Improving Automatic Control of an Ankle-Foot Prosthesis using Machine Learning Algorithms

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1 Background

Most commercially available lower-limb prostheses are designed for walking, not for standing. The Minneapolis VA Health Care System has developed a bimodal prosthesis with distinct modes for walking and standing [1]. With this device, a prosthesis user can select standing or walking mode in order to maximize standing stability or walking functionality, depending on the activity and context. Additionally, the prosthesis was designed to allow for an “automatic mode” to switch between standing and walking modes based on readings from an onboard Inertial Measurement Unit (IMU) without requiring user interaction to manually switch modes. A smartphone app was also developed to facilitate changing between walking, standing and automatic modes.

The prosthesis described in [1] was used in a pilot study with 18 Veterans with lower-limb amputations to test static, dynamic, and functional postural stability. As part of the study, 17 Veterans were asked for qualitative feedback on the bimodal ankle-foot system (Table 1).

<table>
<thead>
<tr>
<th>Question</th>
<th>Yes</th>
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<tbody>
<tr>
<td>Do you want an automatic mode?</td>
<td>82% (14/17)</td>
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<tr>
<td>Do you want smartphone control?</td>
<td>12% (2/17)</td>
</tr>
<tr>
<td>Do you want physical switch control?</td>
<td>82% (14/17)</td>
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Table 1 – Feedback from Veterans

The majority of participants (82%) expressed an interest in having an automatic mode. The participants also indicated that the automatic mode would need to reach walking mode on their first step and to lock the ankle quickly once the standing position was achieved. When asked about how they wanted to control the modes of the prosthesis, 82% wanted to use a physical switch and only 12% wanted to use a smartphone app. The results indicated that the following major design changes would be needed:

1) A fast and accurate automatic mode
2) A physical switch for mode changes

2 Methods

In order to improve the algorithm used to control the automatic mode, we collected IMU data as an able-bodied participant performed a predefined sequence of standing, walking, and turning actions in order to train and test machine learning algorithms. The participant used a pseudo-prosthesis (walking boots attached to an ankle-foot prosthesis with a pyramid connector) with an IMU (Actigraph Link) strapped to the pseudo-prosthesis to record accelerometer and gyroscope data. The participant performed the following actions twice under similar conditions while recording IMU data (Figure 1):

1) Stand still
2) Sway side to side, then stand
3) Sway forward and backward, then stand
4) Walk sideways to the left, then stand
5) Walk sideways to the right, then stand
6) Stand, turn left 90 degrees, then stand
7) Stand, turn right 90 degrees, then stand
8) Walk slowly, starting with left foot, then stand
9) Walk slowly, starting with right foot, then stand
10) Walk quickly, starting with left foot, then stand
11) Walk quickly, starting with right foot, then stand
12) Walk, turn left 180 degrees, then walk
13) Walk, turn right 180 degrees, then walk
14) Walk, turn left 90 degrees, then walk
15) Walk, turn right 90 degrees, then walk
16) Stand still

The IMU data was sampled at 100 Hz. We extracted features from the IMU data that are commonly used for human activity classification [2], including mean and standard deviation of the three axes of the accelerometer, the acceleration magnitude, and the three axes of the gyroscope. We used 1-second sliding windows with 50% overlap. Video was also recorded during the data collection and was used to label the IMU data with the intended mode, walking or standing. The data was then analyzed by a variety of machine-learning algorithms to assess which one was the most accurate.

Figure 1 – Gyroscope data recorded during walking, standing, and turning events
To determine how to best add a physical switch to the design of the bimodal ankle-foot system, we purchased a wide variety of three-position switches. We then asked certified prosthetists and experienced prosthetics designers for feedback on which type of switch would be easiest for Veterans with lower-limb amputations to use and where the switch should be located on a prosthesis.

3 Results

We compared the performance of several classes of supervised machine learning algorithms including decision trees, support vector machines, k-nearest neighbors, and ensemble classifiers using the MATLAB Statistics and Machine Learning Toolbox. We used 10-fold cross-validation to protect against over-fitting the data. Using principal component analysis, we found that four features explained 98% of the variance in the data. Although bagged trees had the highest accuracy at 96.8%, we chose to use a linear support vector machine with a slightly lower accuracy (95.8%) because it was faster to train and easier to interpret. When we looked at the misclassified predictions, we found they mainly occurred during the walking-standing transitions and may be due to the temporal inaccuracy of using video to label the data. We don’t anticipate these misclassifications will cause problems in actual use, because the algorithm updates every 500 ms while the bimodal ankle-foot system requires 750 ms to unlock. We expect the ankle to switch to the correct mode before the user finishes the first step or comes to a complete stop.

Using input from the prosthetists and prosthetics designers, we selected a three-position switch that allows for prosthesis users to quickly and easily put the device into a standing, walking, or automatic mode (Figure 2). The switch would provide tactile information about which mode it is in. The lateral side of the prosthetic socket was chosen as the location to position the switch, so users can operate the switch without bending down too far. Additionally, a recessed housing was designed for the switch to prevent inadvertent toggling.

We have substantially improved the design of the bimodal ankle-foot prosthesis by adding a fast and accurate classification algorithm and an easy-to-use physical switch. Future work will include extended testing of the system by several prosthesis users, further algorithm refinements to adjust for individual preferences and needs, and take-home testing. Ultimately, we believe this approach will significantly enhance the stability, functionality, and ease-of-use of ankle-foot prostheses in real-world environments.

Acknowledgments

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