# LOWER LIMB EXOSKELETONS: POSTURAL EQUILIBRIUM ENHANCEMENT AND PATIENT COMPLIANCE

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## Introduction

Exoskeletons allowing a complete support of body weight from the bottom have been recently designed for application in rehabilitation. An ideal exoskeleton should provide postural stability, while allowing patients practicing postural and gait tasks.

*Postural equilibrium enhancement* is directly related to the ability of the system to control posture and balance. This occurs through the control of zero moment point (ZMP, corresponding to the centre of pressure), i.e. the joints are controlled to keep the ZMP inside the base of support of the subject.

*Patient compliance* is the ability of the exoskeleton to content the efforts of the patient. Compliance is obtained through mechanical admittance control. In this way, the exoskeleton adapts to the efforts of the patients and acts as a haptic device.

This study describes preliminary results obtained in the design of the control of a lower limb exoskeleton for rehabilitation purposes, presenting simulations of postural tasks obtained combining postural equilibrium enhancement and patient compliance controls.

## Materials and Methods

The exoskeleton has been designed to maintain the controlled degrees of freedom at a minimum: 3 in the sagittal plane (one for each pairs of hips, knees, ankles) and 2 in the frontal plane (one for each hip) (Fig. 1A). Therefore, in the frontal plane, the control is under-actuated (i.e., the ankles are free). The exoskeleton will not allow gait but in place activities, as for example sit-to-stand (Fig. 1B), body weight transfer and lifting one foot (Fig. 1C), stepping (Fig. 1D).

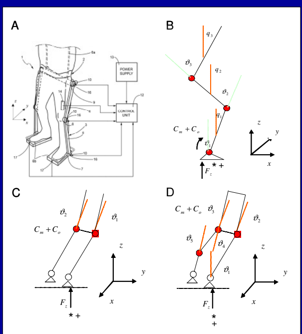


Fig. 1. A: Schematic view of a lower limb exoskeleton. B: coordination in the sagittal plane during the stand-to-sit-to-stand task. C: coordination in the frontal plane during weight transfer and foot lift. D: coordination while stepping on the spot. Red circles represent the joints actuated in each task. Fz, ground reaction forces; Cm and Co, motor and patient torques; q1, q2, q3, inertial angles of the segments of the body; theta1, theta2, theta3, joint angles; red and green line represent the zero reference of joint angles; +, the projection of the centre of gravity on the ground; *, the position of the zero moment point.

The control of the exoskeleton is achieved in two steps (Fig. 2):

1. a *preview trajectory* (reference signal), *open-loop* generated, nominally satisfies the condition of keeping the ZMP within the base of support.

2. a *closed loop* introduces perturbation on the nominal joint position in order to maintain equilibrium in the presence of uncertainty. This control relies on two stages:

*2.1. postural equilibrium enhancement* obtained by real-time measurement of:

- 2.1.1. ZMP from pressure sensors under the feet
- 2.1.2. joint angles from motor shaft positions
- 2.1.3. estimate of COG from joint angles

*2.2. patient compliance* through mechanical admittance control using EMG signals.

Modern multivariable robust control theory has been adopted for combined joint position tracking and patient compliance: the so-called two degree of freedom control. To guarantee stability in a strongly nonlinear environment, COG-Jacobian and Lyapunov techniques are used to control ZMP in real-time.

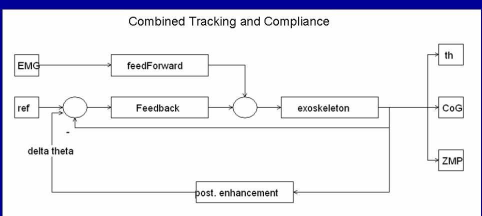


Fig 2. Combined 1) tracking and compliance control from theta and EMG (inner loop) and 2) postural equilibrium enhancement through ZMP measure and COG calculation (outer loop).

## Results

Figures 3, 4, 5 show examples of simulation of postural tasks with and without activation of the postural equilibrium enhancement module.

