34th Annual International Conference of the IEEE EMBS
San Diego, California USA, 28 August - 1 September, 2012

A Paradigm for the Control of Upright Standing in Paraplegic Patients

J. Jovic, V. Bonnet, C. Azevedo-Coste *Member, IEEE*, and P. Fraisse *Member, IEEE*

Abstract— **The objective of this paper is to present a new paradigm in control strategy for unsupported paraplegic standing, based on closed-loop control of paraplegics' lower extremities. The main advantage of our approach is taking into account voluntary motions of the upper-part of the body by controlling Center of Mass (CoM) position. The validity of our approach is tested, in computer simulations, using human CoM trajectories estimated from experimental data and by applying perturbations in simulation during quiet standing in order to simulate voluntary upper body movements. From the results presented in this study it can be seen that controller is able to track desired CoM position with sufficient precision and to maintain stability even in the presence of simulated movements of the upper body.**

I. INTRODUCTION

The application of Functional Electrical Stimulation (FES) for the purpose of quiet standing of individuals suffering from SCI is well documented topic [1]-[7]. Majority of the FES-assisted system provides open-loop stimulation of the knees extensors [1]. Even though this type of stimulation is commonly used in clinical practice, there are several limitations such as muscle fatigue or the fact that the arms of the patient are engaged in maintaining standing posture which makes standing nonfunctional.

Therefore, many research groups worked on restoring “arm-free” standing by means of closed-loop FES-assisted systems [2]-[7]. The control of the ankle joint was specially investigated since ankle strategy has been identified as the most relevant in standing of healthy subject [8]. Jaeger has used a single inverted pendulum in combination with a classical proportional integral derivative controller to investigate arm-free FES-assisted standing [3]. Khung and Zajac used a planar three Degrees Of Freedom (DOF) model which includes muscle properties. The algorithm they have developed calculates muscle activation which would enable standing posture and minimize energy expenditure [3]. Matjacic et al. have used a double inverted pendulum model and demonstrate that as long as the ankle stiffness is appropriate, the model could be stabilized by controlling only lumbosacral joint [4]. Hunt et al. took into account actions of upper part of the body. They proposed single inverted pendulum model and two-level tree nested linear quadratic Gaussian controller to control position of the ankle joints [5]. Soeatno et al. used proportional-derivative (PD) controller to stabilize the position of the joints of three DOF model in sagittal plane during quiet standing [6].

Those models assume that motions of the legs are identical and that there is no motion in the frontal plane. However, those assumptions are incorrect [7]. Therefore, 3D model with 12 DOF have been proposed [7]. This 3D model has been used to show that FES-assisted arm-free standing is possible using PD controller in joint space and controlling 6 DOF of lower legs.

However, the above-described approaches focused on the control of each individual joint, i.e. joint space control. In those cases the balance of the postural system is not directly controlled which can be problematic especially when only the lower limbs are controlled. Our application deals with slow dynamics motion for which safety is of primary concern and thus the projection of the CoM must be contained in the base of support. In that context, we propose 3D control of the CoM position. Dealing with 3D motions in the Cartesian space, the system redundancy needs to be managed. Various techniques were applied within the robotics field to address redundancy problem [9]. For the specific purpose of CoM control, Cotton et al. developed a new representation of the CoM for arborescent chains. Those authors proposed to describe the CoM location as a Statically Equivalent Serial Chain (SESC) and thus allow the use of classical robotics tools developed since the 70's [10].

The goal of this paper is to develop a simple balance controller which would, by means of FES, enable quiet standing of individuals suffering from SCI while taking into account the voluntary motion of the upper limbs. The proposed approach is composed by a 10 DOF biomechanical model and a PI controller which follows desired CoM trajectories. The validity of our approach is tested using real human CoM trajectories and by applying perturbations in simulation during quiet standing.

II. METHOD

A. Biomechanical model

The biomechanical model used to represent the human postural system in 3D was composed of 5 rigid segments (shanks, thighs, HAT (Head, Arm, Trunk)) connected by ten cylindrical hinge joints (Fig. 1). Winter tables [11] were used to estimate segment lengths and inertial parameters of the model segments as a function of the height and body mass. Inverse dynamics and estimated ground reaction forces were

This work was supported in part by the authors' institutions, and in part by the Egide programme (PHC Galileo n. 26078TE).

