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 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 pair 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 transfer and lifting one foot (Fig. 1C), stepping (Fig. 1D).

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.

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

Conclusions
Biped robotics technology and modern multivariable control theory can be adopted to control a lower limb exoskeleton to enhance 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 limb 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.