Initial Investigation of a Self-Adjusting Wrist Control System to Maintain Prosthesis Terminal Device Orientation Relative to the Ground Reference Frame

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Abstract— **Lack of adequate wrist control in prostheses forces people with upper limb amputations to use compensatory movements that eventually result in overuse injuries. This is partly because conventional control of myoelectric wrists involves switching between directly controlling the wrist and fixing the wrist relative to the forearm. We propose that by implementing a wrist that is able to maintain the hand's orientation relative to the ground reference frame, here termed *a self-adjusting wrist*, users may see benefits in terms of both compensatory movements and ease of control. In this design study, we describe a simple initial implementation of a self-adjusting wrist. We then introduce and compare five control methods for the system. These methods were tested with six able-bodied participants who used a desk-mounted robotic arm to perform an object transfer and manipulation task. Quantitative and qualitative analyses coupled with user feedback suggest that a self-adjusting wrist may reduce task completion time and number of control interactions, and increase user satisfaction compared to conventional switching-based control. Our results indicate that use of a momentary switch to toggle a robotic hand's orientation between being fixed to the ground reference frame and being either fixed to the forearm reference frame or employing direct wrist control may be the best choice for a self-adjusting wrist. More broadly, by considering a wrist that automatically and continually orients itself to the user and their environment, this work contributes insight about how prostheses and other assistive robotic technology may intelligently adapt in real time to support the daily-life tasks faced by their users.**

I. INTRODUCTION

There were approximately 41,000 people affected by major upper limb loss in the United States in 2005, and that number is expected to increase 131% by 2050 [1]. Improved wrist function, simultaneous two-joint movement, and less need for visual attention were among the top reported research priorities of upper limb amputees in 1996 [2]. This was true for both transhumeral and transradial amputees alike, and similarly among both body-powered and myoelectric prosthesis users. More recent reviews also indicate a need for better wrist control [3]. A 2015 review of the state of the art in wrist prostheses found that powered wrist movement is still rare in commercial systems, and all of those that are powered have only one degree of freedom (DOF), most often rotation [4]. Many researchers have shown that limitations in ease of wrist movement force people to use compensatory movements [5]–[8], as seen in Fig. 1. Some researchers have also shown that despite recent focus on multi-articulating hands, evidence suggests that wrist dexterity may be more important than finger dexterity to avoiding compensatory movements [9].

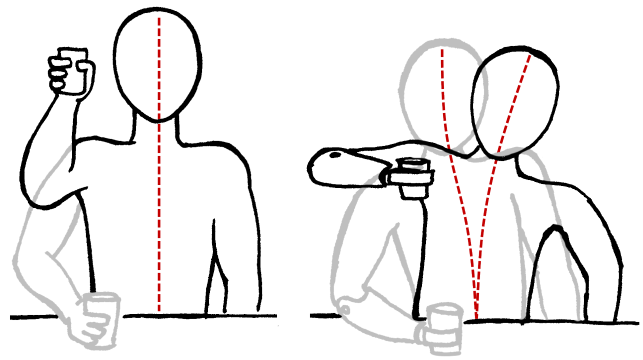

Fig. 1: Lack of wrist dexterity forces users to compensate using shoulder, elbow, and trunk movements in order to keep objects level during lifting.

There is a higher prevalence of self-reported musculoskeletal pain in the neck, upper back, shoulder, and remaining arm of upper limb amputees than in the able-bodied population, and the use of prostheses does not change this prevalence [10]. This indicates that current prostheses do not reduce overuse injuries caused by compensatory movements. We suggest that a wrist that can automatically adjust its position to maintain the hand's orientation as the rest of the arm moves may reduce instances of injuries by reducing the need for compensatory movements.

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II. WRIST FUNCTION

Wrist movement is commonly used for three functions [11], as depicted in Fig. 2:

1) holding the hand fixed relative to the *forearm reference frame*, as when swinging a hammer,
2) reorienting the hand, and
3) holding the hand fixed relative to the *ground reference frame* (i.e., aligned according to the direction of gravity), as when lifting a glass of water.

Conventional myoelectric control typically allows the user to switch between functions (1) and (2). Currently, no commercial system is able to perform the third task: keeping the terminal device fixed relative to the ground reference frame. One of the reasons for this inability is that this third task requires coordinated, synergistic movements between the wrist, elbow, and shoulder. Typical myoelectric prosthesis users are only capable of sequential single-joint movements—the exception to this being skilled users that have also undergone targeted muscle reinnervation surgery. Pattern recognition systems are capable of some coordinated movements [12], [13], but are limited by the available degrees of freedom in commercial wrists, the number of control signals available, and the amount of thought required for control. Wrist flexion units are being developed toward commercial availability [14], [15], but control of these extra degrees of freedom remains challenging [16].

