Training balance recovery in people with incomplete SCI wearing a wearable exoskeleton

E.H.F. van Asseldonk[1], A. Emmens[1], T.J.H. Brug[1], I. Pisotta, M. Arquilla, F. Tamburella, M. Masciullo, N. L. Tagliamonte, R. Valette, M. Molinari, H. van der Kooij[1,3]

Abstract—**Improving stability of people wearing a lower extremity Wearable Exoskeleton (WE) is one of the biggest challenges in the field. The goal of this preliminary study was to improve balance recovery from perturbations in people with incomplete Spinal Cord Injury (SCI) assisted by a WE with specifically developed balance controller. The WE has actuated ankle and knee joints, which were controlled by using a body sway-based balance controller. Two test pilots participated in 5 training sessions, devoted to enhance the use of the robot, and in pre/post assessments. Their balance during quiet standing was perturbed through pushes in forward direction.**

The controller was effective in supporting balance recovery in both tests pilots as reflected by a smaller sway amplitude and recovery time when compared with a minimal impedance controller. Moreover, the training resulted in a further reduction of the sway amplitude and recovery time in one of the test pilots whereas it had not an additional beneficial effect for the other subject.

In conclusion, the novel balance controller can effectively assist people with incomplete SCI in maintaining standing balance and a dedicated training has the potential to further improve balance.

I. Introduction

Nowadays, there are several commercial and research Wearable Exoskeletons (WEs) that provide people with SCI with the necessary support to restore their ability to walk. The WE does not yet provide the user with support on balance maintenance. Consequently, people walking in a WE have to rely on crutches losing the possibility of using their arms and hands for other activities of daily living like carrying a cup of coffee. Adding balance control capabilities to WEs is currently one of biggest challenges in improving the use and functionality of WE.

Human balance control during stance is all about controlling the Center of Mass (CoM) movements over the base of support. In a previous study [1], we have developed a balance control strategy for an ankle WE based on the CoM related body sway. This balance control strategy generated human-like response torques to perturbations and was effective in supporting healthy subjects in maintaining balance. Here, we will extent this control strategy to also include stabilization of the knee joint and evaluate it in people with an incomplete SCI. The goal of this study was to improve balance recovery during quiet stance from perturbations in people with an incomplete SCI through training in an ankle/knee WE with this novel balance controller.

II. Materials and Methods

A. Subjects

Two male test pilots with an incomplete SCI (AIS D) participated in this experiment. The experiments were approved by the Ethical Committee of Fondazione Santa Lucia.

B. Wearable exoskeleton

The modular Symbitron WE was used [2]. This is a torque controlled WE consisting of 8 actuation modules. As it is modular it can be configured to the patient's needs. Since subjects with a good voluntary control of their hip joints were enrolled, we used only two modules for each leg to actuate knee flexion/extension and ankle plantar/dorsiflexion. The WE is controlled using EtherCAT. The EtherCAT Master runs on a computer in a backpack. This master communicates with the custom-made EtherCAT slaves in each of the actuation modules. During the training, subjects did not wear the backpack.

The WE was used to assist subjects in balance recovery from perturbations. This was achieved by a body sway-based control strategy (PD_{CoM}). Body sway is defined as the angle between the line from the CoM to the ankle and the vertical. The desired ankle torque ($\tau_{A,d}$) was the same for both ankle joints and was computed from a PD control law using the body sway θ_{sway} as input.

$$\tau_{A_d} = P_A\left(\theta_{sway_d} - \theta_{sway}\right) + D_A\left(\dot{\theta}_{sway_d} - \dot{\theta}_{sway}\right) \quad (1)$$

where P_A and D_A are proportional and derivative gains respectively and the subscript d indicates desired.

The controller for the knee joints tries to keep the knee stretched by using a PD control law with the knee angle as input.

$$\tau_{K_d} = P_K\left(\phi_{K_d} - \phi_K\right) + D_K\left(\dot{\phi}_{K_d} - \dot{\phi}_K\right) \quad (2)$$

[1] Department of Biomechanical Engineering of University of Twente, Enchede, The Netherlands (e.h.f.vanasseldonk@utwente.nl).

[2] Laboratory of Robotic Neurorehabilitation, Neurorehabilitation 1 Department, Fondazione Santa Lucia, Rome, Italy). [3] Department of biomechanical Engineering, Delft University of Technology, Delft, The Netherlands.

where ϕ_K is the knee angle, and P_K and D_K are proportional and derivative gains, respectively.

The gains were tuned for each test pilot in a separate session taking into account the pilot's feedback.

