Sit-to-Stand Control of Powered Knee Prostheses

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1 Background

Standing from a seated position is a common, yet dynamically challenging task. Due to the vertical ascent of the body center of gravity, sit-to-stand (STS) transition requires high torque output from the knee. As a result, STS transition poses a major barrier to the mobility of individuals with lower-limb issues, including the transfemoral (TF, also known as above-knee) amputees. A study showed that unilateral TF amputees suffer from high asymmetry in ground reaction forces (53–69%) and knee moments (110–124%), while the asymmetry for healthy controls is less than 7% [1]. Note that, although a powered TF prosthesis (Power Knee™) was used in this study, it generated resistance in the STS and thus produced similar results as the passive devices. The inability of existing prostheses in generating knee torque and regulating the torque delivery in the STS seriously affects the mobility of TF amputees in their daily life.

Motivated by this issue, researchers have developed numerous powered TF prostheses (e.g., Vanderbilt powered TF prostheses [2]). These devices are able to generate torque and power for challenging tasks such as STS transition. Making full use of such capability, however, requires an effective controller. Currently, walking control for powered prostheses has been well established, but STS control is much less investigated. Varol et al. developed a multi-mode TF prosthesis controller, in which STS is treated as a transitional motion between sitting and standing states [2]. However, no details were provided on the rationale of the STS controller structure or the determination of the control parameters.

In this paper, a new prosthetic control approach is presented, which regulates the power and torque delivery in the STS process. Inspired by the biomechanical behavior of the knee in the STS motion, the new controller provides two desired functions (gradual loading of the knee at the beginning, and automatic adjustment of the knee torque according to motion progress) with a single equation. Combined with a simple yet reliable triggering condition, the proposed control approach is able to provide natural STS motion for the powered knee prosthesis users.

2 Methods

To provide a natural control experience for amputee users, an STS controller should replicate the biomechanical behavior of the knee in this process. However, exactly replicating the motion of the biological knee is unfeasible, since such position control approach precludes the interaction between the prosthesis and its user and results in a poor control experience. Biomechanical data, on the other hand, provide insight to the dynamic behavior of the knee and thus can be used as an inspiration for the controller.

Unlike cyclical motion modes such as walking, STS is a typical transitional motion with clearly defined start (seated position) and end (standing position). The typical joint position and torque trajectories are shown in Fig. 1 (data from [3]). The entire process can be divided into two phases, separated by the instant of Seat-Off (SO):

1. Loading phase: with the body weight shifted from the seat to the lower limb, the knee torque increases rapidly to support the body weight and initiate the upward motion. The knee position remains almost constant until the final portion of the phase, and the torque increases at a nearly constant rate after the initial dormant period.

2. Rising phase: after reaching the maximum value, the knee torque reduces with the joint extension, and settles at a steady-state value after the standing position is reached.

Such segmentation of the STS motion can be clearly seen in Fig. 1. For a powered knee prosthesis to generate natural motion in this process, the controller should follow the same strategy. Also, to facilitate the implementation, the STS controller structure should be adequately simplified while retaining the essence of human biological control. Based on such requirement, the authors propose a control structure consisting of a ramp-up function for gradual loading of the knee combined with an impedance function for automatic adjustment of knee torque according to the motion progress:

\[ \tau = R \left( \frac{t-t_0}{T} \right) \tau_{imp} (\theta, \dot{\theta}) \]

In this equation, the impedance function \( \tau_{imp} \) is defined as:

\[ \tau_{imp} = K(\theta - \theta_e) + B \dot{\theta} \]

where \( \theta \) is the joint position, \( \dot{\theta} \) is the joint angular velocity, \( K \) is the spring stiffness, \( \theta_e \) is the equilibrium point, and \( B \) is the damping value. The ramp-up function is defined as:

\[ R \left( \frac{t-t_0}{T} \right) = \left\{ \begin{array}{ll} \frac{t-t_0}{T} & \text{when } t_0 \leq t \leq t_0 + T \\ 1 & \text{when } t > (t_0 + T) \end{array} \right. \]

where \( t \) is current time point, \( t_0 \) is the starting time point of the ramp-up period, and \( T \) is the length of the ramp-up period.