J. Jovic, C. Azevedo-Coste and P. Fraisse were with the LIRMM/INRIA Montpellier, France (e-mail: jovana.jovic@lirmm.fr).

V. Bonnet was with the LABLAB, Department of Human Movement and Sports Sciences, University of Rome “Foro Italico”, Italy.

978-1-4577-1787-1/12/$26.00 ©2012 IEEE

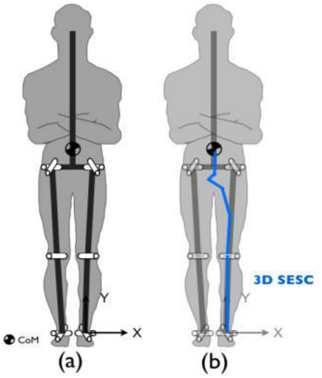

Fig. 1: Biomechanical model of the postural system (a). Representation (blue line) of the 3D statically equivalent serial chain (SESC) used to estimate the CoM location (b).

computed using recursive Newton-Euler equations. Integration of the dynamical model was performed using commercial modeling software (*LifeMOD Brg*). SESC modeling process was used to obtain a serial-chain-like model (Fig 1b) to determine the CoM positions of the human model [10]. This process describes equations of CoM location by merging segmental parameters and thus is very efficient in term of computational cost [10].

B. Postural controller

In this study, the 3D CoM is described as a serial chain, which makes calculation of the analytical Jacobian matrix of the CoM trivial. In general, serial representation allows us to use classical tool developed for serial robots. In addition, inspired by the robotics field, researchers in biomechanics [12] have shown that the pseudo-inverse of the Jacobian matrix could lead to minimum energy joint coordination, i.e. the minimum instantaneous Euclidian norm of the joint torques, during a dynamic postural task.

In this context and in the general purpose of developing the simple controller to minimize computational cost the following postural controller is proposed (Fig. 2).

In Fig. 2, FKM is the forward kinematics model, PI is the proportional and integral controller in the Cartesian space, respectively.

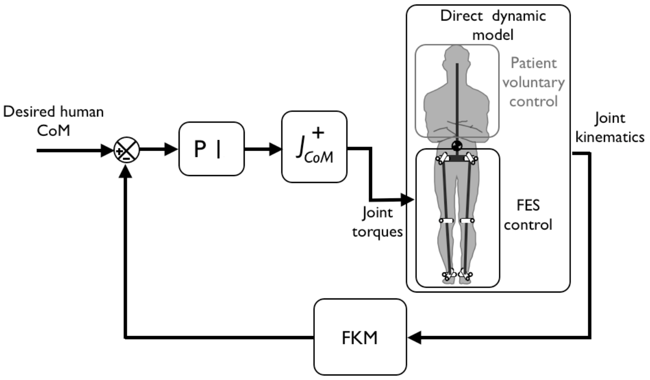

Fig. 2: Block diagram of the proposed postural controller. Controller follows desired 3D CoM positions and controls the lower limbs by applying torque at ankle, knee and hip joints (10 degrees-of-freedom).

The values of the gains K were empirically determined to be stable trough all simulations: K_P: 350, K_I: 250. J_{CoM}^{+} is the pseudo-inverse matrix of the CoM expressing the relationship between the velocity of the CoM in the global reference frame and the joint torque.

C. Human data collection

The aim of the experiment is to provide a database of human CoM trajectories and joint coordination that can be used to evaluate our approach. Two young healthy volunteers (1 male and 1 female, age=25.6±3.2 years, mass= 66.3±9.8 kg, stature=1.7±0.69 m) were included in the study after signing an informed consent. Participants were asked to keep their arms crossed on the chest, the trunk straight and the soles flat on the ground during the entire test. Starting from this position, they were then asked to stand as comfortably as possible while watching a documentary during 10 minutes. No other constraints were specified to the participants in order to let them freely choice their postural strategy.

Kinematic variables were measured using a stereophotogrammetric system (*9 Mx cameras, VICON*). In order to estimate accurately small postural modifications, twenty reflective markers were located on both legs on the heels, on the second metatarsal heads, on the lateral and medial malleolus and epicondyles, on the anterior and posterior superior iliac spines, and on the both acromia. The marker trajectories were used to estimate the position of the center of rotation of each joint and to drive the motion of the mechanical model described in Fig. 1. Anthropometric tables [11] were used to estimate the total 3D CoM trajectories corresponding to the above-described mechanical model. CoM trajectories were expressed in the global reference frame located at the center of rotation of left ankle thought rigid transformations.