III. PROPOSAL

Designers of above-the-knee leg prostheses have used the predictability of gait patterns to develop microprocessors for artificial knees that adapt stiffness parameters to provide optimal performance at each stage of walking [17]. Typical upper limb tasks seldom involve such predictable movements, making control design difficult—but the third function of the wrist may be suitably predictable. A scheme that maps multiple wrist DOF in a useful way to a single degree of control could improve function. *We propose a self-adjusting wrist control system that would allow automatic repositioning of the wrist in response to arm position to keep the terminal device fixed relative to the ground reference frame.* Autonomous levelling systems have been widely explored in other robotic applications such as camera stabilization [18], and also have applications in rehabilitative and medical technologies [19]. A wrist control system that would work on similar principles was suggested in 1980 [11], and again in 1995 [20], but the technology had not been researched until recently. In 2013, Japanese researchers developed a wrist and hand system that dynamically adjusted hand orientation through a specific pick-lift-place task using lookup tables, multimodal sensors, and state machine logic [21]. A wrist capable of reading RFID tags to re-orient the hand to match a platform's orientation (either vertical, horizontal, or at a random angle) was also explored by Shibuya et al. in 2017 [22]. They showed some initial evidence of reduced compensation, but task time tended to increase because of the need to interact with RFID tags in the environment. The

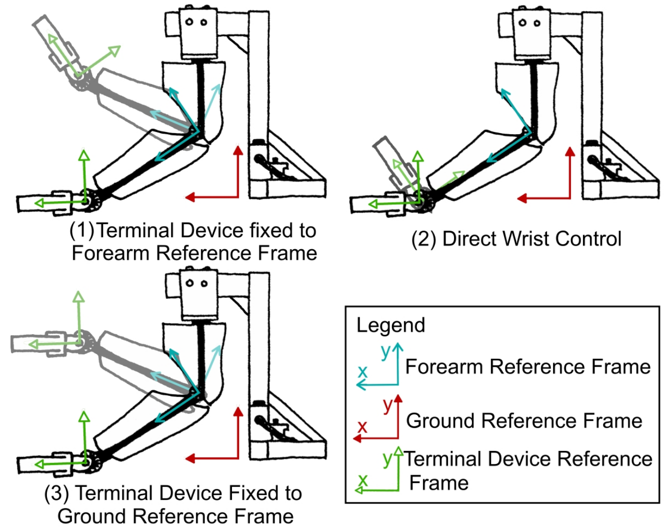

Fig. 2: The wrist has three primary functions, which form the basis of each control mode: (1) holding the terminal device fixed to the forearm reference frame, (2) providing direct control of the terminal device orientation, and (3) holding the terminal device fixed to the ground reference frame.

success of any human-machine interface hinges on the ease with which the human is able to indicate to the machine what operation to perform. In the case of prosthetic limbs, where the machine is integral to the body, this interface is crucial. *This work represents an early concerted focus on the control interface of a self-adjusting wrist, which is important to ensure future user satisfaction and performance.*

IV. METHODS

A. Control Modes

This study compares five methods of interfacing with the self-adjusting wrist. The objective is to determine which method or which characteristics of each method might make the most intuitive interface. The conclusions from this study will be applied to a more rigorous future study comparing the self-adjusting wrist to conventional myoelectric wrist control. The five modes were denoted A through E, and were composed of the three possible types of wrist function: (1) fixed to forearm, (2) direct control, or (3) fixed to ground reference frame, each of which are depicted in Fig. 2.

Each of the control modes switches between two of the above mentioned functions: fixing the terminal device relative to the ground-frame (3), and either function (1) or (2). Depending on the mode, switching is accomplished by either a held button press (the secondary function performed only while a button is pressed), a momentary button press (toggling between the primary and secondary functions), or by input from a secondary control channel (overriding the primary function with the secondary). A visual categorization of how each control mode functions is given in Fig. 3, and examples of the resulting motion are shown in the accompanying video. The control modes are as follows:

A. Momentary button press toggles between fixed to forearm frame (1) and ground reference frame (3)
B. Momentary button press toggles between direct wrist control (2) and ground reference frame (3)
C. Held button press switches from ground reference frame (3) to fixed to forearm frame (1)
D. Held button press switches from fixed to forearm frame (1) to ground reference frame (3)
E. Secondary input channel overrides ground reference frame (3) with direct wrist control (2)
X. *Control Condition:* Conventional control scheme. Momentary button press switches between fixed to forearm frame (1) and direct wrist control (2).

