

Towards Crutch-Free 3-D Walking Support with the Lower Body Exoskeleton Co-Ex: Self-Balancing Squatting Experiments

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Abstract—In this paper, we succinctly present the hardware properties and capabilities of the lower body exoskeleton Co-Ex, which was developed to attain self-balancing and crutch-free walking support for those experiencing ambulatory difficulties in general. To provide full 3-D walking support while containing the number of required actuators, it includes 4 active joints per leg. Custom-built series elastic actuators enable the torque sensing and controllability at each joint, enhancing the robot’s physical interaction capabilities. While limiting the number of active joints minimizes the weight and energy requirements, the underactuated leg configuration increased the computational load. The preliminary squatting experiments revealed that Co-Ex may provide crutch-free 3-D movement support.

I. INTRODUCTION

Robot-aided walking support and rehabilitation enabled various patients with gait disorders to regain ambulatory functionality. The recent advances in lower body exoskeleton technology allowed a significant leap to ensure safe and dependable walking support, particularly for SCI patients. A great majority of SCI walking support exoskeletons have 2 active joints per leg to support hip and knee joints through the F/E (Flexion/Extension) axis [1]. While such a configuration significantly simplifies the hardware, users must engage their upper bodies via crutches to achieve static balancing.

An active ankle D/PF (Dorsi/Plantar Flexion) joint is definitely required for balancing in the sagittal plane. With this addition, Morimoto et al. developed the lower-body exoskeleton XoR, which can provide *crutch-free* sit down & stand up rehabilitation and can actively reject disturbances in the sagittal plane [2]. In a recent example, Harib et al. developed a fully-actuated lower-body exoskeleton named Atalante, which possesses 6 active joints per leg [3]. This impressive *wearable humanoid* is a great achievement as it was able to fully support SCI patients with no need for crutches.

Although the solution provided by Harib et al. [3] solves the issues related to upper body engagement, the equipment of 12 active joints causes hardware complexity problems. Unlike the case of humanoids, the placement of motors and

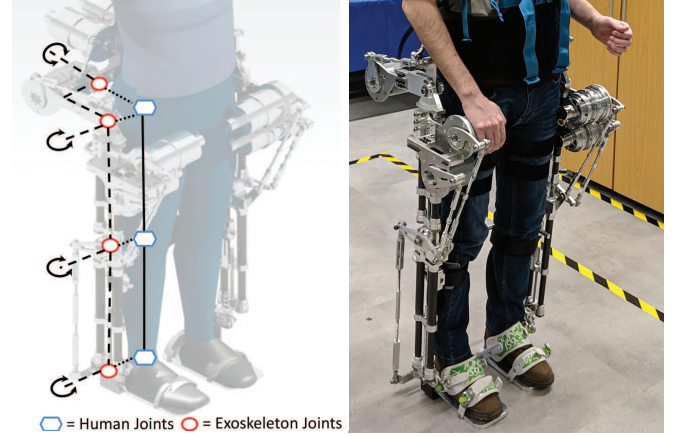


Fig. 1. Left: The joint configuration of a leg. Each leg contains 4 DoF: a 2 DoF hip joint, a knee joint, and an ankle joint. Right: the actual exoskeleton with an able-bodied user.

sensors are quite challenging. Another major concern appears to be power requirement and energy autonomy. All these issues raise several questions: Do we really need to place 6 active joints per leg? What is the minimum number of active joints to achieve crutch-free 3D walking support?

In addition to knee and hip F/E joints, which are included in conventional exoskeletons, an active ankle joint along the D/PF axis is necessary for balancing [2]. Furthermore, the study in [4] suggested that a hip joint along the A/A (Adduction/Abduction) axis is essential in 3D walking to achieve lateral swaying. Combining these pieces of information, we built an exoskeleton with 4 active joints per leg to see to what extent 3-D walking support can be provided [5], [6]. The rest of the paper is organized as follows: In section II, our methodology is succinctly explained. The paper is concluded in section III with further discussion.

II. METHODS

A. Hardware of Co-Ex

The lower body exoskeleton Co-Ex is a torque-controllable system, actuated via custom-built series elastic actuators with a high torque-to-weight ratio (94/2.45 Nm/kg). Each leg contains 4 DoF (Degrees of Freedom), namely, a 2 DoF hip joint that can rotate along with the A/A and F/E axes, a 1 DoF F/E knee joint, and a 1 DoF D/PF ankle joint. To improve usability and to reduce leg inertia, all actuators are gathered around the waist. A series of 4-bar mechanisms are

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used to transmit torque. Fig. 1 illustrates the actual robot and its joint configuration.