D. Simulation of the closed-loop control

In order to validate our approach and to test the robustness of our controller, two different scenarios were evaluated. In the first case, controller tracked the CoM estimated from experimental data and joint patterns produced by our closed-loop controller and the ones obtained during the above-described experiment were compared. Secondly, while tracking the human CoM, external disturbances were applied on the upper part of the body to simulate voluntary motion of subject while our controller was controlling the lower limbs. To do so, the above-presented model (see section II.A) was extended by adding supplementary joints at the thoracal level and at the shoulder (Fig. 3). Note that the additional joints were used only in the computation of the total CoM location and were not directly controlled.

Step functions were applied on the joints to create a disturbance similar to a bending of the subject first in the antero-posterior (A/P) and second in medio-lateral (M/L) axis. Also, in order to simulate a grasping like motion, step function was applied in the right shoulder joint in the A/P direction. The amplitude of the step applied on the thoracal

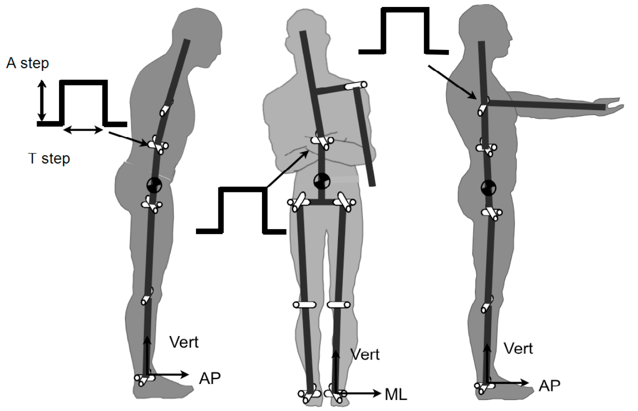

Fig. 3: Additional upper limb DOF used to simulate voluntary upper body motions.

joint in A/P direction was A_{step}=40° during T_{step}=5s and appears at 100s of the simulation while the amplitude of the step on the joint in M/L direction was A_{step}=10° during T_{step}=10s and appears at 200s of the simulation. Concerning the motion applied to the shoulder, the value in A/P direction has changed at 400s with A_{step}=90° during T_{step}= 60 s. Initial value of all joints was 0°.

III. RESULTS AND DISCUSSION

Representative results (Fig. 4) show the good tracking of CoM obtained from stereophotogrammetric system with the proposed closed-loop approach. One can see that, despite the large and abrupt motions of the CoM when the subject was changing his support leg, the proposed postural controller is able to follow the 3D CoM trajectories.

A representative set of joint patterns obtained during control simulations is compared with the ones estimated from experimental data in Fig. 5 for the right leg and in Fig. 6 for the left leg. One can see that similar general patterns are reproduced by our approach. However, differences concerning the amplitudes can be observed. These discrepancies may be induced by the approximate nature of our model and especially by its rigid structure. Also, in human the natural standing and rest positions do not correspond to zero angles as in our model. This could explain the offset difference observe on some joint angles. In our model the upper part with respect to the lower part of the body did not move during the simulation, which was not the case during the experiments with human subjects.

Fig. 7 illustrates the ability of our closed-loop controller to maintain balance and follow desired CoM position even when external disturbances were applied as described in section II.c. It can be seen that, after a short transitory phase (around 10 seconds), the controller is able to continue the CoM tracking.

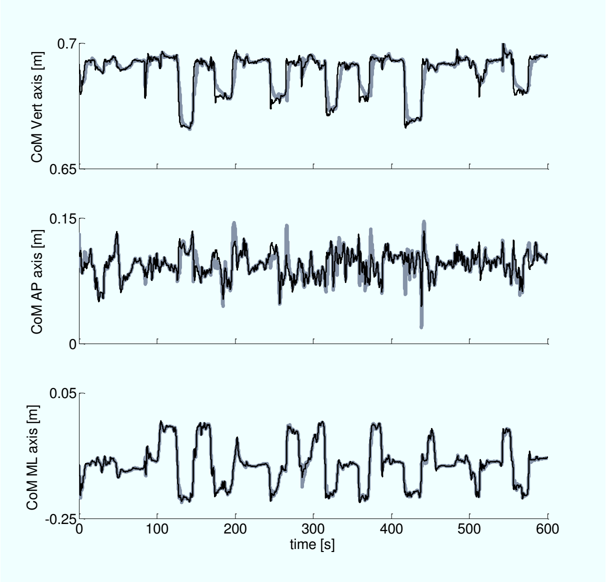

Fig. 4: Representative tracking of human CoM by the proposed closed-loop controller. CoM trajectories obtained from stereophotogrammetric system are indicated by gray lines and model output is indicated by black lines.

