Control Engineering Practice 49 (2016) 1–13

Contents lists available at ScienceDirect

Control Engineering Practice

journal homepage: www.elsevier.com/locate/conengprac

Intelligent control of a prosthetic ankle joint using gait recognition

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ARTICLE INFO

Article history:
Received 3 February 2015
Received in revised form
15 January 2016
Accepted 19 January 2016
Available online 4 February 2016

Keywords:
Prosthetic foot
Gait analysis
Intelligent control
Biomechanics
Amputation

ABSTRACT

Desire for better prosthetic feet for below-knee amputees has motivated the development of several active and highly functional devices. These devices are equipped with controlled actuators in order to replicate biomechanical characteristics of the human ankle, improve the amputee gait, and reduce the amount of metabolic energy consumed during locomotion. However, the functioning of such devices on human subjects is difficult to test due to changing gait, unknown ankle dynamics, complicated interaction between the foot and the ground, as well as between the residual limb and the prosthesis. Commonly used approaches in control of prosthetic feet treat these effects as disturbances and ignore them, thereby degrading the performance and efficiency of the devices. In this paper, an artificial neural network-based hierarchical controller is proposed that first recognizes the amputees' intent from the actual measured gait data, then selects a displacement profile for the prosthetic joint based on the amputees' intent, and then adaptively compensates for the unmodeled dynamics and disturbances for closed loop stability with guaranteed tracking performance. Detailed theoretical analysis is carried out to establish the stability and robustness of the proposed approach. The performance of the controller presented in this paper is demonstrated using actual gait data collected from human subjects. Numerical simulations are used to demonstrate the advantages of the proposed strategy over conventional approaches to the control of the prosthetic ankle, especially when the presence of noise, uncertainty in terrain interaction, disturbance torques, variations in gait parameters, and changes in gait are considered.

1. Introduction

Loss of limbs has far reaching impact on the mobility, emotional and physical health of an individual. According to the recent estimates (Ziegler-Graham, MacKenzie, Ephraim, Travison, & Brookmeyer, 2008), over 1.6 million Americans, or roughly 1 in 190 persons, are currently living with a loss of a limb. Amongst them, 62% underwent an amputation procedure to the lower extremity. It is anticipated that the number of people living with limb loss would increase to 3.6 million by the year 2050, with over 1.4 million of them being under 65 years of age. Clinical studies indicate that 68–88% of amputees wear prostheses at least 7 h a day (Pohjolainen, Alaranta, & Karkkainen, 1990; Walker, Ingram, Hullin, & McCreath, 1994) and lead an active lifestyle (Brodzka, Thornhill, Zarapkar, Malloy, & Weiss, 1990). These people need highly functional prostheses in order to maintain healthy and good quality of life (Ziegler-Graham et al., 2008). In the short term, the use of passive prosthetic foot with fixed ankle can lead to asymmetric gait (Bateni & Olney, 2002; Kovac, Medved, & Ostojic, 2010), increased intact muscle contraction (Fey, Silverman, & Neptune, 2010), and higher metabolic energy expenditure in an individual (Torburn, Powers, Guiterrez, & Perry, 1995). Long-term health complications such as osteoarthritis, osteoporosis, back pain, and other musculoskeletal problems can also be linked to the poor fit and improper alignment of the prosthesis and can lead to poor overall quality of life of the individuals (Gailey, Allen, Castles, Kucharik, & Roeder, 2008).

Research into amputee gait has shown that it is desirable that future prosthetic feet replicate the biomechanical characteristics of the biological ankle joint (Versluys et al., 2009). It is necessary for the prosthetic ankle joint to follow the typical joint displacement profile of a human ankle. Such profile helps absorbing shock due to the ground interaction and generating propulsion energy for the body to move forward, therefore guaranteeing the stability and mobility during gait. The displacement profile in Fig. 1 (Winter, 2009) is shown normalized with respect to the gait cycle and is related to the phases and events of the gait (Winter, 2009; Perry, 1992; Uustal & Baerga, 2004). The joint displacement profile is typical for all humans and is presumed to minimize the energy consumption during gait (Anderson & Pandy, 2001; Ackermann & van den Bogert, 2010).

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[1] http://www.springer.com/sgw/cda/frontpage/0,11855,5-40109-70-35711063-0,00.html.

http://dx.doi.org/10.1016/j.conengprac.2016.01.004
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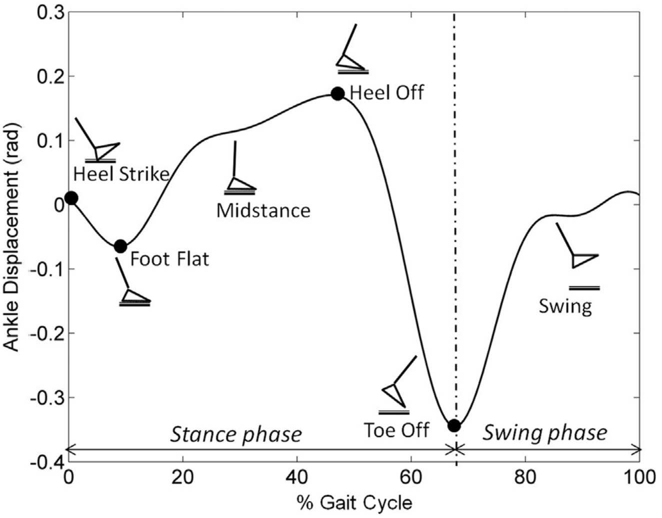

Fig. 1. Typical human ankle displacement profile.

