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A new 3D center of mass control approach for FES-assisted standing: First experimental evaluation with a humanoid robot

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ABSTRACT

This paper proposes a new control framework to restore the coordination between upper (functional) and lower (paralyzed) limbs in the context of functional electrical stimulation in completely paraplegic individuals. A kinematic decoupling between the lower and upper limbs controls the 3D whole-body center of mass location and the relative foot positions by acting only on the lower-limb joints. The upper limbs are free to move under voluntary control, and are seen as a perturbation for the lower limbs. An experimental validation of this paradigm using a humanoid robot demonstrates the real-time applicability and robustness of the method. Different scenarios mimicking the motion of a healthy subject are investigated. The proposed method can maintain bipedal balance and track the desired center of mass trajectories under movement disturbances of the upper limbs with an error inferior to 0.01 m under any conditions.

1. Introduction

Spinal cord injuries (SCI) are a frequent cause of disability and may result in the total or partial obstruction in the flow of both sensory and motor information below the level of the lesion [40]. In other words, the central nervous system (CNS) does not receive sensory feedback from body areas below the lesion level, and is unable to control muscles in these areas. Beside limited independence, individuals with paraplegia due to SCI face numerous medical problems, such as the loss of bone calcium, reduced bone density, urinary tract infections, spasticity, poor control of blood pressure, pressure sores, and/or muscular atrophy. As well as reducing medical problems [28], the standing posture greatly improves the quality of life of wheelchair-bound individuals [12,40]. Using functional electrical stimulation (FES) to restore motion in paralyzed limbs has the potential to provide both therapeutic and functional benefits [8,15,28,40]. However, fatigue occurs rapidly during FES-induced muscle contractions, reducing the duration of functional movement. Moreover, most FES-assisted systems for the control of standing provide open-loop stimulation of the knee extensors. Open-loop control cannot take into account changes in internal parameters, such as a loss of muscle force caused by fatigue or voluntary motions of the upper limbs, and cannot control the balance of a person with SCI [28].

To improve the efficiency, robustness, and adaptability of FES-assisted standing, closed-loop control approaches have been proposed [1,30]. In the literature, two types of control variables are considered: local and global variables. Local variables such as the angular joint position [41] or the joint stiffness [18] are defined at each joint level, i.e. in the joint space, and do not consider the multi-body nature of the human body. Global variables such as the trunk Cartesian acceleration or the 3D whole-body center of mass (CoM) position [21,46] focus on realizing a task such as maintaining balance rather than tracking a desired joint angle. Controlling a global variable could compensate for the loss of force in a particular joint, e.g. because of fatigue. An FES system would still benefit from tracking the desired joint angle as accurately as possible. However, tracking errors could be corrected in Cartesian space. In addition, the desired trajectory of a Cartesian variable could be designed to distribute the joint torques over different muscle groups, thus reducing the fatigue of each muscle. In healthy subjects, three strategies have been identified for minimizing fatigue and discomfort during prolonged standing [10]. These can be observed by analyzing the whole-body CoM trajectory. These strategies are to shift the CoM from one foot to another, modify the CoM position slightly followed by a return to the initial position, and the slow continuous displacement of the CoM. Inspired by CoM movements during prolonged standing in healthy

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humans, it is probably possible to artifficialy generate the desired Cartesian CoM trajectory to decrease overall muscle fatigue and discomfort. However, tracking whole-body Cartesian variables with a reduced number of degrees of freedom (DoFs) (as only the lower limbs are under FES control) and ensuring dynamic balance is not an easy task. As shown in the next section, the field of humanoid robotics could inspire the development of such a control law.

Validating a closed-loop control system with human subjects is a long-term objective. Ensuring the safety of FES systems used by humans is of crucial importance. A closed-loop system can, by definition, become unstable, and thus requires its gains and adaptive saturations to be carefully tuned.

The optimal analytic value of the control gains is difficult to obtain, as the targeted closed-loop systems are highly nonlinear and the model parameter values are usually incorrect. The geometrical and inertial parameters of body segments are usually estimated from population-averaged anthropometric tables. Dealing with pathological population anthropometric tables, which are not subject specific, can lead to very inaccurate estimates of the joint kinetics [42]. Consequently, control gains are usually tuned experimentally. However, the fine-tuning of the gains is difficult, as humans cannot reproduce the exact same motion repeatedly. The simulation of human motion is a good solution for pre-tuning the control parameters and validating a new method. However, when simulating a complex 3D whole-body motion, numerous parameters need to be set and strong assumptions must be made. For example, estimating the force distribution during a bipedal stance remains an open issue. To simplify the validation process, before performing the necessary experiments with human subjects, several groups have used humanoid robots to evaluate compliant assistive devices [34] or validate the human behavioral model [5]. The results indicate the possibility of using these dynamically unstable anthropomorphic structures, with their ability to reproduce the exact same motions and their numerous embedded sensors to normalize the analysis of assistive devices [34]. In this context, the feasibility of using a closed-loop real-time system to control a Cartesian variable using only the lower limbs was initially assessed using a humanoid robot as an experimental validation platform. The contributions of this study are following:

