AN INEXPENSIVE AND ADAPTABLE PROSTHETIC WRIST IMPROVES DEXTERITY AND REDUCES COMPENSATORY MOVEMENTS

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ABSTRACT

Many presently available prostheses lack a functional wrist. Here, we highlight the development of an inexpensive prosthetic wrist that can be adapted to work with various sockets and prostheses. Using this prosthetic wrist, we explore the functional and cognitive impact of using a prosthetic wrist to perform activities of daily living. We measured task performance, compensatory movements, and cognitive load while transradial amputees performed a Clothespin Relocation Task (CRT) using a prosthesis attached to the wrist controlled by surface electromyography (EMG). Three transradial amputees performed the task with and without EMG control of the wrist. In aggregate data, the success rate was significantly higher in the wrist condition (61% ± 9% mean, ± standard error) than in the no-wrist condition. Compensatory movements were also better; e.g., the maximum leftward bend at the hip was less in the wrist condition (18.9° ± 1.2°) than in the no-wrist condition (15.0° ± 1.4°). The addition of controlling a prosthetic wrist had no significant impact on cognitive load, as assessed by the NASA Task Load Index survey and the detection response time to a secondary task. This work suggests that using a prosthetic wrist may increase dexterity and reduce joint strain for amputees without requiring a significant increase in cognitive effort compared to that of EMG control of a hand alone. These results can guide future development and prescription of upper-limb prostheses.

INTRODUCTION

Transradial amputees have expressed a strong desire for powered wrist prostheses. Indeed, the top five priorities for transradial amputees, in order of importance, were reported as: wrist rotation, simultaneous movements of multiple degrees of freedom, wrist deviation, wrist flexion/extension, and reduced cognitive demand [1]. Other priorities included reduced weight, improved durability, and increased strength [1]. Without a wrist, amputees are forced to compensate with unnatural movements to complete routine activities of daily living (ADLs) [2], [3]. The continual use of these motions causes damage to the musculoskeletal system over time [4], [5].

Despite the end-user desire for functional wrist movements, very few prostheses incorporate a powered wrist module [6], [7], and those that do are often expensive or not widely available. Here we describe the development of a powered, 3D-printed, inexpensive and adaptable prosthetic wrist. We also validate the function of this wrist with three transradial amputees and show more natural upper-limb kinematics without a significant increase in cognitive load. This work constitutes an important step towards addressing amputees' self-reported needs and reducing compensatory movements that would otherwise cause musculoskeletal damage.

METHODS

Wrist Design

The Utah wrist was designed with two degrees of freedom (DOFs) to provide pronation/supination and flexion/extension of the wrist (Fig. 1). The second DOF can also be used for deviation depending on how the prosthesis is mounted to the wrist. To mimic the strength of a natural wrist, two high-power hobby servo motors (Hitec D980TW, Hitec RCD USA, Poway, CA) were used with a 7.5-V, 20-A power supply (967-CUS200LD7R5, TDK-Lambda Americas Inc., National City, CA) to provide 4.3 N-m of torque. The wrist was designed to adapt to different prosthetic hands (Fig. 1C) and sockets (Fig 1E). The wrist was 3D printed using polylactic acid (PLA) to minimize the weight and cost of materials. See Table 1 for the full design specifications.

Functional Assessment and Participants

The clothespin relocation task (CRT) is a commonly used upper-limb dexterity assessment that involves moving a clothespin from a horizontal bar to a vertical bar. The clothespin is placed 8 inches down the length of the horizontal bar and 8 inches up the vertical bar (Fig. 2A) [8]. Participants were instructed to move as many clothespins in a 30 second window as possible. Dropped clothespins were recorded against successful attempts to measure success. The CRT was completed by three transradial amputee participants with and without the wrist enabled. The wrist was connected to a functional check socket (Citterman et al., MEC 2022) and a left-handed TASKA hand (Fig. 2B). All participants gave written informed consent before taking part in experiments, in accordance with the University of Utah Institutional Review Board and the Department of Navy Human Research Protection Program.