Next generation prosthetic feet are likely to be equipped with controlled actuators in order to provide variable stiffness and range of motion of the artificial ankle joint, and help achieve desired gait performance (Versluys et al., 2009). However, control of the ankle prosthesis to replicate the movement of a healthy ankle during gait is a difficult task due to the following reasons.

a) The ideal ankle displacement profile depends on several factors such as user gait (e.g., stance time, swing time, step length, and stride length), selected walking speed, inclination of the terrain, and type of activity (e.g., walking on level ground, ascending/descending stairs). Due to changes in gait and terrain and unknown intent of the user, the ideal ankle displacement profile cannot be specified *a priori*.

b) During gait, the movement of the prosthetic foot is influenced by the reaction force resulting from the interaction of the foot with the terrain. This ground reaction force (GRF) plays a critical role in supporting the body weight, ensuring stability, and providing the necessary propulsion for the gait (Perry, 1992). GRF causes a reaction torque at the joint that has to be compensated in order to achieve proper tracking behavior. GRF is usually measured using motion tracking systems and force plates in a laboratory setting (Winter, 2009). Unfortunately, real-time measurement of GRF is not feasible during normal gait and therefore cannot be used in the control of the prosthetic joint.

c) The dynamics of the foot are affected by the nonlinear coupling between the prosthetic ankle joint and the biological knee and hip joints of the amputee. These effects depend on anthropometric measurements of the human body and vary with gait. Neglecting these interactions will lead to larger tracking errors for a specified ankle displacement profile.

Commercially available below-knee controlled prostheses such as Proprio Foot (Össur, 2015) and BIOM Ankle System (BIOM, 2015; Au, Weber, & Herr, 2009) are capable of manipulating the movement of the ankle joint and adapting to different gait and terrain (Versluys et al., 2009; Jiménez-Fabián & Verlinden, 2012). Improvement in gait performance with these controlled prostheses has been reported in several case studies (Wolf, Alimusaj, Fradet, Stegel, & Braatz, 2009; Ferris, Aldridge, Rábago, & Wilken, 2012; Grabowski & D'Andrea, 2013). Performance of other active foot prototypes such as SPARKy (Hitt, Sugar, Holgate, Bellman, & Hollander, 2009) and PPAMs (Versluys et al., 2008) in generating torque to manipulate the ankle movement is also promising. In general, control algorithms neglect the dynamics of the ankle joint, the interaction of the ankle with the remaining healthy joints of the residual limb, and the effect of the ground reaction torque. These devices are based on the linearized dynamics of the joint and use proportional-derivative control with fixed control gains. While these controllers guarantee local stability, their performance might deteriorate quickly in the presence of unmodeled system dynamics and measurement noises. Advanced bionic feet in recent literature can vary the ankle stiffness and generate power to support the gait. These designs are in early development stage and researchers are aware of the challenges in achieving satisfactory performance when gait conditions change (Markowitz et al., 2011). Researchers have also shown that supervisory control schemes that implement different control strategies based on perceived gait help achieve desired performance of the foot (Au, Berniker, & Herr, 2008). However, the effect of gait and terrain changes, unmodeled dynamics and noise on the performance of these supervisory controllers have not been systematically studied (Jiménez-Fabián & Verlinden, 2012).

In recent years, several researchers have investigated the use of artificial neural networks (ANNs) for recognizing the users' intent during gait (Au et al., 2008; Jin, Zhang, Zhang, Wang, & Gruver, 2000; Varol, Sup, & Goldfarb, 2008; Torrealba et al., 2010). However, the information gained was not used to directly control the prosthetic joint. In this paper, an artificial neural network-based control structure performs multiple tasks including learning the ankle dynamics, recognizing the varying gait intent, and generating an appropriate torque to drive the ankle joint along a desired displacement profile. The controller proposed in this paper is based on a hierarchical adaptive learning strategy and includes the following steps.

- Generate an ankle joint displacement profile based on the measured gait data,
- Estimate the ground reaction force during gait using a viscoelastic contact model, and
- Implement an artificial neural network (ANN)-based control to approximate the ankle dynamics and track the generated ankle displacement profile.

The closed-loop stability of the proposed approach is rigorously analyzed using Lyapunov stability theory and the robustness of the controller is studied using actual gait data collected from human subjects. Numerical simulations in the presence of noise, uncertainty in terrain, disturbance torques, and changes in gait are then used to demonstrate the tracking

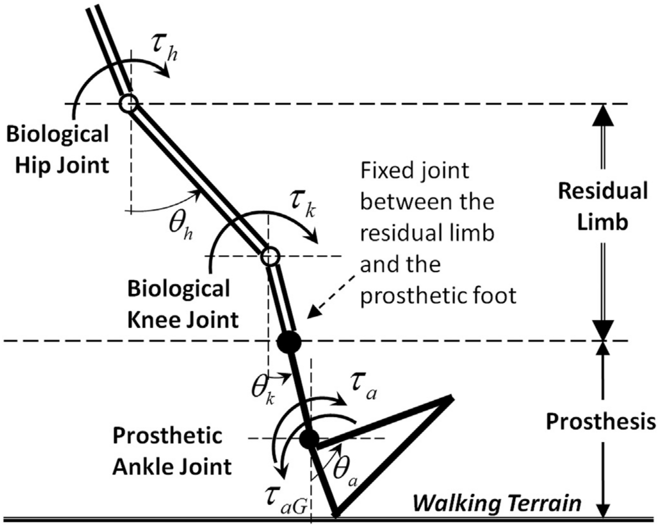

Fig. 2. Link-segment diagram of the residual limb and the prosthetic foot.