Vibrotactile Haptic and Gesture Feedback in a Smartwatch for Controlling a Multi-Activity Powered Knee-Ankle Prosthesis

Amy E. Lang, Curt A. Laubscher, Shihao Cheng, and Robert D. Gregg

***Abstract*— For powered lower-limb prostheses to be translated from research environments to real-world use, they must be able to perform a variety of daily activities, such as walking on level or ramped surfaces, stair climbing, sitting, and standing. The device must quickly and predictably switch between the modes corresponding to these activities. Multiple methods exist to trigger activity mode transitions, but they can overlook user agency, be slow and cumbersome to enact, lack discretion, or have limited predictability. This work presents a smartwatch application that allows the user to wirelessly control the activity mode of the prosthesis. The user can perform a swipe gesture on the smartwatch to transition to the desired mode, while the smartwatch provides vibrotactile haptic and visual feedback to the user to indicate the activity mode of the device. An experiment with one transfemoral amputee participant showed that the smartwatch application is viable for providing user control of the activity mode to traverse a multi-activity circuit using a powered knee-ankle prosthesis.**

I. Introduction

Individuals who underwent lower-limb amputation can see great improvements in mobility by using powered prostheses due to their ability to provide net-positive work and active control [1]–[6]. For these devices to be accepted by users outside of controlled laboratory environments, they must be practical for everyday use. Translation to these real-world settings requires the device to successfully function in the various activities expected in daily life, such as level or incline walking, stair climbing, and sitting/standing.

In practice, prostheses support multiple activities by implementing them as separate activity modes, typically within a finite state machine [6]. The amount of modes can be excessive when accounting for various terrains, though it can become tractable through consolidation. Researchers have achieved this by unifying walking at variable slopes [7]–[9] and speeds [9], stair climbing at multiple inclines [10], [11] and speeds [10], and sitting/standing at different seat heights [12]. Transitions between these activity modes are dictated by a set of conditions defined by a control policy. The choice and complexity of conditions depend on the number of activity modes, available sensors, and processing capability of the on-board electronics.

For simpler systems, a manual control policy is often used to change the activity mode [13]. For example, researchers remotely trigger transitions in some laboratory studies [14], [15], but this removes agency from the user and prevents translation into real-world use. User autonomy can be restored through user-held accessories, such as a key fob [16], [17] or smartphone [17], but its frequent retrieval would be slow, tedious, and indiscreet. In other setups, the user can trigger activity transitions without external tools by deliberately positioning themselves in certain configurations [16], [18], but this can also be slow and cumbersome. While manual methods can guarantee proper function and instill trust when first using the prosthesis [19], practical use cases require solutions that are more accessible, convenient, timely, and discreet.

For more capable systems, an automatic control policy using a real-time intent recognition system can rectify the limitations of the aforementioned manual control policies by automatically classifying and changing the activity mode. One avenue for such systems is to use a heuristic method [6], [20]–[22]. Users can easily learn and understand this rule-based approach as their transitions are triggered from interpretable measured quantities crossing thresholds. An alternative method is to use machine learning [23]–[26]. Such black-box models are trained using data in a rolling time window from a sensor suite to recognize non-obvious patterns that correspond to specific modes or their transitions. Both methods offer ways for prosthetic devices to automatically transition between activity modes quickly and unobtrusively.

Although these classifiers are able to automatically change between activity modes with up to 99% accuracy in real time [20], classification errors are still inevitable. These errors can be exacerbated by prolonged use [27] and by operation in untested or unpredictable environments, such as inclement weather or crowded areas. Any misclassification could lead to a stumble or fall, posing a safety risk to the user. This risk can be furthered if the user is unaware of changes in the activity mode [19]. Unpredictable behavior can result in user distrust and reduced acceptance of the device. Thus, it is essential to retain a simpler manual control policy wherein the user has direct influence over the activity mode of the device. When used in conjunction with an automatic control policy with an intent recognition system, the user can use the manual method to override automatic prosthesis decisions in such undesirable circumstances. Additionally, providing the user with information about the internal state of the controller can reduce uncertainty about prosthesis behavior.