The impedance function, as the major part of the controller, simulates the dynamics of a mechanical spring combined with a viscous damper, which are purely passive in nature. The passivity guarantees the stability in the control process, but it also dictates that all the required artificial
mechanical energy (in the form of artificial spring deflection) to be introduced at the onset of STS motion, such that sufficient power output can be provided while lifting the user. Consequently, the torque output of the spring-damper combination immediately reaches the maximum at the motion onset, as opposed to the gradual increase as shown in the biomechanical data. To address this problem, the time-based ramp-up function is introduced. As Eq. (3) shows, the value of the function increases linearly from 0 to 1 within the ramp-up period, and stays at 1 afterwards. As such, it only takes effect in the ramp-up period, providing the gradual energy injection required in the loading phase. It is worth mentioning that the use of the ramp-up function eliminates the need for explicit phase transition from loading to rising as a result of the limited effective period, which significantly simplifies the implementation of the controller.

For the triggering of the control action, the axial load in the prosthesis combined with the knee joint angle serves as the indicator for the user’s readiness for the STS motion. When the user prepares for standing up, he/she first bend the knees by a large angle (usually greater than 90º) such that the feet can be directly underneath the body center of mass. Subsequently, the weight is gradually shifted to the feet, increasing the axial load born by the prosthesis. Based on such biomechanical process, the trigger condition is set as: the prosthesis axial load greater than a certain threshold \( F_L \), and the prosthesis knee angle also greater than a certain threshold \( \theta_L \). This condition can be easily implemented by using the embedded sensors in the prosthesis, and provides an intuitive and reliable way to initiate the STS motion.

3 Results

To demonstrate the effectiveness of the STS controller, the authors conducted a set of human subject experiments. The human subject participated in the testing was a 22-year-old male unilateral amputee, 178 cm in height, and weighed 57 kg. He was fitted with a powered knee prosthesis prototype developed by the authors’ group, namely Alabama Powered Prosthetic Limb – Knee (APPL-K). This prosthesis is powered by a 70 W brushless DC motor through a two-stage transmission, which provides a 150:1 gear ratio by combining a timing belt drive and a harmonic drive. For the controller implementation, the prosthesis is instrumented with various components for computing, sensing and regulation of power delivery. The joint position is measured with a rotary magnetic encoder, and a custom load cell is used to measure the axial force in the prosthesis. The motor power output is regulated with a PWM servo drive. The STS controller is implemented on a microcontroller, which communicates with a host desktop computer to record and display experimental results for controller tuning and data analysis.

The typical trajectories of the experimentally measured prosthetic joint position and torque are shown in Fig. 2, and a sequence of snapshots of the STS process is shown in Fig. 3. As shown in Fig. 2a, the joint position stayed almost constant until the rising phase started, and the whole trajectory shows smooth and controlled motion throughout the process. There is a period of saturation in the torque plot (Fig. 2b), but it did not affect the dynamics of the STS motion, according to the feedback from the test subject. The subject stated a natural control experience in which the prosthetic motion coordinates with the sound-side leg motion well, and the knee extension torque enabled him to stand up with much less effort.

4 Interpretation

In this paper, the authors present a new control approach for powered knee prostheses in the STS motion, with the objective of regulating the knee extension torque to obtain smooth standing up motion. A unique control structure was created, which combines an impedance function with a time-based ramp-up function. The use of such unified control structure simplifies the controller implementation while maintaining the unique biomechanical characteristics of each motion phase. This new STS controller was implemented on a powered knee prosthesis, and human testing results demonstrated the effectiveness of this approach in generating smooth standing-up motion according to the user’s will.

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References

