Feasibility of Hybrid Gait Training with Kinesis Overground Robot for Persons with incomplete Spinal Cord Injury

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Abstract: Hybrid actuation and control have a considerable potential for walking rehabilitation but there is a need of novel hybrid control strategies that adequately manage the balance between FES and robotic controllers. A hybrid co-operative control strategy for overground gait training with a wearable robotic exoskeleton for persons with incomplete spinal cord injury (SCI) is presented. The feasibility of the control strategy to overcome muscular stimulation electro-mechanical delay, deterioration of muscle performance over time, and to balance muscular and robotic actuation cyclic overground walking is tested in one subject with incomplete spinal cord injury (L4, ASIA grade D). The results demonstrate that the proposed hybrid cooperative control in Kinesis overground robot is able to autonomously compensate a bilateral pathologic walking pattern and the suitability of Kinesis hybrid gait training robot for conducting clinical experimentation.

1 BACKGROUND

Most therapies for rehabilitation of walking rely on the assumption that task-oriented practice promotes mechanisms of neural plasticity, muscle strength and learning of compensation strategies that increase walking ability of the person with SCI. Robotic technology holds a considerable potential to drive such interventions. Ambulatory robots, that have been developed mainly for functional compensation of walking, can offer a challenging and rich walking therapy. Furthermore, functional electrical stimulation can drive rehabilitation interventions of SCI providing several physiological and psychological benefits to the user through artificial activation of paralyzed muscles. On the other hand, robotic exoskeletons can be used to manage the unavoidable loss of performance of FES-driven muscles. Hybrid exoskeletons are then regarded as a promising approach that blends complementary robotic and neuroprosthetic technologies. The overview of the state of the art on hybrid gait systems has demonstrated that such redundant actuated solutions can produce feasible systems for accurate control of joint movement (Del-Ama et al., 2012a). Also, it has shown that diverse muscle fatigue management strategies could be applied for an effective closed-loop control of FES.

Under this hybrid scenario, the assist-as-needed control strategy has been proposed as a new redundant neuroprosthetic and robotic system that cooperates to optimize the outcome of the active control of the motion of the knee joint while providing assistance (Del-Ama et al., 2013). While various wearable exoskeletons were successful in achieving gait in subjects with incomplete SCI (Dollar and Herr, 2007), (Dollar A.M.; Herr, 2008), (Hesse et al., 2010) this has generally been proposed as a functional substitution. In this case study, we tested the feasibility of a novel hybrid gait training approach with an overground robot on a person with an incomplete SCI.

2 MATERIAL AND METHODS

2.1 Subject

Target population of Kinesis is comprised by patients whose SCI is located under the second lumbar vertebrae. The subject was a 43-year old male (75 kg. and 1.77 m. height). The subject suffered a traumatic lesion at L4 (ASIA grade D). The subject met the criteria of the target population of Kinesis, categorized as Conus Medularis (Hayes et al., 2000). The prognosis of functional recovery of walking is that the subject could walk short distances but depending on

the wheelchair for community ambulation, therefore a successful hybrid walking therapy could provide benefits to this population. The subject has a preserved hip flexion ability, partial ability to generate voluntary knee extension and is in presence of mild spasticity. The subject provided written informed consent by signing a form that was approved by the Spinal Cord National Hospital Review Board. As consequence of the accident, the patient had a limited articular range at both knees, which led to adaptation of the kinematic pattern of the left leg to meet these physical constraints. The modification consisted on increasing the stance angle to met the maximum extension angle for the left leg, and to scale the flexion-extension pattern from stance angle to 60 degrees.

2.2 Protocol

The subject participated in the hybrid gait training testing session (HGTT) to determine the feasibility of overground control of walking with Kinesis. Prior to the HGTT, the patient underwent a stimulation test and a training session. The stimulation test was employed to quantify the muscular response to the muscle stimulation and also to get the patient used to the stimulation. Within this stimulation test, both flexor and extensor knee muscle groups of both legs were stimulated for 15 minutes. Then, a training session took place in which the subject carried out learning exercises with the Kinesis system. In this training session the basic walking technique was explained to the user (bend to the side to lift the heel prior to initiate a step and then pressing a manual button). Kinesis was adjusted to the patient anthropometry within this session. Total time walking in this training session did not exceed from 10 minutes. During HGTT kinesis hybrid-cooperative controller modulated both stimulation and robotic assistance during walking.