The main contribution of this paper addresses the need for an accessible, convenient, timely, and discreet means to directly and reliably interface with a prosthesis. This was

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done by developing a feedback system featuring bidirectional wireless communication between a smartwatch application and a powered knee-ankle prosthesis. The user can input gestures on the smartwatch to change the activity mode of the prosthesis, and the system provides vibrotactile haptic and visual feedback to the user to indicate changes in activity mode. This is an extension of prior work in [14], which evaluated a controller in a multi-activity circuit. The researcher changed the activity mode at timely points during the experiment, and the user was provided audio-visual feedback of the mode through a television. The work in this paper uses the smartwatch to enable the user to directly change the activity mode while providing a means of alerting the user of changes in these modes. These features are validated with a transfemoral amputee participant traversing the same multi-activity circuit. The participant used the smartwatch to successfully navigate 15 laps on the circuit while accurately changing activity modes at the transition locations.

II. Methods

A. Prosthesis Hardware and Control

In this paper, we integrated the smartwatch with our powered knee-ankle prosthesis, described in [2] and shown in Fig. 1. The device uses low-impedance quasi-direct drive actuators and G-SOLO Twitter R80A/80VDC drivers (Elmo Motion Control, Petah Tikva, Israel) to produce high torque through a 22:1 single-stage stepped-planet compound planetary gear transmission. The joint angles are measured with E5 optical quadrature encoders (US Digital, Vancouver, WA, USA). The thigh and foot global orientation angles are measured via inertial measurement units (HBK Microstrain, Williston, VT, USA). Gait events and center of pressure are calculated from ground reaction forces and moments measured with a 6-axis load cell (M3564F, Sunrise Instruments, Nanning, China) mounted above the foot. A forward-facing ultrasonic distance sensor (LV-MaxSonar-EZ4, MaxBotix, Brainerd, MN) affixed to the device measures distances to obstacles or stairs [28]. The prosthesis controller operates in LabVIEW software (National Instruments, Austin, TX, USA) running on a myRIO microcontroller (National Instruments, Austin, TX, USA) interfacing with the sensors and actuators.

The prosthesis can select from four mid-level controllers corresponding to the four activity modes: walk, stair ascent, stair descent, and sit-stand [14]. The walk controller adjusts joint impedance and kinematic references (during stance and swing, respectively) based on estimates of a phase variable, defined as the progression through the gait cycle, and task variables, namely walking speed and incline angle [9]. This allows the prosthesis to continuously adapt to changing speeds and ramps, while also reducing the size of the activity space by unifying the ramp and level walk activities. The stair controller extends this phase-based architecture to stair ascent and descent for various staircases [11]. Additionally, the ultrasonic distance sensor is used to prevent toe stubbing on stairs [28]. The sit-stand controller likewise uses phase-based control to allow both standing and sitting motions with a unified activity mode [12]. The prosthesis has an automatic

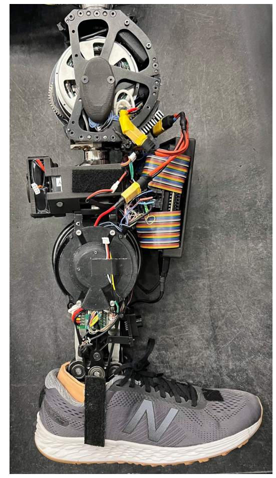

Fig. 1. The powered knee-ankle prosthesis used for this study. Users of the device can perform multiple activities: level and ramp walking, stair climbing, and sitting/standing.

classifier that can select between activity modes based on real-time measurements of the configuration and environment [20], though this feature was disabled in this study.

B. Smartwatch and Application

The smartwatch used for this study was the Google Pixel Watch 2, model G4TSL (Google, Mountain View, CA, USA). The device includes an eccentric rotating mass vibration motor which can provide vibrotactile haptic feedback to the wearer. It can also directly connect to a Wi-Fi network and communicate wirelessly to other devices on the local network without needing a paired smartphone. The smartwatch battery lasts 3.5 hours while the application is running.

For the prosthesis to provide vibrotactile haptic feedback to the user and receive input gestures from them, we developed a smartwatch application using Java in Android Studio. The application communicates with the prosthesis via a transmission control protocol (TCP) connection to the LabVIEW software. This allows for bidirectional communication between the prosthesis and smartwatch while ensuring a reliable and correctly ordered transmission of the data.