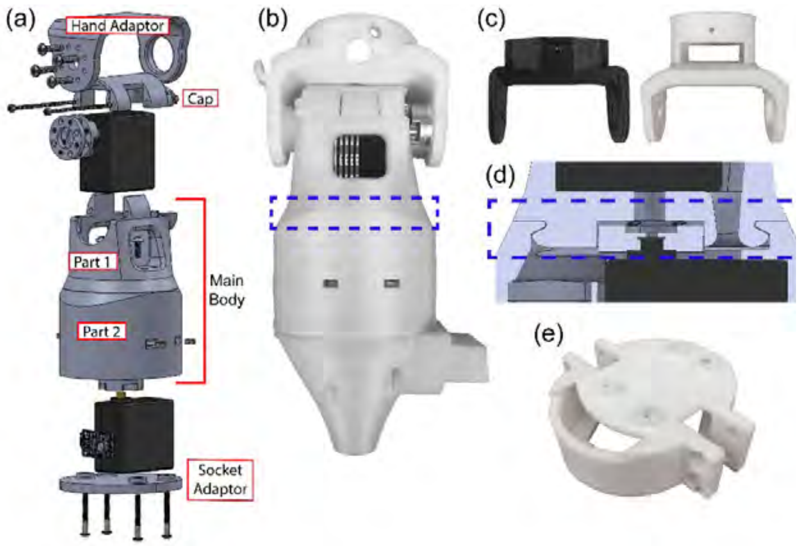

Figure 1: **A)** Exploded view of the Utah Wrist. **B)** A photo of the assembled wrist with the attachments to connect to a bypass socket. **C)** The wrist can adapt to a variety of different terminal devices by printing a new interface part such as the two shown here. **D)** Expanded view of the rotary joint mechanism, as highlighted in part B. **E)** The wrist can connect to different kinds of sockets by printing out a new interface such as the part shown here.

During the CRT, the participants had inertial measurement units (IMUs) attached to their chest and left bicep to measure any compensatory movements (Fig. 2C). While completing the holding task, the participant simultaneously completed a detection-response task (DRT) to measure their cognitive load [9]. The DRT requires the participant to push a button in response to a small vibrating motor on their collar bone. Both the response rate (i.e., how often they respond to the vibratory stimuli) and response time (i.e., how long it takes to press the button after vibratory stimuli) are used as direct measures of cognitive load. Participants completed the CRT as many times as possible within 30 seconds. Data were collected with and without the wrist in a pseudo-randomized counter-balanced blocks. The success rate was defined as the total number of successful transfers out of the total number of attempts within the 30-second time period. Participants completed the NASA Task Load after each block (i.e., with the wrist and without the wrist).

Table 1: Design Specifications

Degrees of Freedom	Pronation/Supination in series with Flexion/Extension or Radial/Ulnar Deviation
Length	11.8 cm
Weight	360 g
Range of Motion	Pronation/Supination – 180 Degrees Radial/Ulnar Deviation or Flexion/Extension – Up to 175 Degrees
Torque	4.3 N*m (both motors)
Cost	< $600

Signal Acquisition

Surface EMG from the participants was collected using a custom EMG sleeve [10]. EMG was sampled at 1 kHz and filtered using the Summit Neural Interface processor (Ripple Neuro Med LLC) as described in [11]. EMG features used for estimating motor intent consisted of the 300-ms smoothed mean absolute value (MAV) on 528 channels (32 single-ended channels and 496 calculated differential pairs) calculated at 30 Hz, as described in [11]. Joint angles were measured using two shimmer3 IMUs (Shimmer Sensing, Dublin, Ireland) attached to the participant's chest and bicep. A third IMU was placed on the table in a fixed orientation to provide a reference. The IMUs measured acceleration, rate gyration, and magnetic heading at 64 Hz, which were then used to calculate quaternions and generate rotation matrices for leftward bend at the hip.

EMG Control

A modified Kalman filter (MKF) was trained using individual and combination movements to control grasping/opening of the hand, pronation/supination of the wrist, and flexion/extension of the wrist. Training data consisted of participants mimicking pre-programmed movement of the individual DOFs in isolation, as well as combination movements involved simultaneous movement of two DOFs (e.g., grasping and rotating). Additional details regarding the modified Kalman filter and training data can be found in [12]. A latching filter was applied to the kinematic output of the prosthetic hand to increase grasping stability. [13]

Data Analysis

Participants were given two blocks of 30 seconds to complete the CRT as many times as possible for a given condition. Thus, the number of attempted clothespin transfers was variable per condition and per participant, but the overall success rate was fixed to two per participant (i.e., one success rate for each of the two 30-second blocks). Data were aggregated across all participants and blocks and determined to be parametric by the Anderson-Darling test. The success rates with and without the wrist were compared using a paired t-test. Similarly, the detection response rate and NASA TLX scores were compared using a paired t-test. Because the total number of attempted transfers was not consistent between conditions, the maximum joint angles with the wrist and without the wrist were compared using an unpaired t-test. Similarly, the detection response time was compared using an unpaired t-test. Because the data were parametric, all data is reported as mean ± standard error.

