Improving the Standing Balance of People with Spinal Cord Injury Through the Use of a Powered Ankle-Foot Orthosis

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Abstract In this study, our goal was to improve the standing balance of people with a Spinal Cord Injury (SCI) by using a powered Ankle-Foot orthosis acting in the sagittal plane. We tested four different controllers on two SCI subjects that have a lesion at a low level. In the experiments the subjects repeatedly had to recover from pelvis perturbations, while receiving ankle assistive torques from the orthosis. We found that the controllers that use centroidal dynamics as input parameters were able to provide proper support to the subjects after a perturbation had been applied, even though they worked against the subjects after they had recovered from the perturbation. These preliminary results show the potential of balancing controllers that operate in Center of Mass-space.

1 Introduction

For people with a spinal cord injury (SCI) who lack ankle motor control, maintaining balance during standing can be difficult, if not impossible. When properly controlled, exoskeletons could help to improve the standing balance of these paraplegics. For people that have an injury at a low level, but who still have hip function, an ankle-foot orthosis (AFO) may already provide sufficient support.

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Our goal is to improve the standing balance of people with a SCI by using a powered AFO. In this case study, we test standing balance in the sagittal plane using various balance controllers, that operate in Center of Mass (CoM) space or joint space. We have implemented these controllers on the Achilles AFO [1] and compared their balancing performance.

2 Materials and Methods

Two subjects that have a SCI participated in the balance experiments. Their characteristics are shown in Table 1.

The experimental setup consisted of the Achilles exoskeleton; a robotic pusher able to provide systematic perturbations on the trunk [2]; three inertial measurement units (IMUs) placed at the lower leg, the upper leg and the back of the subject; force plates; and a safety harness. Figure 1 shows an overview of the setup.

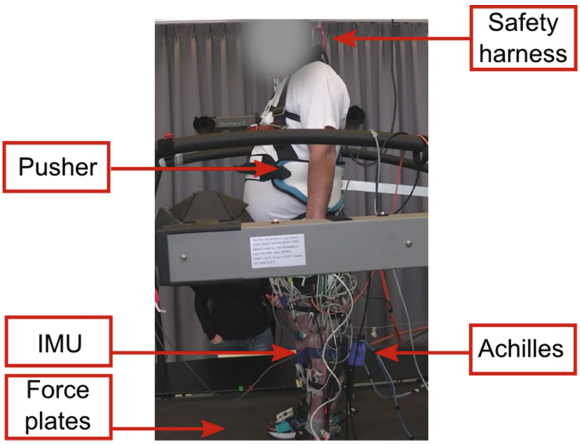
Ethical approval for the experimental protocol was given by the ethical board of Fondazione Santa Lucia, Italy. In the experiments, subjects had to maintain their standing balance, without stepping, while receiving pushes on the pelvis from the pusher. Each subject tested the following controllers:

- a Zero-Impedance controller (ZI) (tested twice)
- a fixed ankle stiffness (Pankle)

Table 1 Test pilot characteristics

Subject code	Sex	Mass (kg)	Height (m)	Lesion level	ASIA
S02	M	71	1.65	C7	D
S03	M	80	1.78	L3	D

Fig. 1 Experimental setup



- a PD-controller on the CoM (PDCoM) that controls the CoM to a reference location.
- a Momentum-based Controller (MBC) that tries to find joint torques such that a certain desired centroidal momentum is obtained [3, 4]. By optimization, torques are found that satisfy constraints on the center of pressure (CoP), joint angle limits and limit torques.

In each trial, one of the controllers was tested and three different perturbation sizes were applied by the pusher: $0.02Mg$ (N), $0.08Mg$ (N) and $0.14Mg$ (N), where M is the mass of the subject and g the gravitational constant. Each perturbation was repeated seven times in one trial, or less when subjects got tired before all perturbations were applied.