When the smartwatch application is open, it automatically connects to the prosthesis and displays the four supported activity modes in four quadrants on the screen. Each quadrant is color-coded and labeled with the name and pictogram representing the mode, similar to prior work where this information was shown on a television [14]. When the activity mode changes, the smartwatch highlights the corresponding quadrant (Fig. 2). In addition, the smartwatch gives vibrotactile haptic feedback to the user by vibrating a unique pattern. The sequences of vibration pulses were designed to be distinct for each activity and are illustrated in Fig. 3.

In addition to haptic feedback, the smartwatch also offers users the ability to change the activity mode of the prosthesis. Swiping across the smartwatch screen from one quadrant to the opposite side changes the activity mode to the one corresponding to the starting quadrant. In addition

Fig. 2. Physical smartwatch (left) and user interface of the smartwatch application (right) highlighting the four available activity modes. Swiping the screen from the quadrant labeled with an activity mode to the opposite side commands the prosthesis to change into that mode.

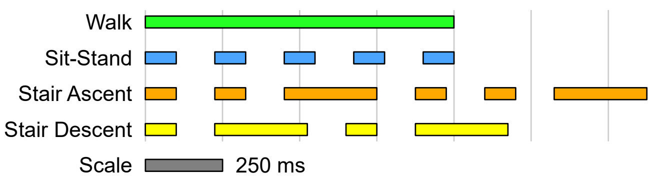

Fig. 3. The smartwatch application vibrates with unique patterns whenever the prosthesis changes activity modes. Solid lines indicate times when the smartwatch vibrations are active, and gaps indicate when they are inactive.

to the swiping gesture, a wrist flick gesture within three seconds of a mode change will revert to the previous activity mode. Transitions to different activity modes are smooth and without discontinuities in the motion and torque due to the continuous, phase-based design of each controller [20].

C. Experimental Protocol

The study protocol was approved by the Institutional Review Board at the University of Michigan (HUM00230065). One transfemoral amputee participant (male, 175 cm, 91.5 kg with the powered prosthesis, 24 years, 10 years since amputation, dysvascular etiology) was recruited to participate in the study and provided written informed consent.

To validate the proposed smartwatch application and feedback system, the participant was asked to navigate the multi-activity circuit based on [14] shown in Fig. 4. The circuit was 42.4 m round-trip and included two stools (44.5 cm seat height), a ramp (11.2° incline), a five-step staircase (14.4 cm riser height and 33.3 cm tread depth), and a walking straight to encompass all of the activity modes on the prosthesis. The ramp, staircase, and straight were equipped with parallel bars. The participant was introduced to the smartwatch and given time to become familiar with the swipe gestures and vibrotactile haptic feedback. He practiced traversing the circuit using the smartwatch for about one hour total prior to the main experiment. The participant was asked to complete 15 self-paced round-trip laps of the circuit using only the

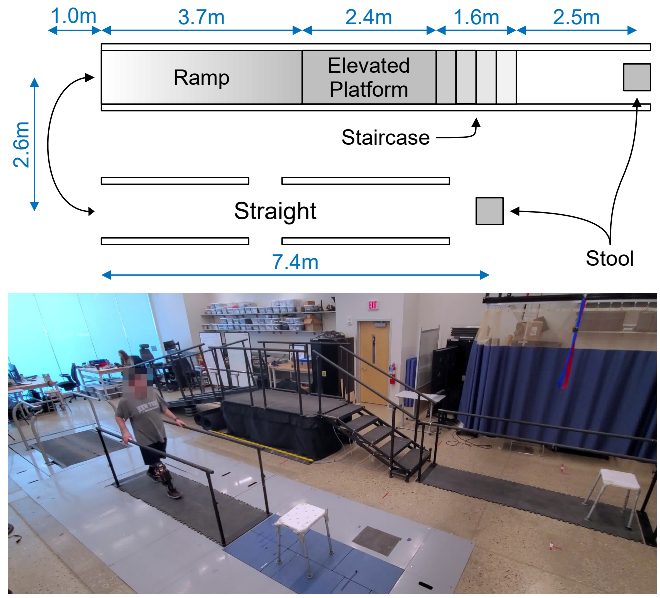

Fig. 4. Experimental setup of the multi-activity circuit, including two stools (44.5 cm seat height), a ramp (11.2° incline), and a five-step staircase (14.4 cm riser height and 33.3 cm tread depth). Top: Aerial schematic with key dimensions. Bottom: Oblique view photograph with the participant during the experiment.

smartwatch to change activity modes. The participant was not given specific instructions on how to transition between activities. He could choose whether to transition with his intact or prosthetic leg and when to swipe to change modes.

