Supplemental Material: Learning Predictive Models for Ergonomic Control of Prosthetic Devices

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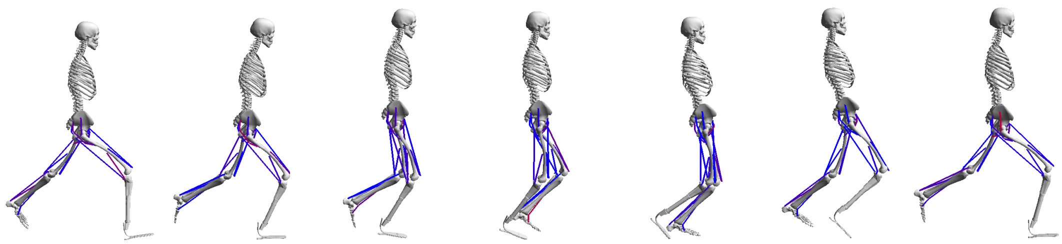

Figure 1: Image sequence of simulated walking using an active prosthesis and the MPIP algorithm.

1 Introduction

The following document provides implementational details regarding all experiments performed in the paper "Learning Predictive Models for Ergonomic Control of Prosthetic Devices". More specifically, we provide information about the simulation environment environment along with all physics constants necessary to reproduce our results. In addition, we provide hardware and software details regarding all sensors used to record the training data. We also provide a description of the of the used commercial lower-leg prosthesis. We finish the supplemental material with a list of the anthropometric constants used in the human biomechanics model.

2 Simulation Environment

Due to this year's ongoing pandemic, large scale human subject testing has been made all but impossible. Therefore it was imperative to incorporate simulation environments into our experiments to illustrate our methods and algorithms. The focus of this research is centered on modeling the relationships between a human and robotic prosthetic. We chose to build upon a readily available framework from the NeurIPS 2018: *AI for Prosthetics Challenge* **?**], as it is freely available along with the winning submission from **?**]. This competition challenged over 425 teams to develop a controller to enable a physiologically-accurate human model in a physics-based simulation environment (OpenSim Delp et al. [1**?**]), with a passive prosthesis (not controlled) to walk at specified speeds with changes in direction. The winning solution produces a stable human-like walking controller **?**] over a broad range of walking speeds.

The problem that is at the center of our paper, however, is the challenge of actively controlling a prosthesis so as to best adapt to a human user (not controlled). Accordingly, we modified the simulation environment by adding a controllable degree-of-freedom for powered actuation at the ankle of the prosthesis. The simulated prosthesis is quasi-active [2], i.e. it is primarily a passive device, however, it is able to change the zero position of the spring between steps effectively modulating the stiffness profile. We further changed the stiffness and damping coeffecient of the active prosthesis in the .osim model file as depicted in the Table 1. A reduction in spring force and increase in damping was necessary due to restrictions in the simulation environment when moving from a physical spring to a virtual spring, however these coeffecients are still whithin the normal range for healthy

4th Conference on Robot Learning (CoRL 2020), Cambridge MA, USA.

hman walking ?]. Additional, modifications were necessary to both the model and simulation environment, including the time between simulation steps, number of frames skipped between steps, simulation time limit, and the heading and velocity profiles over time; all of which are also detailed in Table 1. Fig. 1 shows an image sequence from a walking gait when using the actuated prosthesis. General biomechanical variables are notably absent from the returned observation in the simulator. We therefore added a new object dictionary to return: joint reaction forces, joint reaction moments, prosthesis spring force, joint kinematics, and summation of muscle forces on the prosthesis side (right).

Table 1: Simulation Constants

Variables	(units)	ProstheticsEnv	Actuated-ProstheticsEnv
Passive Spring Coefficient	(Nm/degree)	225	217
Passive Damping Coefficient	(Ns/m)	1	3
Stepsize	(s)	0.1	0.01
Frameskip	(frames)	10	1
Time Limit	(frames)	500	5000
Initial Velocity	(m/s)	1.25	1.25
Initial Heading	(degrees)	0.0	0.0
Velocity Change	(m/s)	U(-0.5,0.5)	0.0
Heading Change	(degrees)	U(-pi/8,pi/8)	0.0

3 Prosthesis and Sensors in Human Experiments

In Experiment 3: real-world prosthetic experiments, we focused on the utilization of MPIP for a physical human-prosthesis system. The Experimentation employed a number of sensors and devices which will be covered in detail in this section. Two main sensor types in these experiments, namely IMUs and force sensitive ”smart shoes”, were used along with a parallel elastic powered prosthesis. The prosthesis, called the SpringActive Odyssey ankle, is commercially available for purchase.