An Xbox 360 video-game controller was used to control the arm instead of myoelectric control in order to achieve cleaner, clearer control signals, thereby reducing inadvertent movements which would make the system more difficult to learn. The "A" button was used for momentary button-presses, held button-presses were accomplished by pressing the joystick button, and the secondary joystick served as the secondary input channel. Rather than using sequential joint control as is typical in myoelectric systems, each joint was mapped to a separate input except wrist control, to facilitate faster learning of the system in general. The right joystick x-axis (side-to-side) controlled shoulder rotation, while the y-axis (up-and-down) controlled elbow movement. The right trigger closed the hand; the left trigger opened the hand. For extension to an electromyography (EMG) system, co-contractions would serve as momentary button-presses, and secondary inputs would require an extra set of EMG channels. The held button-press of modes C and D does not directly translate to EMG control, since a held co-contraction is infeasible. EMG systems can however be paired with other

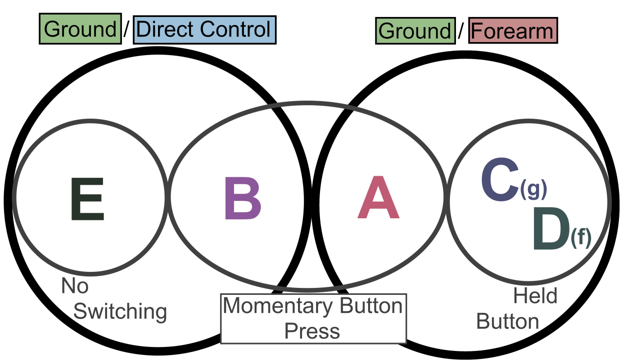

Fig. 3: Each mode can be categorized by the two functions it switches between (either fixed to ground-reference-frame and direct control, or fixed to ground-reference-frame and fixed to forearm-reference-frame) and the method of switching (alternate channel, momentary button-press, or held button-press). The subscripts (g) and (f) indicate the default function of the mode when the button is not held, i.e. ground-fixed reference frame or forearm-fixed reference frame, respectively. The accompanying video further clarifies these modes.

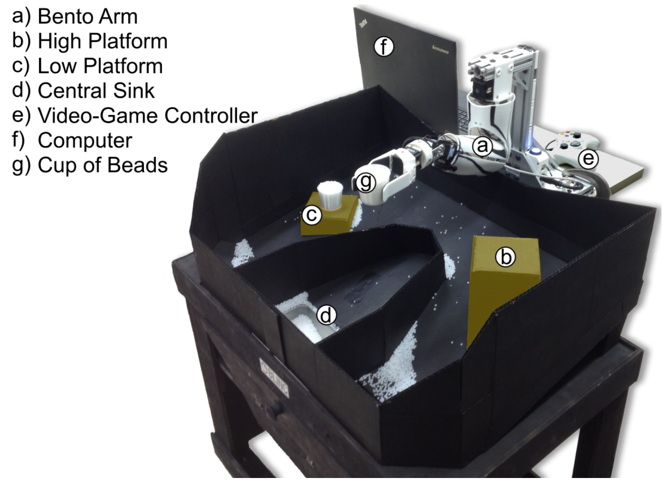

Fig. 4: Bento Arm and a custom cart built to facilitate the tasks, with low and high platforms (highlighted here in yellow) and a central sink. The participant would stand behind the arm, and control it using the video game controller.

switching systems such as latching buttons or body-powered LVDTs which may be used to provide a sustained signal, so modes C and D were included for completeness.

B. Hardware

A self-adjusting wrist must be able to perform well in tasks that require hand reorientation as well as in tasks that require dynamic levelling. Standard evaluations such as the box-and-blocks task or SHAP test do not directly evaluate a user's ability to maintain terminal device orientation relative to the ground reference frame, so a custom evaluation was devised that involved two separate tasks:

1) moving a cup filled to the brim with beads from a low platform to a high platform (requiring use of some adaptive levelling scheme to avoid spilling beads)
2) moving a cup filled to the brim with beads to a sink, and emptying the cup (requiring reorientation of the hand to pour)

To perform the tasks, each participant controlled a desk mounted Bento Arm, developed at the University of Alberta [23]. The arm has five degrees of freedom: rotation of the shoulder, elbow flexion/extension, wrist rotation, wrist flexion/extension, and hand open/close. To simplify the implementation of a self-adjusting wrist for this initial usability study, wrist rotation was restricted.