III. Results and Discussion

The participant successfully navigated the multi-activity circuit and completed all 15 laps using only the smartwatch to change prosthesis activity modes. Fig. 5 shows a time series plot of the activity mode along with the prosthetic joint kinematics and reference able-bodied trajectories predicted by the controller [20] based on models trained from able-bodied data [29]–[31].

A. Swipe Gesture Prosthesis Feedback

The participant never unintentionally swiped to an incorrect activity mode in the 360 total transitions. Only one transition required the participant to swipe twice for the input to register. This suggests that the application is reliable and provides a feasible option for the user to control the activity mode of the prosthesis. The lack of misdirected swipes suggests that the layout and gesture were easy to remember and readily accessible throughout the multi-activity circuit. There was a short latency (128 ms mean, 47 ms standard deviation) between when the user swiped on the screen and when the prosthesis changed activity modes, estimated as half the round-trip time for smartwatch-prosthesis communication. Though the lag did occasionally result in the participant looking at the smartwatch display to verify the activity mode, the delay was not long enough to prompt him to swipe on the screen again for most transitions, indicating that the communication was quick enough to remain viable for use.

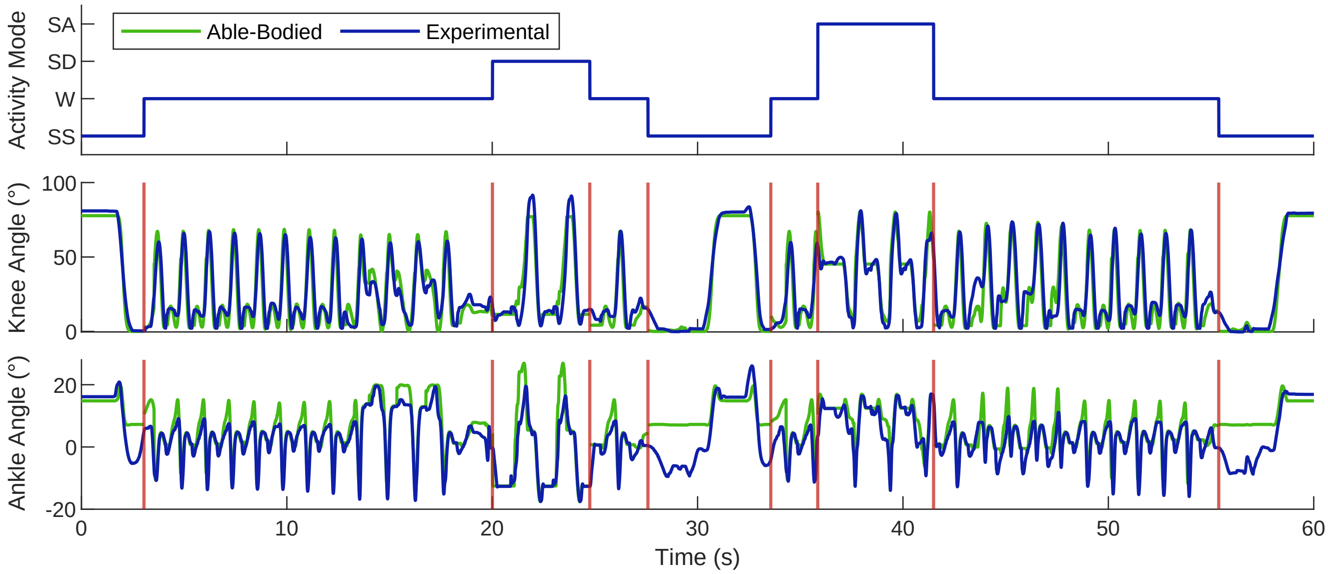

Fig. 5. Time series plot of activity mode and knee and ankle kinematics for one representative lap out of 15 laps where the participant traversed a multi-activity circuit. Activity mode can be sit-stand (SS), walk (W), stair descent (SD), or stair ascent (SA). Red vertical lines indicate occurrences when the prosthesis changes activity modes due to smartwatch swiping gestures from the participant. For comparison, green curves correspond to reference able-bodied trajectories predicted by the prosthesis controller [20] based on models trained from able-bodied datasets [29]–[31]. Positive angles correspond to (dorsi)flexion and negative angles correspond to plantarflexion/extension. During SS, ankle angle deviations can result from compliance allowed by the impedance controller, and the portions of constant able-bodied kinematics resulted from phase saturation due to the participant pausing or turning around.