2.3 Hybrid Cooperative Control in Kinesis

Kinesis is a hybrid robotic device that has been developed for overground gait training in incomplete spinal cord injuries. The Kinesis system is a bilateral wearable knee-ankle-foot orthosis, equipped with active actuators at the knee hinges (Maxon DC flat motor, 90W with Harmonic-Drive 100:1 gear) and a passive elastic actuator at the ankle. Force sensing resistors are employed for monitoring floor contact and custom force sensors are available to measure interaction torques. Kinesis has a PC-controlled stimulator (Rehastim, Hasomed GmbH) which delivers biphasic current-controlled rectangular pulses. Rehastim can

be pulse width and current controlled in real time. The high-level control approach to achieve a cooperative behavior comprises four main components: 1) robotic or joint controller, 2) FES controller, 3) muscle fatigue estimator (MFE), and 4) a finite-state machine (FSM) that orchestrates the FES and joint controllers. Further details on the implementation of the high-level control can be found in (Del-Ama et al., 2012b) and (Del-Ama et al., 2013). The cooperative behavior of Kinesis allows obtaining adequate and personalized stimulation patterns, estimating muscle fatigue and reducing robotic assistance during ambulatory walking. The ultimate goal is to give priority to the muscle-generated torque during gait training. A finite-state machine is employed to iteratively control the FES of knee muscles in a learning scheme during for each leg while adapting torque field stiffness for a reference kinematic pattern. In this scheme, the resulting interaction torque (with added mass and inertia of the leg) is monitored and used towards convergence of stimulation parameters. The robot modulates its assistance by reducing joint stiffness and ensuring the target flexion angle for effective swing of the leg. A muscle fatigue estimator is employed (based on the measurement of interaction torque) to trigger a fatigue compensation strategy (change stimulation firing rate). More detailed descriptions of the technique for hybrid cooperative control of Kinesis are discussed in (Del-Ama et al., 2013) and (Del-Ama et al., 2012b).

2.4 Robot Stiffness Modulation Strategy

The strategy to modulate the exoskeletal knee stiffness during cyclic walking is described in this section. The efficacy of the FES controller to generate the knee movement is inherently limited, due to the low efficiency of the force generated by the stimulated muscles and the electromechanical delay between the stimulus and the onset of joint movement. The goal of the hybrid control strategy was therefore to exploit the joint movement generated by the NP while supporting the movement through the NR. A controller was employed to provide compliant assistance to the knee, depending upon the parameter K_k, the stiffness of the force field applied around the trajectory. Modulation of K_k was executed depending on the gait phase and the contribution of the FES to the knee trajectory. Thus, gait phase and muscle contribution were managed within a finite state machine (FSM), comprised of two FSMs operating in parallel: one FSM runs in the time domain (t-FSM) while the other operates in the cycle domain (c-FSM). The t-FSM detected the main walking states and the transi-

tions among them. The c-FSM operated with discrete values, during each swing phase, that are related to performance of the stimulated muscle. This allows to uncouple the closed-loop control of stimulation from the muscle fatigue monitoring and management.

Muscle fatigue results in a decrease of muscle performance thus increasing the interaction torque. This increase can be automatically compensated with the closed-loop FES controller reducing the interaction torque.

The t-FSM modulated the force field stiffness K_k and set the kinematic pattern, depending on the walking state. The compliant behavior of the exoskeleton was achieved by controlling knee trajectory through a first order torque field imposed around the joint trajectory. As a result, the joint torque imposed by the robot depended on the deviation of the knee trajectory from the kinematic pattern and the stiffness of the torque field K_k. The width of a virtual tunnel where the knee can actually move could be adjusted along time. During stance, a high stiffness torque field was imposed to provide sufficient support and avoid knee collapse. Conversely, the supportive actions of the exoskeleton must be reduced during the swing phase to allow for the contribution of stimulated muscles and passive dynamics. The former requirement was achieved by reducing the support of the robot through a wider virtual tunnel. At the end of each swing phase, prior to contacting the floor, the robot gradually increased its support to ensure full knee extension, through a progressive increment in the force field stiffness. However, this late stiffness for foot contact is insufficient for weight support and therefore, a quick transition to high stiffness required for stance was implemented.

2.5 Biomechanical Evaluation

The analysis of feasibility was performed at the biomechanical level. We assessed the actual knee joint kinematics and stiffness during overground hybrid control of gait.

