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A novel supervisory control scheme to tackle variations in step length for walking with powered ankle prosthesis

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ABSTRACT

In daily-life activities, it becomes essential to modulate the walking speed, when an amputee wishes to walk outdoor wearing his/her powered prosthesis. Different walking speeds can be achieved by varying the step length or stride length, and ankle torque requirement during push-off varies significantly with the desired step length. Thus, in order to mimic the natural gait for varying step lengths, it is essential to develop a control algorithm that can predict the amputee's desired step length and modulate the ankle torque of a powered ankle prosthesis, accordingly. Therefore, in this study, a control scheme has been proposed to solve the said purpose. The prediction of step length is achieved with the help of an Adaptive Neuro-Fuzzy Inference System (ANFIS) and multisensory data fusion. Experiments are carried out on walking of four healthy adults and a large amount of data are collected to train the ANFIS. After the training is over, the trained fuzzy inference system is used to evaluate the efficiency of the algorithm for a set of test data. Finally, the predicted step length value is used to calculate the required force during push-off (where the prosthesis has to be put) with the help of biped walking dynamics. Thus, the novelty of this study lies with the proposal of a new strategy for deciding adaptive step length and control algorithm. The key features of this algorithm include its simplicity, good prediction accuracy, ability to tackle uncertainty or imprecision and fast response.

1. Introduction

Along with the design of a powered ankle prosthesis [1], a suitable control algorithm is also needed for the movement of motorized ankle joint. The modern approach to control the powered lower limb prostheses is the supervisory control, where the intent of the user is recognized in order to design a robust and precise control strategy [2]. This type of supervisory control works in a hierarchy of three stages: first stage is the supervisory control, second stage is considered as finite-state control and low level control or the torque control is considered as the third stage. The powered prosthesis is able to mimic the behavior of an intact ankle joint with a suitable coordination among these three stages. The finite-state controller helps to detect different sub-phases in a gait cycle and decides the necessary joint torque based upon the output of supervisory controller, the low-level controller controls the actuator movement to generate the required torque [3]. Till date, the supervisory control is designed to recognize different types of terrains, for example, level ground walking, stairs climbing and descending, walking on slopes etc. [4]. While in daily-life activities, both a normal person as well as a lower limb amputee spends maximum time in level ground walking rather than negotiating stairs and slopes. For walking outdoor after wearing a prosthetic device, the amputee needs to change the walking speed depending upon various circumstances. For example, when an amputee wishes to walk either on the streets or in the market, sometimes it may be required to walk either faster or slower than the normal walking speed, depending upon the traffic situations and friction of the road surface. Hence, an adaptive speed control algorithm is equally significant as the classification of locomotion modes. The incorporation of a suitable adaptive speed control mechanism may be able to provide an extra freedom and comfort to the amputee by accurately monitoring the torque of powered ankle prosthesis. Thus, in this study, we focus on the development of a supervisory control scheme for a powered ankle prosthesis in order to deal with the varying step lengths for level ground walking.

The effects of step length on lower limb muscles [5] and joint kinetics [6] are well studied. Lim et al. [5] investigated the contributions of different lower limb muscles on varying step lengths and concluded that the change in step length has significant influence on muscle functions and joint moments mainly ankle torque. Sawicki et al. [7] examined how the ankle plantar flexion work changes

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with the variations in step length, and tried to reduce it using a powered ankle exoskeleton, where the exoskeleton was controlled by soleus muscle-based proportional myoelectric control. From the above studies, it is clear that to walk with varying step lengths, the ankle push-off force plays the major role. The effect of step length for biped walking also confirms the same findings [8]. Thus, it seems essential to design a proper control scheme to tackle the ankle torque requirements according to variable step lengths while using a powered ankle prosthesis. This could help to restore the lost gait of a transtibial amputee more precisely. A few studies had already been done on walking with speed adaptation using powered ankle prosthesis [9]. For example, Fey et al. [10] developed an impedance-based control strategy to control knee swing and ankle plantar flexion torque of an active prosthesis at different speeds of walking. The impedance-based model works on measuring the joint angle and velocity, and then, adjusting the joint torque according to the impedance-based model. The ankle torque is represented as a function of the measured quantity and some predetermined impedance parameters. The determination of impedance parameters is again a tough job. Markowitz et al. [11] used a data driven neuromuscular model to evaluate the ankle torque with respect to varying speeds of walking. The neuromuscular model was tuned by measuring muscle activation force of soleus and gastrocnemius muscle, and the prosthesis was controlled by measuring the ankle angle. Similarly, Huang et al. [12] proposed a method for auto-tuning the stiffness and damping parameters of an impedance controller that was used to control the knee torque of a powered knee prosthesis. The above discussed models are not supervisory control, rather a feedback control strategy, where the joint torque is updated after the impact of the prosthesis. On the other hand, the accuracy of the aforementioned control approaches solely depends upon the measurement of single input (i.e., either joint angle or muscle force). In this study, we are going to see that how these joint angles and muscle forces vary greatly both for different subjects as well as for a single subject in different gait cycles, even if the subject is walking with a constant speed or step length. The reason is that the distributions of muscle forces are different from subject to subject based on their walking styles and body structures, and it is very difficult to predict the intention by monitoring a single attribute. Furthermore, the single sensor-based strategies are prone to external disturbance or noise.