The amount of wrist deviation was programmed to be kinematically linked to the amount of elbow flexion/extension when performing fixed-to-ground-frame functionality. The equation governing this relationship is

$$\theta_1 = 180^\circ + \theta_3 - \theta_2 \tag{1}$$

The symbols θ_1, θ_2, and θ_3 are defined as in Fig. 5:

θ_1: *Wrist angle.* Clockwise from terminal device to forearm

θ_2: *Elbow angle.* Clockwise from forearm to ground-frame horizontal axis

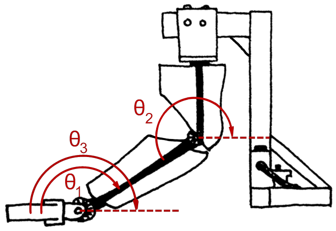

Fig. 5: Schematic diagram of Bento Arm indicating joint angle definitions used in (1).

θ_3: *Terminal device offset angle.* Clockwise from terminal device to ground-frame horizontal axis

The angle definitions correspond with the digital encoder positions built into the servos.

A custom cart was built to satisfy the required environment for the tasks, pictured in Fig. 4. The height difference between the two columns is sufficient to cause beads to spill from a carried cup if the wrist position is not adjusted to maintain a level terminal device. The central sink is too high to allow pouring beads using only elbow motion; a combination of reorientation of the terminal device and elbow position is necessary to completely empty the cup.

C. Experiment Design

The experiment was approved by the Research Ethics Board of the University of Alberta. It was performed with six able-bodied participants, who gave informed written consent prior to participating.

Each participant was first introduced to the general Bento Arm control scheme, and given approximately five minutes to familiarize themselves with the arm and the controls. During this training period no wrist control was given; the terminal device remained fixed to the forearm frame. Participants were then instructed on the format of the trials: each trial consisted of two tasks, each performed once, beginning with the transfer task followed by the pouring task. For each mode the experimenter explained the controls, and then the participant was allowed approximately one minute to gain familiarity. A block of ten trials was recorded for each control mode before introducing the next. The order that the control modes were presented to the participants was randomized. Due to scheduling constraints, the control condition was presented to each participant on a separate day approximately one month after the initial set of trials.

Time of trial completion, number of spills, and number of control switches were measured, and a survey was completed by each participant. Timing began at the first movement of the Bento Arm, and finished after release of the cup upon returning it to the initial platform at the end of the trial. Spills were tracked manually by experimenter observation during the trials, and checked again afterward using recorded video data. A spill was defined as any number of beads falling from the cup unintentionally. The number of beads per spill was not counted, and varied widely. The number of times the "A" button and joystick button were pressed was tracked using the control software.

The survey included four relative comparison questions, a preference ranking, and a section for specific comments. The comparison scores were given throughout the study after each control mode, and participants were allowed to adjust the scores they gave to each mode as the study progressed. The relative comparison questions addressed intuitiveness ("How easy was each control mode to learn?"), effectiveness at the transfer task ("How well did each control mode perform the cup transfer task?"), effectiveness at the pouring task ("How well did each control mode perform the cup pouring task?"), and reliability ("How often did you find the arm moved in a different way than you wanted or expected?"). These comparisons were given scores between 0 and 5, where 0 indicated difficult, very poor, or hardly ever, and 5 indicated easy, exceptionally well, or very often. At the end of the study, participants gave a unique rank to the control modes in order of preference from 1 (most preferred) to 5 (least preferred). Participants then commented on what features of their most and least preferred choices made them the best or worst. Since the control condition was tested on a separate day, it was not included in the qualitative survey to avoid biases due to memory effects.

Mean differences in performance were assessed using a repeated-measures analysis of variance (ANOVA). The F-test of significance was used to assess the effects of the different independent variables. If significance was found, pairwise comparisons (paired-sample t-tests) were made to assess where the differences lie. A Bonferonni correction for multiple comparisons would have been very conservative, so Least Significant Difference was used to highlight differences for this pilot study. Normality was assessed using the Kolmogorov-Smirnov Test and sphericity was assessed through a Mauchlys Test of Sphericity. In cases where the assumption of sphericity was unmet, a Greenhouse-Geisser Correction was applied and reported. This sequence of analyses was followed in all the repeated-measures ANOVA conducted on the datasets in this study. All results were found to follow assumptions of normality with the exception of mode C spill data, and modes A and C control switch data. These deviations from normality were minor, so the data was included in the ANOVA regardless.