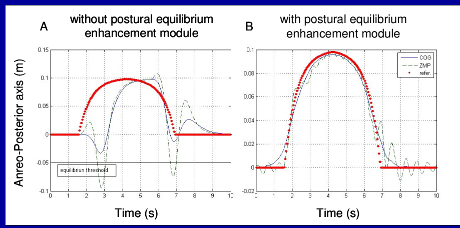


Fig. 3. Simulation of a stand-to-sit-to-stand exercise (see Fig. 1B) without (A) and with (B) activation of the postural equilibrium enhancement module. The displacement of COG along the sagittal axis is shown simultaneously to the displacement of ZMP; in red the reference trajectory. A: when the postural control is deactivated, the subject falls backward because of improper trajectory planning of the joints. In fact, ZMP crosses the equilibrium threshold given by the heel (5 cm posteriorly to the ankle, arbitrarily given 0 cm). B: when the postural control is active, the subject displaces smoothly the COG forward and backward.

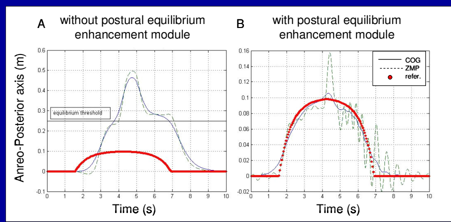


Fig. 4. Simulation of a stand-to-sit-to-stand exercise (see Fig. 1B) without (A) and with (B) activation of the postural equilibrium enhancement module in a patient with impairment of leg muscle control. A: when the control at the ankle by the patient is lost, the subject falls forward. In fact, ZMP crosses the equilibrium threshold given by the big toe (25 cm anteriorly to the ankle, arbitrarly given 0 cm). B: when the postural control is active, the subject smoothly displaces the COG forward and backward. ZMP shows perturbations due to the action of the control to counteract the failure of the ankle. Same labels as in Fig. 3.

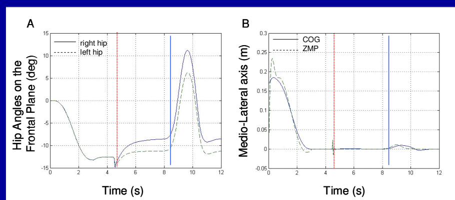


Fig. 5. Simulation of weight transfer followed by a transition from double to single stance (see Fig. 1C) and concluded with a postural perturbation to the ankle. A: from the beginning of the acquisition to the red vertical line, the subject is transferring body weight from one limb to the other through movements of both hips. The vertical red line indicates the instant when the under-actuated control is enabled to maintain equilibrium on one foot. At the vertical blue line, a destabilizing torque is delivered to the ankle. The control, guaranteeing dynamic stability, automatically reacts acting only on the hips. B: displacement of COG (continuous line) and ZMP (dashed line) along the medio-lateral axis with reference to the ankle of the supporting foot (arbitrarily set at 0 m in the medio-lateral axis). At the beginning of acquisition, the subject is standing symmetrically on both limbs, and COG corresponds to the median axis of symmetry of the body, i.e. at about 18 cm from the supporting limb. It is shown that the control system is able to minimize the perturbation of COG along the medio-lateral axis (vertical blue line).

## Conclusions

Biped robotics technology and modern multivariable control theory can be adopted to control a lower limb exoskeleton to offer enhanced postural equilibrium and patient compliance. Simulations have shown that the postural equilibrium enhancement control system is able to reduce to a minimum perturbations induced by patient's impairment in programming a movement or in activating leg muscles.

Considering the exoskeleton as a simple aid for in place activity, different exercises involving a limited number of controlled degrees of freedom can be conceived. These exercises can be performed just acting on the stiffness of the controlled ankle, knee and hip.

Using a lower limbs exoskeleton with a 5-degree of freedom (Fig. 1A), three groups of exercises, usually performed in rehabilitation settings, can be performed:

1. coordination in the sagittal plane: forward and backward leaning using ankle and/or hip strategy, stand-to-sit and vice versa, far forward reaching (Fig. 1B)

2. coordination in the frontal plane (Fig. 1C) with underactuated control: weight transfer using a hip strategy, passing from double to single stance

3. stepping on the spot (Fig. 1D), mixing movements in the sagittal and frontal planes, transferring body weight along a medio-lateral and posterior-anterior direction as occurs during the preparative phase of stepping forward.