This study proposes a supervisory control approach to control the speed of walking by accurately predicting the intended step length and then, evaluating the push-off force impulse with the help of a biped walking model. Furthermore, we will investigate how a multisensory fusion strategy can provide the better accuracy, robustness and consistent prediction of step length compared to single sensory control. The control inputs are collected from the sensors, which are attached to the contralateral limb to measure the user's intent based on its behavior. This control logic is called the echo control. The echo control was proposed earlier [13], but not explored much to control a powered prosthesis. Though it is a feedback control strategy, the advantage of echo control is that the control decision can be generated prior to the push-off of the amputated leg. The design of control algorithm is based on an input-output modelling technique to map the relation between the input sensory data and varying step lengths, thus, the push-off force with the help of an Adaptive Neuro-Fuzzy Inference System (ANFIS). In 2002, Hussein and Granat [14] used the neuro-fuzzy EMG classifier for user intent detection. Later on, Yuan et al. [15] developed a fuzzy logic-based terrain identification technique for a powered ankle prosthesis using the concept of multisensory data fusion. Similarly, Fan et al. [16], Lauer et al. [17] and Momen et al. [18] used either fuzzy logic control or neuro-fuzzy system to detect the user intention in order to control prosthetic or orthotic device. The multisensory data fusion approach is widely used for locomotion mode selection [19] but probably it is not used for step length adaptation. Joshi et al. [20] used ANFIS for the prediction of knee angle from contralateral knee angle to assist different speeds of walking. As concerned, none of these algorithms discussed above was used to design a step length adaptive control logic for powered ankle prosthesis.

Table 1
Details of the subjects participated in the experiment.

Subject	Gender	Age (year)	Height (cm)	Weight (kg)
Subject A	Male	28	175	70
Subject B	Male	19	174	67
Subject C	Male	28	183	71
Subject D	Male	29	163	68

The algorithm is designed based on the walking data collected from four healthy subjects. An ANFIS is used to map the input-output relationship between the sensory data and step length. The walking data for different step lengths have been collected from eight sensors (four EMG sensors, two goniometers and two force sensors) and their individual efficiency is evaluated in terms of root mean squared error (RMSE). On the basis of their individual RMSE value, the sensors are chosen to build a multisensory ANFIS network for the prediction of step length more accurately. The predicted step length value is then fed to the inverse pendulum model of biped walking to evaluate the force required for push-off. The prediction accuracy of the multisensory fusion technique is evaluated individually for four subjects. The multisensory fusion approach is able to encounter the irregularities of human walking and any kind of uncertainty that may occur due to many reasons like body-sensor integration problem or data distortion due to sweating or human intervention, with a graceful degradation. Moreover, the proposed technique is completely automated and no user input is required for execution.

The remaining part of the text is organized as follows: Section II deals with the methods of data collection and feature extraction. The proposed algorithm for the analysis is discussed then. Results are stated and discussed in section III. Some concluding remarks are made in section IV.

2. Methods and tools

2.1. Data collection

Walking data have been collected for the analysis from four able-bodied subjects, the details of the subjects participated in the experiment are provided in Table 1. The data have been recorded using some ground markers in order to maintain a constant step length throughout the track. Four such tracks are created with four different step length values that consists of short (25.4 cm), medium (38.1 cm), normal (50.8 cm) and long (63.5 cm). In this study, for the sake of comparison of the results between the subjects, same step lengths are considered for all. The subjects are asked to make heel-to- heel coordination with the ground markers. To accumulate a large set of data for training and testing, the participants have undergone six trials per track. A training session, prior to the experiment is carried out in order to make the subjects walk comfortably along with the sensors attached to their body.

Eight sensors are used to collect different activities during locomotion. It consists of four electromyogram (EMG) sensors, two goniometers and two force sensors. It is to be noted that all the sensors are attached to the contralateral leg that is considered as left leg of the subject and they are asked to start walking with their left leg, considering that the powered ankle prosthesis is put on the right leg. All the sensors and wireless data acquisition system are acquired from Biometrics Ltd., UK.