V. RESULTS

Fig. 6 shows the average performance of the participants using each control mode, including time of task completion, number of spills per trial, and number of control switches per trial. This aggregate data obfuscates a few interesting features visible in each participant's detailed data, most notably: learning curves throughout each control mode and the study in general, mis-pressed buttons, and the order the control modes were presented. Fig. 7 shows this detail for one participant (P3), representative of the group. Note the erroneous use of the joystick button in modes A, B and Control. Such mis-presses are not included in the control switches plot of Fig. 6. Also note the general learning curve of the participant throughout the progression of the study.

Significant differences were found in all measures: $F(5,25)$

TABLE I: p-values for comparisons across control modes in quantitative results

Comparison	Time	Spills	Switches
A vs B	0.055	0.491	**0.005***
A vs C	0.163	0.887	0.396
A vs D	0.075	**0.026***	**0.013***
A vs E	0.140	0.152	-
A vs X	0.055	**0.002***	**0.036***
B vs C	0.075	0.297	0.206
B vs D	**0.025***	**0.016***	**0.001***
B vs E	0.654	0.514	-
B vs X	**0.021***	**0.001**	**0.008***
C vs D	0.793	**0.012***	**0.001***
C vs E	0.062	**0.025***	-
C vs X	0.093	**0.002***	**0.006***
D vs E	0.034	**0.011***	-
D vs X	0.521	0.259	**0.005***
E vs X	**0.030***	**0.001***	-

TABLE II: Corrected p-values for comparisons across control modes in qualitative results

Comparison	Effectiveness (Transfer)	Intuitiveness	Preference
A vs B	1.000	1.000	1.000
A vs C	1.000	1.000	1.000
A vs D	1.000	1.000	1.000
A vs E	0.490	0.479	0.448
B vs C	1.000	1.000	1.000
B vs D	1.000	1.000	1.000
B vs E	1.000	0.850	0.709
C vs D	1.000	1.000	1.000
C vs E	**0.033***	**0.021***	**0.050***
D vs E	**0.035***	**0.013***	**0.006***

= 5.557, p = 0.001 for time of trial completion; F(5,25) = 18.201, p <0.001 for spills per trial; F(5,25) = 30.055, p = 0.001 (Greenhouse-Geisser correction applied) for control switches per trial. Pairwise comparisons indicated a number of significant differences, summarized in Table I. Analysis of Fig. 6 along with Table I shows some interesting trends:

- Control modes A and B (the two modes that require a momentary button press to switch functions) perform similarly in all measures. B (direct control) tends to perform better than A where they do differ.
- Mode E (no switching, direct control) showed the fastest trial times and the fewest number of spills. By the nature of the mode, E necessarily has the fewest number of switches.
- The control condition (no self-adjusting wrist) induced the greatest number of switches and the greatest number of spills and the longest trial times.
- Of the self-adjusting modes, the highest number of spills occurs in mode D (fixed wrist by default, held button press for ground-frame self-adjustment).
- Though modes C and D are similar (both require held button presses), C (ground reference frame by default) performs significantly better than D for spills and control switches.
- Toggling modes (A and B) perform as well as or better than held button press modes (C and D) in all measures.

The survey results are summarized in Fig. 8. For these charts, the scores given by the participants for reliability and preference were inverted to facilitate ease of comparison across measures (i.e. 5 always indicates better performance, 0 indicates worse). Note that the preference rankings exist on a scale from 1 to 5. A Kruskal-Wallis test revealed a significant effect of mode on effectiveness in the transfer task (H(4) = 11.746, p = 0.019), intuitiveness (H(4) = 13.352, p = 0.010), and user preference rank (H(4) = 13.372, p = 0.010). A paired t-test post-hoc analysis with Bonferroni correction showed where the significant differences lie, as outlined in Table II.

User comments from the survey are all given in a randomized order in Table III and Table IV, respectively. These statements were made in response to the question "What about your #1 choice made it your favourite?" and "What about your #5 choice made it your least favourite?"
Mode E scores and ranks the highest for each qualitative measure. Modes A and B never show significant difference from mode E. Among all self-adjusting modes there exists no significant difference, but trends indicate modes A and B scoring somewhat higher than modes C and D. In the user responses regarding their most preferred mode, common themes involved users having more control, enjoying the lack of switching, being able to make fluid, dynamic movements. One user, who favoured mode C, enjoyed having the held button press as a tactile indicator of which function the mode was controlling. Regarding their least preferred mode, three of six participants cited disliking holding the button down. Another common theme was that these modes were non-intuitive or hard to learn. One user, who disliked mode A, cited not being able to tell which function was being controlled as the cause for distaste.

