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Dynamic modeling, parameter estimation and control of a leg prosthesis test robot

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ABSTRACT

Robotic testing can facilitate the development of new concepts, designs and control systems for prosthetic limbs. Human subject test clearances, safety and the lack of repeatability associated with human trials can be reduced or eliminated with automated testing, and test modalities are possible which are dangerous or inconvenient to attempt with patients. This paper describes the development, modeling, parameter estimation and control of a robot capable of reproducing two degree-of-freedom hip motion in the sagittal plane. Hip vertical displacement and thigh angle motion profiles are applied to a transfemoral prosthesis attached to the robot. A treadmill is used as walking surface. Aside from tracking hip motion trajectories, the control system can be used to regulate the contact force between the treadmill and the prosthesis. The paper summarizes the overall development process, with emphasis on the generation of a dynamic model that can be used to design closed-loop motion and force control algorithms.

1. Introduction

Concepts for advanced prosthetic devices have been developed at a very fast pace in recent years. In particular, the literature continues to report significant progress in passive, semiactive and fully-active leg prostheses [1–7]. These advances are evident at all technology readiness levels, from conceptual design and mathematical models to demonstrated prototypes. Concomitant to these developments arises the need for systematic prototype testing programs. During the product development phase, testing under normal and hazard conditions involving patients is problematic. Legal clearance burdens, required safety harnesses and a lack of repeatability across test subjects place significant restrictions on the scope of the tests that may be conducted and the quality of the data being gathered.

Robotic testing can eliminate or reduce many of these obstacles and bring additional benefits. For instance, robots may be commanded to simulate conditions which are deemed unsafe for patients, such as near-fall situations. A robot may be operated continuously for long periods of time, as necessary for certain real-time optimization of prosthetic control algorithms [8] or to evaluate the mechanical endurance of a prototype. Also, robots may be fitted with sensors to measure quantities of interest which are difficult to measure directly in a human subject, such as hip torque and angle. Finally, performance comparisons among various candidate designs can be conducted in a meaningful way only if controlled test conditions are assured, with sufficiently large trial data sets.

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Although some use of commercial manufacturing robots in prosthesis testing has been reported by the Fraunhofer Institute [9] and the Cleveland Clinic [10], the use or development of a machine aimed at reproducing prosthetic gait has not been reported, to the best of the authors' knowledge. In this paper, robotic testing of transfemoral prosthesis is proposed, and the development, modeling and control of a two-degree-of-freedom robot to emulate hip motions is described. It is expected that robotic testing of prostheses will play a major role in evaluating the dynamic characteristics of prototypes because the input displacements, velocities, accelerations, torques and forces can be measured with much more accuracy and repeatability than during human gait trials.

The robot described in this paper is designed to test transfemoral prostheses [11]. A simple passive knee with a blade foot is used to illustrate the approach to modeling and control and to conduct proof-of-concept tests with the newly designed robot. However, any prosthesis, including powered knee-ankle devices can be attached to the machine and the model can be modified to reflect the dynamics of the prosthesis in use. Irrespective of the kind of prosthesis attached, the robot has full authority over hip vertical displacement and thigh angle. In this paper we consider pure motion tracking for these two degrees of freedom, but the actuation, sensing and control hardware are ready for objectives other than trajectory control, for instance force control, hybrid force/trajectory control and impedance control.

The sample test modality used in the experimental section of this paper is to track hip displacement and thigh angle data gathered from able-bodied subjects walking normally. Since a passive knee was used, knee angle and ground force profile are observed variables that can be compared against able-bodied data matching normal walk data. This comparison provides an indication of the prosthesis' gait fidelity. Other tests and studies can be conducted by suitably changing the control objective and algorithm, the sensed variables used for feedback and/or the tracking references. For instance, combined hip motion and ground reaction control has been achieved with this machine [12]. In this modality, a passive prosthesis is also used and a set of baseline hip displacement and thigh angle references are used. Active biasing of the baseline references is performed using online evolutionary optimization so that ground reaction force tracks a ground reaction profile corresponding to the same able-bodied walking data. This study provides insight about the compensation that a patient would need to apply to reproduce normal gait while wearing that specific prosthesis. These kinds of studies have so far relied on patient trials or biomechanical models [13–17].

The overall design of the robot responds to high-level requirements such as the number of degrees of freedom, the shape of the motions to be generated and load capacity requirements, which leave few options for the mechanical configuration. Upon fixing the kinematic concept, electromechanical actuation was favored over hydraulics due to the higher achievable positioning accuracy and generally faster control bandwidth of the former. Besides, a hydraulic system requires several ancillary components such as pumps, a tank, valves and filters, resulting in a bulkier and overall less efficient solution for this particular application. Installation of a hydraulic system in a clinical research facility may not be feasible due to noise and cleanliness concerns. This paper focuses on the modeling, parametric estimation and baseline feedback control of the robot. The remainder of the paper is organized as follows: Section 2 describes machine functionality and components; Section 3 first derives separate models for the machine and for the prosthesis, and then integrates them into one, following a robotic manipulator dynamics framework; Section 4 describes various parameter estimation procedures used to populate the dynamic model; Section 5 presents preliminary independent-joint controller that can be used to accurately track motion profiles; Section 6 reports our success in achieving the desired motion profiles and Section 7 offers conclusions and some recommendations for future improvements to the design and possible test modalities.

2. Machine design

The robot must produce motions that mimic those of a human hip during walking and running. This design is limited to two degrees of freedom, namely hip vertical displacement and hip swing, which are the minimum required to reproduce two-dimensional gait patterns. Normal hip displacement and swing are periodic oscillations with amplitudes and waveforms that depend primarily on the height of the patient and the walking or running speed. Normal gait profiles used as a guideline for design are a subset of the data collected by van den Bogert [18], which includes walking and running in healthy subjects. The machine is designed for hip displacement amplitudes of up to 50 mm, with a maximum velocity of 1 m/s. Vertical force capacity is specified at 1200 N, which exceeds the ground force generated by a 78 kg normal subject during fast walk/slow running. The vertical motion stage is comprised of a DC motor, a ballscrew and a linear slide. Overall vertical motion range is 12 inches, of which up to 100 mm are used to accommodate the expected vertical hip motion profiles. The remaining space is used to shift the center of oscillation, as it may be required to test prostheses of various lengths. The center of oscillation may also be changed during real time operation to initiate and regulate contact between the foot and the walking surface. Since the machine has a fixed vertical axis, a treadmill is used as a walking surface.

The rotary motion stage, including motor, is carried by the vertical slide. Prostheses are attached to the rotary plate by means of an adjustable threaded rod, which is secured to a bracket on the plate with two 2.75-inch nuts. The threaded rod, in combination with the adjustable center of oscillation of the vertical stage, offer great flexibility for standoff adjustments. Although thigh angular excursion in the normal gait data does not exceed 50 degrees, the rotary actuator has an unlimited angular range. Following biomechanical data from [18], the design values for thigh angular velocity and torque are is 150 degrees per second and 75 Nm.

A schematic diagram of the robot and its components is shown in Fig. 1, and the finished machine is shown in the photograph of Fig. 2.

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