Minimum effort optimal control of ankle joints for unsupported standing in paraplegia

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Abstract

Limited unsupported standing has been restored in a patient with thoracic spinal cord injury through functional electrical stimulation of paralyzed ankle joint muscles and voluntary activity of intact upper trunk musculature. The paraplegic subject was considered an underactuated double inverted pendulum structure with an active degree of freedom in upper trunk and paralyzed ankle joints. An optimal control system for paralyzed ankle muscles was designed that enables the subject to stand without support in sagittal plane. The control system design was based on minimization of a cost function that estimates the effort of ankle joint muscles through observation of the ground reaction force position relative to the ankle joint axis. The designed control system integrates voluntary upper trunk activity and artificial control of ankle joint muscles resulting in a robust standing posture, while minimizing stimulated muscles effort. The benefits of the proposed control are the prolonged standing sessions and the fact that the subject maintains voluntary control over the upper body orientation in space resulting in a simple functional standing.

1 Introduction

Limited standing can be restored in patients with spinal cord injuries through functional electrical stimulation of paralyzed quadriceps muscles and arm support [1]. However, to achieve arm free standing also ankle joints need to be controlled. Unsupported standing has recently been achieved by bracing the paraplegic person’s body above the shanks in a single link inverted pendulum structure and applying electrical stimulation to the ankle muscles [2, 3]. A different control strategy for unsupported paraplegic standing, utilizing the residual sensory and motor upper trunk abilities of a thoracic spinal cord injured subject, was proposed by Matjačić and Bajd [4, 5]. The knees and hips were maintained in the extended position. Thus, the subject was constrained in an underactuated double link inverted pendulum structure. When assisted by an artificial ankle joint stiffness paraplegic subjects were capable of the proposed balancing.

The major issue in any control based on functional electrical stimulation is the fatiguing of stimulated muscles. In the case of stiffness supported standing, the subject would have to control the muscle fatiguing by using his upper trunk to balance his body in a least fatiguing posture. In order to remove the burden of controlling the fatiguing from the subject himself, the artificial control system needs to be designed in such a way that allows sustained functionality of the upper trunk and minimizes fatiguing by its own rules. The most important source of ankle muscle fatigue is the compensation of the gravity generated torque around the ankle joints. In order to minimize this torque, the vertical projection of the total body’s center of mass needs to be located within close proximity of the ankle joint axis. Another major contribution to the muscle fatigue is the control of body sway in anterior/posterior direction and the associated torque required to sustain the vertical body equilibrium.

2 Methods and Results

Based on the requirements for the minimization of ankle muscles effort, an optimal control system structure was selected for ankle control during unsupported standing. The implementation of the suggested controller requires a selection of an adequate optimization criterion, that satisfies the proposed control objectives. Based on analytical and empirical analysis the position of ground reaction force (CoP) relative to the ankle joint axis was found as an adequate biomechanical variable for ankle muscle effort estimation.

Movement of a double inverted pendulum structure is reflected in forces and torques acting at the ankle joint. Kinematic and dynamic relations in foot during standing are presented in Fig. 1.

Since foot linear and angular acceleration equals zero during quiet standing, the position of CoP can be determined as a function of forces and torque acting in the ankle
The proposed cost function for the design of a linear quadratic Gaussian control system [6] includes the cost related to the CoP position, as well as the cost related to torques in both joints of double inverted pendulum structure, \( \tau(t) = [\tau_1(t) \ \tau_2(t)]^T \), weighted across matrix \( R \):

\[
J(T) = \int_0^\infty (CoP^T(t)CoP(t) + \tau^T(t)R\tau(t)) \, dt.
\]  

(2)

By including the double inverted pendulum dynamics of unsupported standing in Eq. (1) and solving the optimal control problem pertaining to cost function (2), a full state feedback control gain matrix was computed. System states were estimated using Kalman observer, based on a plant model through measurement of system output that consists of ankle torque and segment positions and velocities. Due to front/back unsymmetric support surface, \( f_y \) in Fig. 1, it is however not desirable to set the position of the body center of mass exactly above ankle joint axis, since it would result in narrow stability margins for posterior disturbances. Therefore, a slightly anterior posture is maintained, by the means of prescribing small negative ankle torque operating point for the posture control system. The output of the posture control system presents the reference for the ankle joint torque control loop [7]. The plant and control system are presented in Fig. 2.

Optimal control design approach enables attainment of unsupported standing without explicitly prescribing the desired posture, and at the same time maintains ankle muscle fatigue reduced. The user is free to select the orientation of his upper body in space, since the upright balance is maintained by rotating ankle joints in a position where ankle torque coincides with the prescribed torque operating point.

The efficiency of the designed control system was evaluated on a complete T6 spinal cord injured subject. Results in Fig. 4 demonstrate fatiguing of ankle muscles in the case when the torque operating point was set to -40 Nm for robust anterior posture. It is obvious that nevertheless the ankle torque remains constant throughout the session, the stimulation level of plantarflexor muscles monotonically increases indicating fast muscle fatiguing. After only 80 seconds of such standing, stimulation level reaches saturation value, thus disabling further increases. Due to the fatigued muscles, the subject is no longer able to sustain upright posture and falls in anterior direction. A detailed analysis of muscle properties indicates a 50% decrease of muscle gain in the last 60 seconds.

Results in Fig. 5 indicate that prolonged unsupported standing can be achieved by prescribing ankle torque operating point close to zero. Stimulation pattern indicates coactivation of dorsiflexor and plantarflexor muscle groups because of a very low ankle torque. No significant fatiguing occurred in 3 minutes long trial. The trial finished when the subject acquired posterior posture, thus too much loading dorsiflexor muscle group. Since he was not able to generate active trunk movement to switch to anterior posture and maximal dorsiflexion stimulation was insufficient,
Figure 4: Paraplegic standing – increased fatigue.

Figure 5: Paraplegic standing – minimum effort.

the subject fell backward.

3 Summary and Conclusions

The paper considers the development of a novel control strategy for a dynamic closed-loop control of functional electrical stimulation of ankle joint antagonist muscles for restoration of unsupported standing in spinal cord injured subjects. The presented algorithm integrates the preserved upper body motor and sensor functions with the artificial control of the paralyzed ankle joints and ensures a stable standing of the paraplegic subject being constrained in the mechanical rotating frame that limits the motion to the sagittal plane [5]. Control system implicitly detects subject’s volition through observation of subject’s upper body voluntary activity and based on the optimization criterion determines the adequate lower body orientation. The proposed control does not allow autonomous standing of a paraplegic person, however it enables a stable posture in the sagittal plane.

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References