TABLE III: User responses to the question "What about your #1 choice made it your favourite?"

Most Preferred Control Modes	
E	I could make dynamic movements.
E	Easiest to learn. Didn't get confused, steps easy to plan.
E	Being able to control both without switching and having separate controls.
B	Very fluid with having auto level by default, and having the ability for precision when needed.
C	Tactile way of telling me which mode I'm in.
E	Had all control. No extra thinking about switching.

TABLE IV: User responses to the question "What about your #5 choice made it your least favourite?"

Least Preferred Control Modes	
D	Clunky to have fixed by default given having auto level simplifies majority of task, very awkward to push in joystick while moving in two directions (up/down and left/right).
A	Too easy to forget which mode I'm in.
B	Took a lot of effort to learn. Often mis-pressed. Mapping between stick and buttons.
D	Memorization. Not adaptable to other tasks or distraction.
D	Pouring is difficult, non-intuitive, hard to hold button at same time as moving.
C	Holding the button while performing the action is non-intuitive.

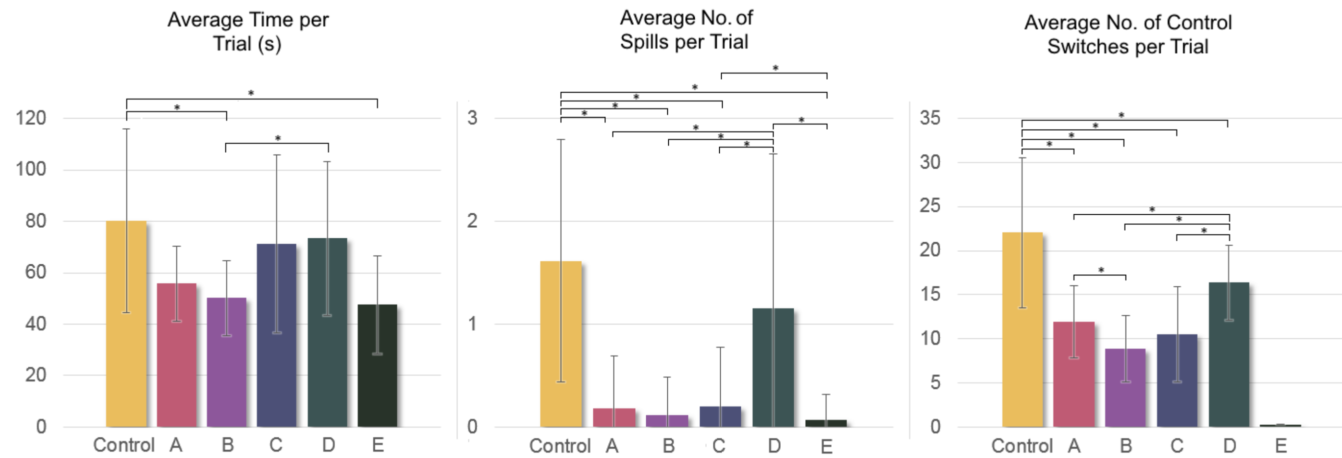

Fig. 6: Average trial performance across all participants, showing time of trial completion, number of spills and number of control switches. Lower bars indicate better performance in all measures. Error bars indicate one SD. Note that mode E required no switching, and therefore shows zero with no variance in the control switches plot, and no significance is indicated between it and the other modes.