3 RESULTS

We describe the observed performance of the overground hybrid control during the first and last steps of the HGTT followed by the observed evolution in the automatic control of the stimulation of the quadriceps muscles.
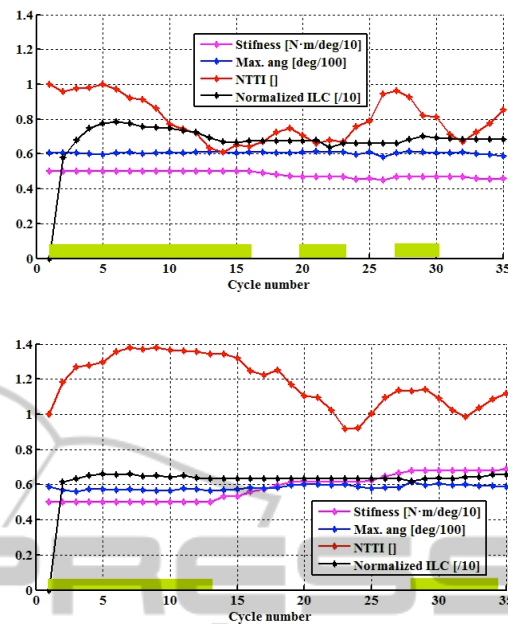

Figure 1: Results of HGTT session (cycle domain) for left (top) and right (bottom) legs. Controller stiffness (magenta curve), normalized torque-time integral (NTTI, red curve), maximum angle achieved during flexion (blue curve) and normalized stimulation intensity for knee flexor muscles (NILC, black curve) of both legs. Active learning state is represented by green boxes, otherwise monitoring state. Controller stiffness, maximum angle and normalized stimulation curves are scaled.

3.1 Stiffness Modulation Performance and FES Management

The stimulation pattern of both legs is represented in the cycle-domain (Figure 1). The NILC of the right leg reached a 60% of the maximum stimulation intensity achievable for the swing phase in the first iteration, thus reacting to the voluntary knee extension exerted by the patient. The active contribution of the patient had also an impact on the interaction forces, as shown in the Figure 1, in particular in the progressive increase on NTTI (normalized time torque integral) values along the first 7 steps.

These can be explained as a particular strategy adopted by the patient towards the robotic and neuroprosthetic assistance. After the first swing cycle, the patient reacted by increasing the active knee extension during consecutive cycles, and thus, increasing the NTTI. It is noticeable that after the learning period (cycle 14), the stiffness was automatically increased as a response to the augmented active extension, targeting 60 degrees of knee flexion (Figure 1b). After the first learning period, a decrease on NTTI is observed, explained by the stimulation effect and

patient learning. Then, until cycle 27, fatigue was detected and a new learning period took place. Conversely, the increase on the stimulation intensity for the left leg muscle was significantly slow. After the learning period was completed for this muscle, the stiffness could not be significantly reduced to accomplish the kinematic pattern.
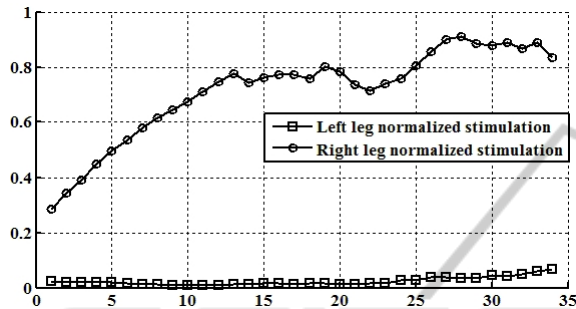

Figure 2: Normalized stimulation of the right and left quadriceps muscles during stance with hybrid cooperative control (x axis: number of steps).

Figure 2 depicts the averaged quadriceps stimulation intensity for the stance phases for both legs during the HGTT. It is noticeable the high stimulation intensity applied to the left leg, in response to a flexion posture exhibited by the patient during stance phases. Furthermore, as the experiment progressed and more steps were taken, the stimulation intensity progressively augmented until reaching a plateau (step 13).

4 DISCUSSION

The specific functional deficit of the subject lead to a limitation on the maximum (left) knee extension, which caused the patient to exert compensating actions. These compensations were effectively counteracted by the hybrid gait control. The compensating actions differed for both side and stance and swing phases of gait. During stance, on average, the patient flexed the right knee in an attempt to compensate for the flexion angle of the left knee. The robotic actuation compensated the stimulation as needed: the displayed stiffness was sufficient to provide compliant but adequate support during stance phases. We also noticed that during pre-swing phases, the subject consistently changed from flexion to extension, probably as a response to the limited range of movement of the right knee. We concluded that the hybrid cooperative control in Kinesis is able to compensate a bilateral pathologic walking pattern by autonomously increasing the stimulation of the flexor muscles and increasing the displayed stiffness of the robotic actuator.

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