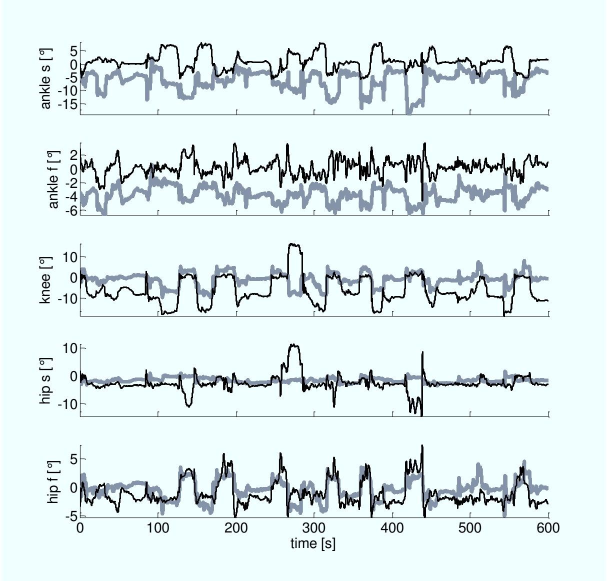

Fig. 5: Representative joint patterns produced by our closed-loop approach (black lines) and the ones measured in right human leg (gray lines).

The Root Mean Square (RMS) difference between the CoM position estimated from experimental data and its tracking by our closed-loop controller has been calculated. The results for both subjects are presented in Table 1.

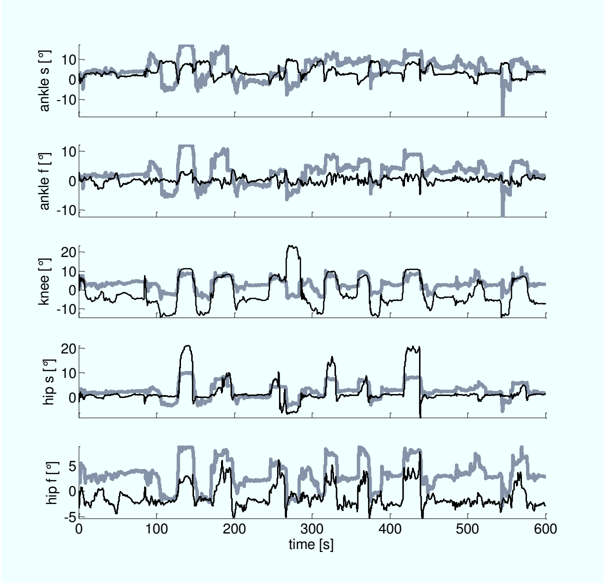

Fig. 6: Representative joint patterns produced by our closed-loop approach (black lines) and the ones measured in left human leg (gray lines).

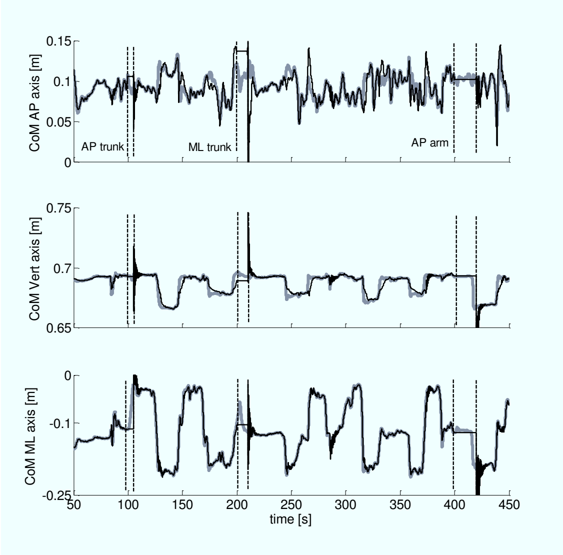

Fig. 7: Representative tracking of human CoM by the proposed closed-loop controller under perturbations indicated by dashed lines.