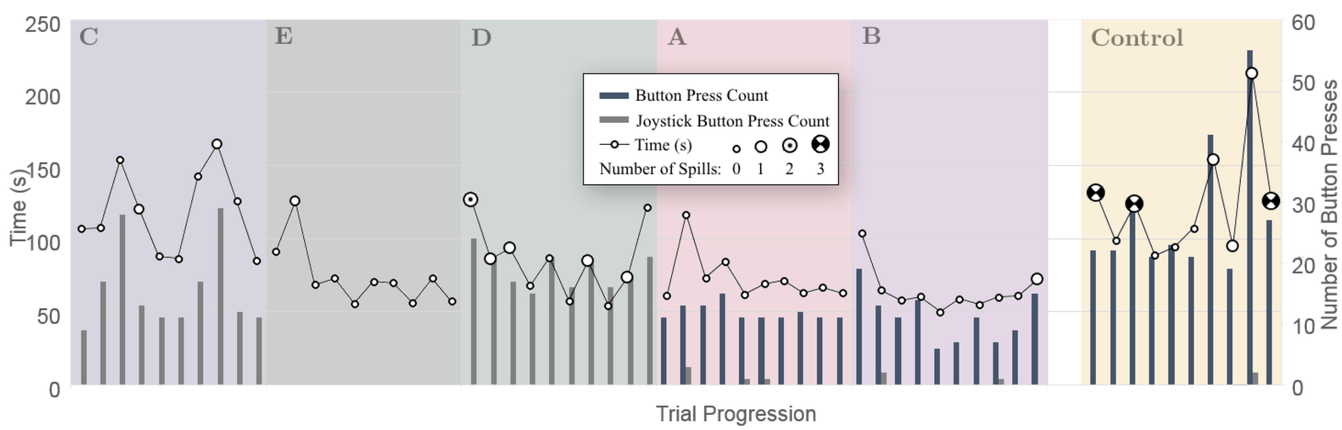

Fig. 7: Detailed performance of Participant 3, representative of the group, showing time of trial completion, number of spills, and number of button presses. Control modes are shown in the order they were presented to the participant. Note the overall learning curve and mis-presses of joystick button in control modes A, B and Control, which are not represented in the aggregate data.

VI. DISCUSSION

In this study we aim to determine an appropriate method of interfacing with a prosthetic arm that employs a self-adjusting wrist. A further goal of the study is to provide initial evidence regarding self-adjusting wrist performance compared to conventional control to motivate further investigations. Comparison of both quantitative and qualitative measures will elucidate what sort of control interface may be most effective to move forward with for future development.

A. Quantitative Measures

These observations suggest that, for these participants in this test setup, any of the self-adjusting modes perform as well as or better than the conventional control scheme. This preliminary comparison provides evidence that further investigation comparing a self-adjusting wrist to conventional control will be a worthwhile endeavour. Of the self-adjusting modes, mode E performs the best overall. Modes A and B perform the next best, with a slight edge in favour of mode B; modes C and D perform the least well. The quantitative performance trends suggest that, among the self-adjusting modes, *performance improves with ease of switching*: mode E required no switching, modes A and B required a momentary button press, and modes C and D required a held button press. This observation aligns well with prior findings in adaptive and autonomous switching [24], [25].

B. Qualitative Measures

These qualitative measures strongly favour mode E over the other schemes, and in general show a preference for more readily available control (i.e. favouring no switching to switching, and momentary button presses to held buttons).

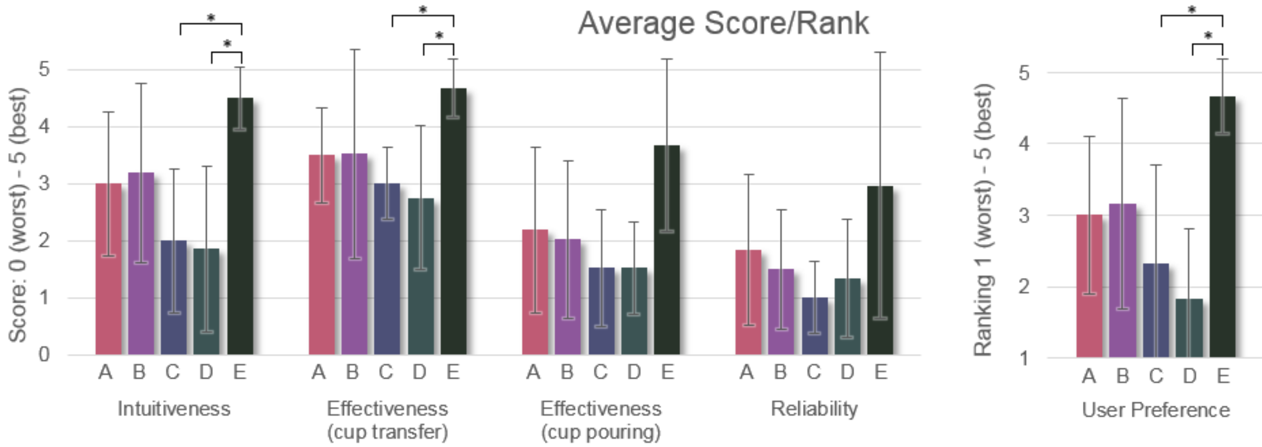

Fig. 8: Scores and ranks for each control mode, averaged across participants. Error bars indicate one SD. For all scores, 5 indicates best performance, 0 indicates worst performance (Scores for reliability and preference were inverted for easy visual comparison with other scores). Note that preference was ranked on a scale from 1 to 5. Statistical differences were calculated using post-hoc analysis of the Kruskal-Wallis test with α = 0.05, with the Bonferroni correction for multiple tests.

