 and remained constant for ten consecutive gait cycles. The trigger signal provided by a data acquisition card (CompactRIO Systems) was used to synchronize the frequency change with the right heel-strike defined by the Lokomat. Stepping without stimulation was repeated at random throughout the recording. Data from 310 consecutive gait cycles were analyzed of which the first ten gait cycles without stimulation were used for normalization.

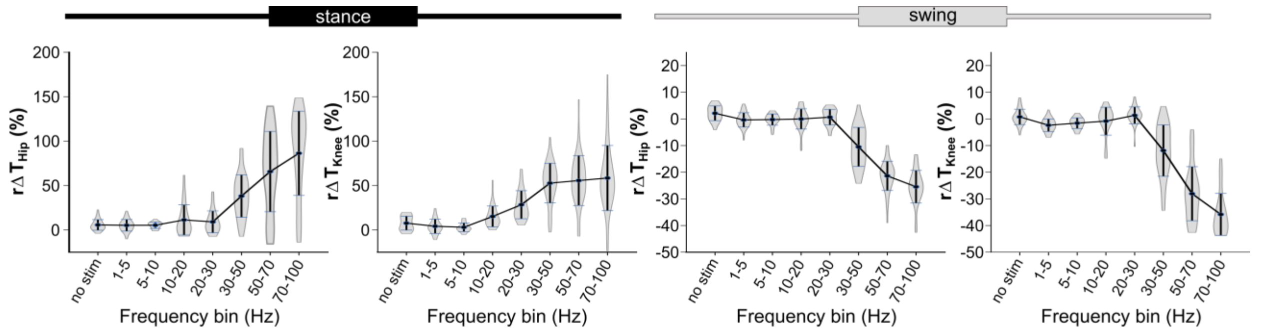

Figure 3. The violine plots for the relative changes in hip and knee torques for each stimulation frequency bin during stance and swing. The line graph presents the mean (avgT) and standard deviation of each frequency bin.

Data analysis
The subsequent heel identified a gait cycle–strike signals from the Lokomat output and divided it into the stance (62%) and swing (38%) phase. The robotic torques (T) generated by the Lokomat hip and knee actuators during stepping were calculated as the area under the curve (Fig. 1B), separately for stance and swing, hip and knee, and left and right sides. The relative change in torque (rΔT_{gc}, in %) was calculated as the normalized difference between the torque during each gait cycle (T_{gc}) and the averaged torque across the first ten gait cycles without stimulation (T_{avg}[1:10]) for each side, joint, and gait phase (Eq. 1).

$$\mathrm{r}\Delta \mathrm{T}_{gc} = \frac{\mathrm{T}_{gc} - T_{\mathrm{avg}[1:10]}}{T_{\mathrm{avg}[1-10]}} \cdot 100\% \quad (1)$$

Results

An example of relative changes in the robotic torques (rΔT) are shown in Figure 2B-D for the entire recording session (310 gait cycles) with and without TSS applied at randomly selected stimulation frequencies in a participant (left leg). The robotic torques for no stimulation conditions (baseline), interspersed throughout the recording session, was stable (Fig. 2B, first and last columns). Administering the stimulation at different frequencies produced instantaneous changes in torque predominantly sustained in magnitude over multiple gait cycles or showed an incremental or decremental change (Fig. 2C). The changes in robotic torques during stimulation were largely in opposite directions between stance and swing in both hip and knee joints (Fig. 2B, middle columns; Fig. 2C). With frequency data aggregated in bins, it became apparent that the hip and knee robotic torques increased during stance and decreased during swing at higher frequencies in this participant (Fig. 3).

Discussion

In this study, we examined the immediate effect of TSS across different stimulation frequencies on robotic support of hip and knee kinematics and muscle activation patterns during treadmill stepping. We have found individually distinct patterns of changes in the robotic torques that differed in magnitude and direction depending mainly on the applied stimulation frequency and gait phase (Fig. 2).

Recently developed methods of transcutaneous posterior root stimulation have opened a new avenue to provide non-invasive, multi-segmental input to modify the motor output of the lumbosacral spinal cord. This study has presented that TSS has the potential to modify the state of the lumbosacral network during stepping. However, an injured spinal cord provides opportunities for more in-depth comparative studies to deduce the nature and scope of changes after SCI.

The study demonstrates that robotic torques and angle cyclograms can be informative for evaluating a patient’s progress during gait training. Additionally, we raise the awareness for and establish the impact of Lokomat parameters on gait kinematics and robotic torques, which can enrich the knowledge of rehabilitation progression when used as an assessment tool in research and clinical settings.

Acknowledgments

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