IV. CONCLUSION

The goal of this study is to present new paradigm concerning closed-loop control of paraplegics' standing based on controlling CoM position. The controller appears to be able to track human CoM recorded during 10 minutes of quiet standing with a good precision. This new paradigm, inspired by humanoid robot control schemes, is contrary to the work presented in previous literature [3]-[8], controlling a global variable representing the total balance of the subject, i.e. the CoM. The novelty in the research of CoM control and estimation leads us to believe that recent inexpensive tools such as *Kinect* cameras could be successfully used to track the CoM in real time and provide input of our algorithm.

TABLE I
SUMMARY OF MODEL VALIDATION RESULTS

	RMS [m]	CoM AP	CoM Vertical	CoM ML
No disturbances	Subject 1	0.0071	0.0027	0.0037
	Subject2	0.003	0.0009	0.003
With disturbances	Subject 1	0.0293	0.0115	0.0162
	Subject 2	0.0066	0.0064	0.0353

The proposed closed-loop approach could also find applications in the motor control field, in the framework of Bernstein problem [13] and a recent closed-loop computational model [12], since the comparison between joint pattern produced by our model and the measured ones appears to be similar. In order to improve this specific point, a weighted pseudo-inverse matrix [9] could be used to give more importance to some joints rather than others.

Our future work is aimed at extending our model by adding muscle properties and controlling muscle activation instead of joint torques.

REFERENCES

[1] A. Kralj, T. Bajd, "*Functional electrical stimulation: Standing and walking after spinal cord injury*", Florida, CRC Press, 1989.

[2] R. J. Jaeger, "*Design and simulation of closed-loop electrical stimulation orthoses for restoration of quiet standing in paraplegia*," J. Biomech., vol. 19, pp. 825–835, 1986.

[3] G. Khang and F. E. Zajac, "*Paraplegic standing controlled by functional neuromuscular stimulation- Part I: Computer model and control-system design*," IEEE Trans. Biomed. Eng., vol. 36, no. 9, pp. 873–884, 1989.

[4] Z. Matjacic and T. Bajd, "*Arm-free paraplegic standing- Part I: Control model synthesis and simulation*," IEEE Trans. Rehabil. Eng.,vol. 6, no. 2, pp. 125–138, 1998.

[5] K. J. Hunt, M. Munih, N. de N. Donaldson, "*Feedback control of unsupported standing In paraplegia-Part I: Optimal control approach*", IEEE Trans. Rehabil. Eng.,vol. 5, no. 4, pp. 331–340, 1997.

[6] D. Soetanto, C. Y. Kuo, and D. Babic, "*Stabilization of human standing posture using functional neuromuscular stimulation*," J. Biomech., vol. 34, pp. 1589–1597, 2001.

[7] J. Kim, M. R. Popovic, J. K. Mills, "*Dynamic modeling and torque estimation of FES-assisted arm-free standing for paraplegics*", IEEE Trans. Biomed. Eng., vol. 14, no. 1, pp. 46–54, 2006.

[8] Nashner LM, McCollum G,"*The organization of postural movements: A formal basis and experimental synthesis*", Behavioral and Brain Sciences, vol. 26, pp 135-172, 1985.

[9] Bruno Siciliano, "*Kinematic control of redundant robot manipulators: A tutorial*", Journal of Intelligent & Robotic Systems, vol 3, pp. 201-212 1990.

[10] S. Cotton, A. Murray and P. Fraisse, "*Estimation of the Center of Mass: From humanoid robots to human beings*", IEEE/ASME Trans. on Mechatronics, vol. 14, pp. 707-712, 2009.

[11] Winter, D.A. "*The biomechanics and motor control of human gait: normal, elderly and pathological*." Waterloo, Ontario: University of Waterloo Press.1991.

[12] V. Bonnet, S. Ramdani, P. Fraisse, N. Ramdani, J. Lagarde, B. Bardy, "*A Structurally Optimal Control Model for Predicting and Analyzing Human Postural Coordination*", *J. Biomech*, vol. 44, no. 11, pp. 2123-2128, 2011.

[13] N. Bernstein,"*The Co-ordination and Regulation of Movements*". Oxford, UK:Pergamon Press, 1967.