C. Study Limitations

Employing a desk-mounted arm with 1 DOF at the wrist limits generalization of these results to a wearable system, which will need at least 2 DOF at the wrist. Use of the video-game controller for this study rather than EMG creates some complications for application of these results to an EMG system. Notably mode E, which required use of two separate joystick inputs, will require more EMG input channels than may be available in a typical amputee's myoelectric control setup. A control method similar to mode E may become feasible with a pattern-recognition setup. Modes C and D would require the introduction of an alternate switching signal to facilitate held button-presses.

While restricting rotation greatly simplifies the implementation of the self-adjusting wrist, it does limit the movement of the wrist to 1 DOF, and forces the participant to use a somewhat unnatural strategy to pour the beads from the cup using ulnar deviation (the more natural strategy being to use wrist rotation). This limitation however, is common to all control modes and so will not bias the results in favour of any particular mode, though it may limit generalization of the results to tasks involving rotation.

Since the control condition was tested a month after the initial experiment, care must be taken in drawing conclusions comparing the control condition to the other modes. This paper provides evidence that a future study comparing conventional control to a self-adjusting wrist should produce interesting results, but makes no specific claims at this time.

D. Recommendations and Future Work

For application of these results to a wearable system with EMG control, two constraints must be held in mind:

1) a wearable system will have more range of movement than the desktop-mounted system, and so will require at least two DOF to successfully implement a self-adjusting wrist, and
2) use of an EMG system, in order to not occupy otherwise useful muscle sites, will likely be restricted to two channels of input only.

Constraint (1) will make direct control of the wrist more difficult, likely involving sequential control of each individual degree of freedom, making modes B and E less feasible. Constraint (2) will prohibit the use of mode E entirely. *We therefore recommend use of modes B or A for the implementation of a self-adjusting wrist into a wearable, EMG controlled prosthetic system*. Due to the limitations of the present study, re-visitation of a usability study to evaluate possible control schemes in the wearable system is also recommended, particularly comparing direct control and fixed wrist functions as the secondary function. Further, we recommend including some means of giving feedback to the user (e.g. LED indicator) regarding what function the controller is currently performing (i.e. fixed-wrist or self-adjusting wrist).

Future work will involve the development of a wearable 2-DOF self-adjusting wrist for use with able-bodied participants via a bypass prosthesis simulator. Since elbow angle will no longer be a reliable indicator of hand position relative to ground, an inertial measurement unit must be implemented in the terminal device, and PID control will be used to maintain the hand's orientation. A rigorous study to compare the self-adjusting wrist to conventional control will be performed using motion-capture technology to evaluate effects of the control system on users' compensatory movements. More broadly, this work could be extended to allow fixing the terminal device to reference frames other than the forearm or ground reference frames, given appropriate sensors either on the arm or in the environment, as demonstrated by Shibuya et al. [22]. By selectively attaching to the reference frames of target objects, slanted surfaces, or other useful frames, a self-adjusting wrist could provide even greater benefits for task performance and reduction of compensatory movements. To generalize the system to environments not prepared with appropriate RFID tags, the control system would likely require implementation of machine learning approaches to determine which reference frame might be most appropriate for a particular context. Machine learning could also be used to allow the system to determine an appropriate time to switch between self-adjusting and other functionality (i.e. direct control or fixed-to-forearm). Such adaptive and autonomous switching schemes have been explored for application to conventional myoelectric control [24], [25], and could be applied to a self-adjusting scheme as well.

VII. Conclusion

We contribute the first control interface evaluation for an automatically and continually adjusting wrist that aligns to a frame of reference other than that of the forearm. This work provides evidence that a self-adjusting wrist control system capable of maintaining the terminal device orientation relative to the ground reference frame may perform better than conventional control methods. It further shows that the control interface may have significant implications on the system's success. Future investigation with self-adjusting wrists should include a rigorous comparison of self-adjusting wrist control to conventional control, with measures that show effects on compensatory movements. Our results suggest that a control scheme that employs a momentary switch to toggle wrist function between a fixed-to-ground reference frame and either a fixed-to-forearm reference frame or direct wrist control would be a good first candidate for this future study. Extension of this self-adjusting concept to reference frames other than the ground reference frame may also be useful and warrants future investigation. This study represents a step toward prostheses capable of intelligently adapting themselves to their environment in a natural, intuitive way in order to provide a user with a safer and more easily usable robotic arm.

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