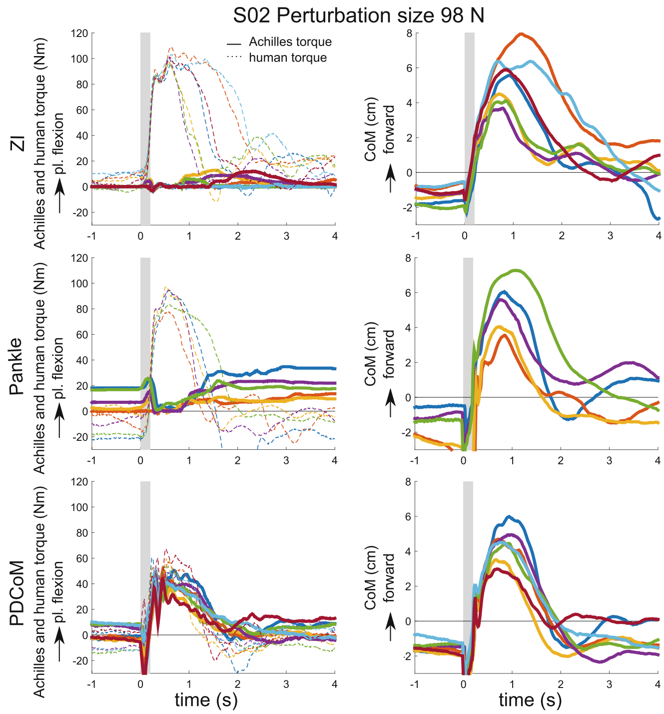
Using the force plates, the torque generated by the subject was estimated and compared to the torque delivered by the Achilles, to evaluate the supportive effect of the Achilles. Furthermore we estimated the CoM based on the IMU data to check when the subjects had restored from a perturbation, that is, when the CoM returned to a steady state.

3 Results

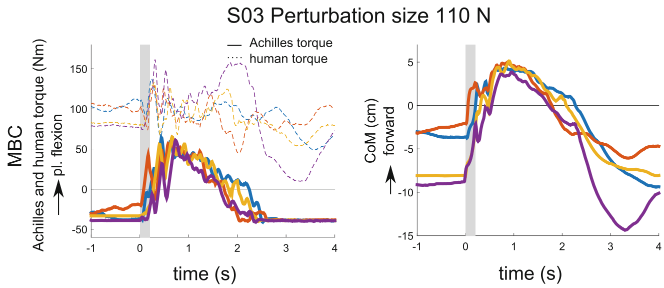
Figure 2 shows that in the PDCoM trial, and to lesser extent in the MBC trial, an assistive torque is applied by the Achilles after the onset of a perturbation. The torque induced by the subject in the PDCoM trial is then reduced compared to the ZI case, while the total ankle torque is similar to that in the ZI trial. This means that the subject could supply less ankle torque to maintain balance, because the Achilles was helping. Figure 2a also shows that the Pankle controller only gives a small support torque shortly after a perturbation is applied and the subject needs to provide most of the balancing torque himself. The time it takes for CoM to return to a steady-state value after a perturbation is similar for all three controllers in Fig. 2a, indicating that the balancing performance is also similar. Strikingly, Fig. 2b shows that before the perturbation is applied and after the subject has recovered from a perturbation (stationary state), the torques delivered by the Achilles and the subject have opposite sign, which means that they work against each other.

4 Discussion

We found that the PDCoM and MBC could provide a support torque to the subjects, so subjects did not have to apply all the ankle torques necessary for balancing themselves. Although we could not make a clear distinction between the balancing performances of the different controllers, this is a promising results, because these controllers could be beneficial for e.g. people with a SCI that are not able to supply



(a)



(b)

Fig. 2 *Left*: torque delivered by Achilles vs. the torque delivered by the subject and *right*: corresponding CoM trajectories. *Each line in the figure* represents a response to the largest perturbation size. The perturbation time is indicated with the *grey box*. **a** Responses of subject S02 in case of the ZI, Pankle and PDCoM trial. Not enough data was available of the large perturbation responses in the MBC trial. **b** Responses of subject S03 in case of the MBC trial

all the balancing torques themselves. Ideally, the Achilles complements the torque provided by the subject, but we found that the Achilles in some cases works against the subject. This occurs because the PDCoM and MBC try to bring back the CoM to a certain desired location (measured in a static pose). When this location is different from the instantaneous desired CoM location of the subject, as is the case in Fig. 2b shown by the difference between the stationary CoM value and zero, he needs to counteract the Achilles torque. It may not be obvious to subjects that changing their CoM location can reduce the opposing torque. In that sense, it would be better to let subjects practice with the controllers first. It is the first time that these controllers are implemented on an AFO and we expect that the problem of the undesired counter-action can easily be solved in next iterations by not defining a desired CoM location, but a desired range within which the CoM must return and by resetting this range when a new steady-state value is measured.

5 Conclusions

We implemented various controllers on the Achilles AFO to improve the standing balance of subjects with a SCI. We found that the controllers working in CoM-space were able to provide support torques to help subjects balancing. This could particularly be useful for paraplegics that can generate little ankle torques themselves. In future work we will improve the balance controllers, based on a centroidal dynamics analysis of standing balance in healthy subjects and extend the controllers to an exoskeleton with more actuated degrees of freedom.

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