B. Vibrotactile Haptic User Feedback

Before performing the experiment, the participant was introduced to the smartwatch. Although not explicitly quantified, the participant found that the vibrotactile feedback patterns were intuitive for each activity mode and was able to easily perceive and discern them. During the experiment, however, the participant reported a reduced capacity to notice and distinguish the vibrations. This disparity may have been due to focusing on the ambulation tasks and switching the activity mode of the prosthesis, which diverted attention away from the low-magnitude vibration. Though, the participant stated how "it was there in the background" and started to notice it more after further experience using the smartwatch.

C. Activity Transitions and Timings

For the sit-stand to walk transition, the participant consistently took the first step with his intact side. He swiped to change to the desired activity mode during late swing, which allowed seamless mode changing around intact heel strike or prosthesis toe-off. For the walk to sit-stand transition, he often took the final half-stride step with the intact side before bringing both feet together. While standing, he swiped and then turned around to sit down. For the walk to stair descent transition, the participant also typically brought both feet together at the top of the staircase, then swiped while lifting or soon after lifting the prosthetic leg to take the first step down. Occasionally, he skipped bringing his feet together and instead swiped during mid-swing of the prosthesis. Either way, the activity mode change occurred before the heel strike of the first step down. For the stair descent to walk transition, he always transitioned using his intact side. He swiped during a brief pause in mid-swing of the following prosthesis transition stride, which was early enough to change modes before the following heel strike. However, he consistently used the handrails to maintain balance at this time. For the walk to stair ascent transition, the participant always took the first step up with the prosthetic side, pausing during mid- to late-swing with the prosthetic leg hovering above the first staircase step to swipe to the desired activity mode. For the stair ascent to walk transition, he always took the last stride with an elevation change on the prosthetic side. He paused and swiped during late-swing, though this pause became negligible later in the experiment with more experience.

D. Limitations and Future Work

There are a few known limitations of the smartwatch application system and possible areas for improvement. First, a desynchronization between the smartwatch and prosthesis led to the participant swiping twice to change activity modes in one instance, ultimately requiring a system reset to fully resolve. Future work entails improving system robustness to prevent such technical faults. Second, the smartwatch vibration was of low magnitude, which likely hindered the ability for the participant to notice the vibration patterns during the experiment. Future work includes replacing the smartwatch with one equipped with a more powerful motor. Finally, accidental pressing of the smartwatch crown can hide the interface, which occurred once during the experiment. The application continued running as a background process, so the participant was able to reopen the application and resume the experiment. However, behavior of the crown is not customizable due to software limitations.

Additionally, there are a few ways to expand the capabilities of the smartwatch application. First, the current implementation is limited to circumstances where the user manually changes the activity mode. Future work could allow the user to switch to the automatic classifier from our prior work [20], using the smartwatch to override occasional misclassifications. This would improve timeliness as it would no longer require pauses during swing in some transitions, as discussed in Section III-C. This also eliminates the need for the user to hold their leg in the air, which would be particularly straining for individuals with weak residual limbs. In conjunction with this, we will test the wrist flick gesture for reverting to the previous activity mode. Finally, future experiments will have a larger sample size of participants in less controlled real-world environments to better interpret the application performance and possible clinical benefits.

IV. Conclusion

In this study, we presented a smartwatch application that wirelessly interfaced with a powered knee-ankle prosthesis to give the user control over the activity mode of the device with vibrotactile haptic feedback about the state of the device. The application enabled a participant to manually change the activity mode of the prosthesis and successfully navigate a multi-activity circuit. The results of this study suggest that the smartwatch offers a viable way to control the behavior of the prosthesis, which can be extended to more use cases.

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