3.1 Sensors

IMU Design: During both training and testing, participants were fitted with custom IMU devices 2 which collect and disseminate world coordinate angles and angular velocities in real-time at a frequency of 100Hz. The sensors are constructed from four components 1.) an ESP32 device with a 240 MHz dual core Tensilica LX6 microcontroller and inbuilt Bluetooth/Wifi, 2.) a Bosch BNO080 VR IMU with an on-board proprietary sensor-fusion algorithm and communication via I2C, 3.) a 3.7V 2200mAh Lithium Ion battery pack, 4.) custom 3D printed band to comfortably hold sensors to human body segments. Each sensor returns data at 100Hz using the real-time capabilities of the ESP32 device.

Smart Shoe Design: We developed smart shoes to measure 1D ground reaction forces at four points: heel, first metatarsal joint (Meta 1), fourth metatarsal joint (Meta 4) and toe, as shown in Fig. 2. Silicone tubes with 2mm internal and 4mm external diameter were wound into air bladders and connected to barometric pressure sensors to measure pressure at each position. Each smart shoe runs independently and reports sensor values along with a center of pressure (COP) measurement generated from averaged sensor values at 100Hz. Fig. 2 depicts the IMU sensor, the smart shoe design, and the location of the four measurement locations.

3.2 Odyssey Prosthesis

The Ruggedized Odyssey Ankle (ROA) by SpringActive inc. is a battery-powered lower-limb prosthesis ?], designed to use sensors, motors, and springs to produce natural walking motions for lower limb amputees. Like a human ankle, ROA captures energy from the natural walking cycle in a titanium spring and is able to add or subtract energy from the cycle through the actuation of a parallel motor. In this manner, the motor is able to either cooperate with the spring to provide additional power at the ankle during push-off. The device has been demonstrated in a Congressionally

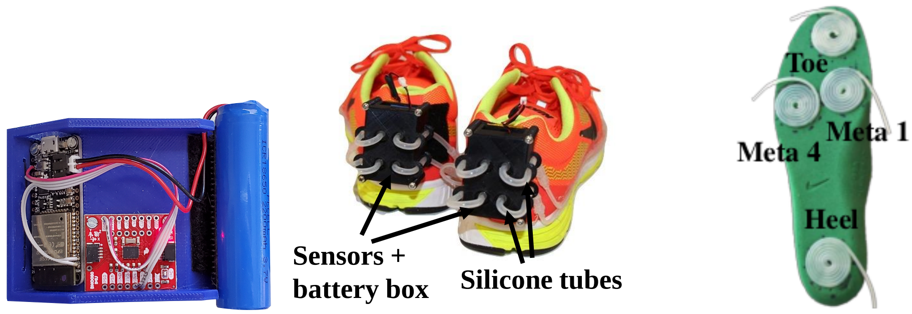

Figure 2: Left: IMU sensor providing orientation information in realtime. Middle: Pressure sensing smart shoes. Right: Location of the four points for measuring ground reaction forces.

Directed Medical Research Program (CDMRP) on amputee volunteers to be able to walk forward and backwards, hop, and transition between forward walking and running at speeds up to 6 miles an hour. It is ruggedized, waterproof, and able to support subject weight of up to 220 pounds. Additionally the device utilizes a carbon fiber foot spring in order to store and return addition power during walking and running or jumping.

Figure 3: The Odyssey battery-powered lower-limb prosthesis which is actuated at the ankle. The Odyssey prosthesis is commercially available through SpringActive inc. [Link].

3.3 Human Biomechanics Model

A simple Biomechanics model of the lower limb and human body was utilized in this work. Our model is formed from the three major physical links of the lower body (femur, shank, and foot). Each of the rigid bodies are connected via revolute joints corresponding to the relevant anatomical joints of (hip, knee, and ankle). To model the important anthropometric dimensions, we turn to [**?**] classic model, with critical constants for the segments and their corresponding bodies listed in Table 2, which denotes: mass as a fraction of body mass, center of mass as a fraction of length, and radius of gyration as fraction of length properties of biomechanical segments used in biomechanical model. Additionally we measured the length value for each subject individually, and assumed the divergence point (CP) or location where the ground reaction force (GRF) for both legs intersect remains 15cm above the subjects Center Mass (CM).

Table 2: Anthropometric Dimensions

	Length (m)	Mass	Center of Mass	Radius of Gyration
Foot		0.0145	0.500	0.470
Shank		0.0465	0.433	0.302
Thigh		0.1000	0.433	0.323
Full Body		1.0	—	—

References

[1] S. L. Delp, F. C. Anderson, A. S. Arnold, P. Loan, A. Habib, C. T. John, E. Guendelman, and D. G. Thelen. Opensim: open-source software to create and analyze dynamic simulations of movement. *IEEE transactions on biomedical engineering*, 54(11):1940–1950, 2007.

[2] S. K. Au, H. Herr, J. Weber, and E. C. Martinez-Villalpando. Powered ankle-foot prosthesis for the improvement of amputee ambulation. In *2007 29th annual international conference of the IEEE engineering in medicine and biology society*, pages 3020–3026. IEEE, 2007.