C. Protocol

Both subjects participated in 5 training sessions and pre/post assessments. During all the sessions, the test pilots received forward pushes while standing at the level of the sacrum by using a push stick equipped with a force sensor (FUTEK LCM 300, FUTEK Advanced Sensor Technology Inc, Irvine, USA). Test pilots were instructed to recover balance without taking a step. The experimenter giving the pushes varied the push force between 70 and 100% of the maximal push force that the test pilot could withstand. In each training session, tests pilots received pushes for 10 minutes with a resting time of about 5 s between pushes. In each assessment session, test pilots received 40 pushes when the WE was controlled with the PD_{com} and 40 pushes when the WE was controlled in minimal impedance mode.

D. Data analysis

Body sway was calculated using the estimated orientation of the different body segments obtained using the encoders in the exoskeleton and two MTx IMUs (Xsens Technologies B.V., Enschede, the Netherlands) placed on the right thigh and trunk. From the body sway, two outcome variables were derived. First, the body sway amplitude was defined as the maximal deviation in body sway in response to the push. Second, the recovery time (r.t.) was defined as the time needed to get the body sway velocity back below 0.015 rad/s.

III. Results

In the pre-test, we evaluated whether the use of the novel PD_{com} assisted in counteracting the perturbations. Both test pilots showed an improved ability to recover after the pushes as reflected in a smaller r.t. and sway amplitude when the PD_{com} was used compared to the case minimal impedance controller was used (see Fig. 1).

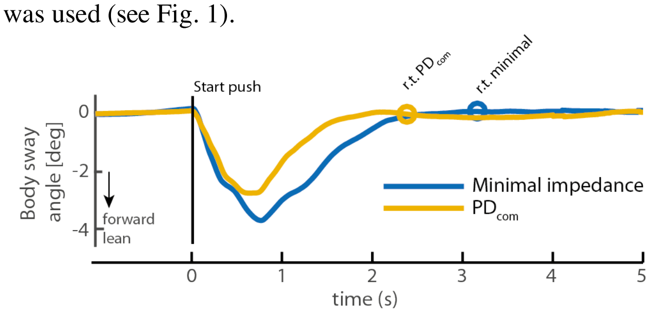

Fig. 1. Body sway angles in response to forward pushes for test pilot 1 during the pre-assessment for two different WE controllers. Lines are averaged trajectories across pushes with the same amplitude. The marker indicates the average recovery time (r.t.).

Training for five sessions with the WE controlled with PD_{com} resulted in a further improvement of the ability to withstand the push perturbations in one of test pilots (as depicted in figure 2) but not in the other one (not shown here). For test pilot 1, the sway amplitude further decreased from the pre-assessment to the post-assessment. As the WE ankle torque was directly dependent on the sway, this decrease in sway was accompanied by a reduction in the WE ankle torques. This indicates that the reduced sway can be attributed to the test pilot who learned how to better counteract the perturbation with the aid of the WE.

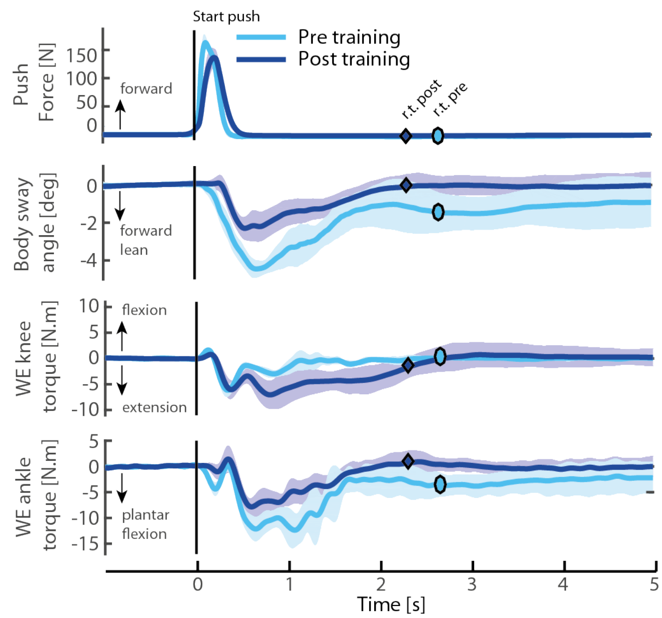

Fig. 2. Push force, body sway and torques exerted by the WE in response to forward pushes for test pilot 1 during the pre and post assessments. In both tests the WE was controlled with PD_{com}. Lines are averaged trajectories across pushes with the same amplitude and shaded areas indicate the standard deviation.

IV. Conclusions

The novel PD_{com} results in torques that are effective in assisting people with an incomplete SCI to counteract push perturbations during quiet stance. Training with PD_{com} has the potential to further improve the ability to withstand perturbations. Future studies will focus on extending the balance controller to the hip such that we can investigate whether people with a complete SCI can be supported during balance tasks.

Acknowledgment

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References

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