The robot is equipped with an IMU (Lord 3DM-GX5-15 VRU) at the pelvis. A group of distributed force sensing elements (Interlink FSR UX 406) is placed at each foot sole to provide vertical force and center of pressure information. Furthermore, SEA units at each joint can provide real-time torque measurement with a torque resolution of 3.93 mNm. The main controller comprises an Intel Coffee Lake i5 9600K 3.7GHz CPU including an 8 GB DDR4 RAM, and a Samsung 250 GB 860 Evo SSD storage device. It runs on a 64-bit GNU/Linux operating system with an RT-Preempt patch enabled Linux kernel. Data communication is performed via a custom-built real-time Ethernet protocol.

B. Control of Co-Ex

1) *Torque Control*: SEA units in each joint are torque-controlled for improved performance, allowing transparency (zero torque mode + gravity compensation) and high fidelity force/impedance control. The sliding mode observer method was employed and as a result, torque control bandwidth was measured to be 19 Hz implying that high frequency inputs may be tracked well.

2) *Locomotion Control*: Due to the underactuated leg configuration, the locomotion control has to include an optimization algorithm that sorts the tasks depending upon their priority levels. For instance, the CoM (Center of Mass) trajectory is given a higher priority compared to torso orientation, as it has a pivotal role in maintaining the balance. The algorithm ensures that the tasks with lower priority do not tamper with the tasks with higher priority.

Walking planning is based on the weighted combination of centroidal momentum and ZMP (Zero Moment Point). The ZMP feedback was achieved using the ZMP impedance method that minimizes ZMP error by means of virtual spring dampers that reside at the feet sole. The centroidal angular momentum was attained via measured contact forces and the dynamic model of the robot. Compared to the classical ZMP-based approach, we could obtain more robust locomotion performance through the combination of centroidal momentum and ZMP feedback controllers. [6].

In our preliminary experiments, the Co-Ex exoskeleton performed self-balancing squatting motion where it moves vertically 15 cm and horizontally 6 cm. The movement frequency was approximately 0.15 Hz. The actual ZMP is displayed in Fig 2. As observed in this figure, ZMP is always within the support polygon, indicating dynamic balance.

III. DISCUSSION

Walking simulation results indicate that crutch-free 3D walking is technically possible with a lower-body exoskeleton with 4 active joints per leg [6]. We argue that the proposed exoskeleton may enable SCI patients to receive hands-free walking support while containing the overall weight, cost, and complexity with relatively improved energy autonomy.

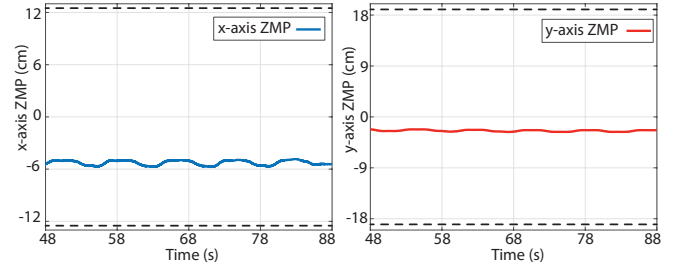


Fig. 2. Self-balancing squatting experiment, actual ZMP.

The same initial results also suggest certain problems to be addressed. As each robot leg has only 1 active joint along the A/A axis, the lateral CoM swaying can be achieved with certain contributions from the torso. While our locomotion controller outputs the optimal joint trajectories given the stack of prioritized tasks, the torso oscillation was observed to be ± 10 degrees. Therefore, the robot could walk in a similar fashion to that of Trendelenburg gait. Thus, particular research questions emerge: Could this problem be solved via a passive joint at the waist area? Could it affect user acceptance?

Another issue is that the underactuated nature of the robot requires an optimization algorithm to prioritize multiple tasks that cannot be collectively achieved. Combining with other full-body controllers, e.g., centroidal momentum, the computational load increases significantly. In our case, the whole computation was completed within 0.7 ms. Although the main controller frequency could go as high as 2 kHz, we had to set it to 1 kHz, thus comprising the controller performance.

In this paper, we reported balanced squatting & swaying experiments where the actual ZMP was within the support polygon. Currently, the walking experiments with dummy load are being conducted and initial tests will be finalized soon. We will report crutch-free 3D walking experiments in our next paper.

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