RESULTS

Task Performance Improved with Use of Wrist

In the data aggregated across trials and blocks, the task success rate (Fig. 3A) was higher with use of the wrist (61% ± 10%) than without the wrist (33% ± 15%); ($p < 0.05$; paired t-test). Thus, task performance was 85% higher with use of the wrist.

Amputees Required Less Compensatory Movements with Use of Wrist

Moving the clothespin from the horizontal bar to the vertical bar without the wrist required the participant to compensate by bending leftward at the hip. When the wrist was enabled, participants naturally used the wrist to perform the task with movements more akin to an intact hand. Collectively, the three participants showed a significant difference in the maximum joint angle at the hip (Fig. 3B). Maximum hip joint angle was 18.9° ± 1.2 without the wrist compared with 15.0° ± 1.4 with the wrist ($p < 0.05$, unpaired t-test). Thus compensatory movements at the hip were 21% smaller when wrist control was enabled.

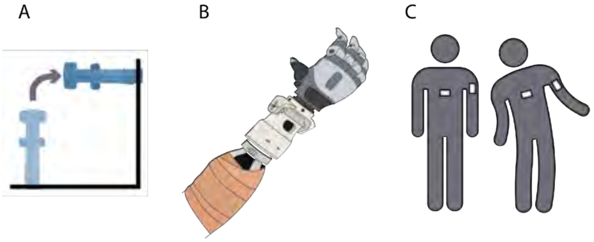

Figure 2: A) The Utah wrist was attached to the amputee participants using the transradial check socket. **B)** IMUs were attached to the amputee participant's chest and bicep to show the deflection angles as the amputee attempts to complete the task. **C)** The amputee was instructed to pick up a clothespin and move it from a horizontal beginning position to a vertical end position.

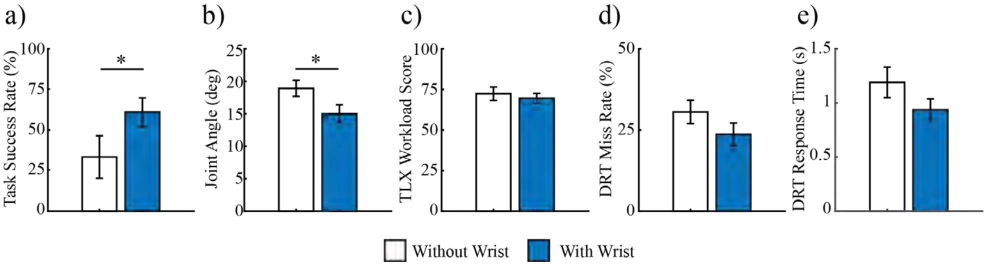

Figure 3: A) Success rate for the CLT was significantly greater with the wrist compared to without the wrist. **B)** Compensatory movement at the hip (i.e., the maximum angle deviation) was significantly reduced with the wrist compared to without the wrist. **C)** No significant differences were seen in the subjective workload with the wrist vs without. **D)** No significant differences were seen in the DRT miss rate with the wrist vs without. **E)** No significant differences were seen in the DRT response time with the wrist vs without. Data show mean ± standard error. * $p < 0.05$. Paired t-tests were used for task success rate, subjective workload, and DRT response rate (N = 6). Unpaired t-test were used for the maximum angle deviation (N = 23 attempts vs N = 25 attempts) and the DRT response time (N = 39 responses vs N = 42 responses).

Use of the Wrist Did Not Significantly Increase Cognitive Load

Somewhat surprisingly, adding two additional controllable DOFs with the wrist did not significantly increase cognitive load. Collectively across participants, the subjective workload was reported as 72.4 ± 4.1 without the wrist and 69.6 ± 2.9 with the wrist ($p = 0.624$, paired t-test; Fig 3C). There were also no significant differences in the DRT response rate, 31% ± 3.6% without the wrist and 24% ± 3.5% with the wrist ($p = 0.33$, paired t-test; Fig 3D), or the DRT response time, 1.19s ± .14s without the wrist and .93s ± .1s with the wrist ($p = 0.1432$, unpaired t-test; Fig 3E).

CONCLUSION

We developed a low-cost 2-DOF prosthetic wrist that can adapt to various prosthetic terminal devices and sockets. We found that task performance was significantly better and compensatory movements significantly smaller when wrist control was enabled. We also found that the cognitive demand on the participants was not significantly different with the addition of two new EMG-controlled DOFs at the wrist. These results constitute an important step towards the widespread availability of functional prosthetic wrists for amputees and researchers alike.

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