- We develop a theoretical framework that decouples the upper and lower limbs to control the balance of a paraplegic individual.
- We describe the control of the 3D whole-body CoM to maintain balance using the lower limbs only and
- We present the results of an experimental validation of the proposed approach with a humanoid robot.

The remainder of this paper is structured as follows. Section 2 gives an overview of closed-loop systems for controlling the standing posture used in the field of human rehabilitation and humanoid robotics. Section 3 describes the proposed global approach to assess FES-assisted motion in people with complete SCI. Section 4 presents a theoretical framework of the kinematic decoupling between lower and upper limbs, which aims to control the standing position of a person with paraplegia through FES applied to the lower limbs. The results of an experimental validation using a humanoid robot are presented and discussed in Section 5. Concluding remarks are given in Section 6.

2. Related work

Closed-loop approaches for controlling standing in subjects with paraplegia using FES has been a topic of research for more than 25 years. While standing, the human body has often been modeled as a single [14,16,17,36], double [32,33,45], or triple [24,25] inverted pendulum. However, before a practical system for paraplegic standing can be used by patients, some critical limitations in the above-mentioned models need to be addressed. These models assume a perfectly planar motion, i.e. the motions of the legs are symmetrical and there is no motion in the medio-lateral plane. As these assumptions are partially incorrect [26], Kim et al. proposed a 3D lower-limb model articulated by 12 DoFs. This 3D model was used in a simulation study to show that FES-assisted arm-free standing is possible using a proportional-derivative (PD) controller in the joint space. The authors showed that, if only six of the twelve DoFs in the lower legs were actively controlled, a standing posture could be achieved for a couple of seconds, despite possible disturbances [26,46]. A PD controller was also used by Nataraj et al. [38] in a simulation study with the aim of driving a neural network. This neural network was trained to produce an activation pattern for 16 different muscle groups so as to minimize the shoulder forces required to stabilize the human body against disturbances while standing. The same group performed another simulation in which proportional feedback from the whole-body CoM acceleration was used to train a neural network to produce a muscle activation pattern for 58 trunk and lower-limb muscles. The desired human posture was the most erect one corresponding to the highest vertical CoM position with zero CoM acceleration. Proportional gains were optimized to minimize the shoulder forces required to stabilize the human body against disturbances [39].

The approaches described above focus on the control of individual joints without taking into account the voluntary motions of the person, which might jeopardize the whole-body balance. By controlling the 3D whole-body CoM position in Cartesian space, the voluntary motions under CNS control could be taken into account. These considerations led our group to propose a solution inspired by humanoid robotics based on the control of the 3D whole-body CoM position [21].

The control laws proposed by the humanoid robots community can be classified as joint space and global space approaches. Joint space control typically uses reference joint trajectories, which are computed through optimization processes [29,43] or captured human motions [27,35]. Global space control, derived from the work of Nakamura [37] and its extension to the general case by Siciliano and Slotine [44], uses a reduced set of control variables in the global space [13].

Optimization-based joint space control strategies require an accurate model of the robot and its environment, leading to a high computational cost, whereas the use of captured human joint trajectories implies a reshaping between the different kinematic structures. In contrast, global space control variables have a lower computational cost and produce human-like desired trajectories without any kinematic reshaping. For these reasons, the global-based control approach was used in this study.

3. Motion assistance in SCI using FES: coordinating upper and lower limbs

As represented in Fig. 1, when dealing with FES assistance in persons with paraplegia, two concurrent controllers act in parallel. The first corresponds to the subject's voluntary control acting on the upper limbs, shown in blue in Fig. 1. This controller performs without any sensory feedback from the paralyzed lower limbs of the body. The second controller, represented in yellow in Fig. 1, corresponds to the artificial FES controller acting on the lower limbs [2,3]. Obviously, these two controllers are mechanically coupled. Thus, the artificial FES controllers for the lower limbs should be designed to take into account the actions of the upper limbs. This can be done by controlling a global variable in the Cartesian space. In a previous study, we demonstrated the importance of synchronizing the motion of the upper limbs with the artificial controller of the lower limbs to minimize the arm participation