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The Effect of an Automatically Levelling Wrist Control System

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***Abstract*— Upper limb loss is a devastating injury for which current prosthetic replacement inadequately compensates. A lack of wrist movement in prostheses due to mechanical design and control system considerations compels prosthetic users to employ compensatory movements using their upper back and shoulder that can eventually result in strain and overuse injuries. One possible means of easing this control burden is to allow a prosthetic wrist to self-regulate, keeping the terminal device of the prosthesis level relative to the ground when appropriate, such as when raising a cup of liquid. This study aims to outline such a wrist control scheme, and evaluate its function in terms of the effect on compensatory movements, objective system performance, and subjective perception of system performance based on user feedback. To that end, twelve able-bodied participants were recruited to control a body-mounted robotic arm using three different control schemes: fixed-wrist (FW), sequential switching (SS), and automatic levelling (AL). The resulting movement strategies were recorded for two different tasks using 3D motion-capture. SS and AL control schemes induced similar movement strategies and less compensation than FW for horizontal movements, while AL reduced shoulder flexion compared to FW and SS for vertical movements. However, AL was ranked less intuitive and less reliable than the FW. AL and SS both seemed to involve more conscious thought to operate than FW. These results suggest that more complex wrist control schemes may indeed be able to eliminate harmful compensatory movements, but reinforce prior observations that control must be reliable and simple to use or people will opt for an easier system.**

I. INTRODUCTION

Amputation of the upper limb is a life-altering event that affects over 41,000 people in the United States alone [1]: it changes the way a person perceives themselves as well as the way a person moves to accomplish a task. These changes in movement strategies can lead to strain injuries which exacerbate the debilitating condition. One major limitation to current prostheses is the lack of wrist motion. [2]. Impaired wrist motion causes compensatory movements [3]–[6], which is of concern given the known increase in musculoskeletal pain related to the neck, shoulder and upper back in those with upper limb amputation [7]. In response to the idea that an automatically levelling wrist might be able to reduce some of these compensatory movements [8], [9], a self-adjusting wrist control system was introduced. Preliminary testing with a desktop-mounted arm showed that it may provide some benefits compared to a conventional control method in terms of the trial time, number of switching signals, and instances of spills [10]. Further, Shibuya et al. have shown some initial evidence that a wearable automatically levelling wrist could reduce compensatory movements [11]. Tests done with a compliant wrist have also shown benefits compared to fixed-wrist control schemes: using a compliant wrist during reaching and grasping and a stiff wrist otherwise may reduce compensatory movements [12].

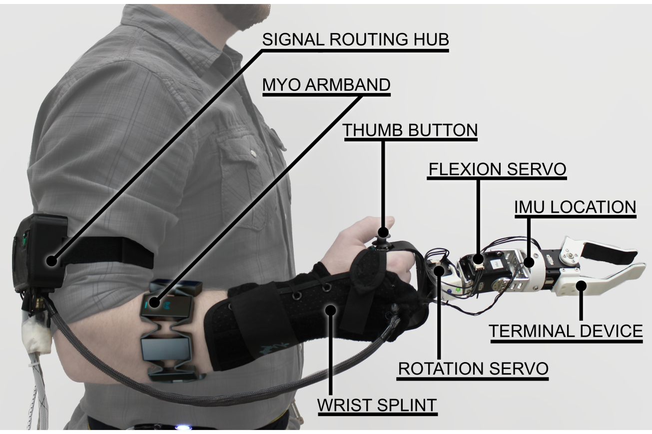

Fig. 1: The simulated prosthesis included all joints of the Bento Arm distal to the elbow, and was attached to a wrist splint by a 3D printed handle. A Myo Armband allowed myoelectric control, and a button at the thumb allowed switching. Computation and power were provided externally.

The purpose of the present study is to further evaluate the effect of an automatically levelling wrist on a person's movements and control strategies, while performing tasks of daily living with a body-mounted robotic limb. This experiment was intended to elucidate differences between the use of a fixed wrist, a sequential switching method, and the proposed automatically levelling method. Three areas of evaluation were explored: kinematic analysis, performance metrics, and qualitative perception of performance.

II. METHODS

A. Simulated Prosthesis

In this work, prior to a study involving participants with amputations, we made use of a robotic device mounted to

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the upper arm of able-bodied participants (termed a *simulated prosthesis*). The simulated prosthesis designed for use in this study consisted of a modified Bento Arm [13] attached to a wrist splint with 3D printed handle as depicted in Fig. 1. The arm was modified to include only wrist rotation, wrist flexion, and the terminal device, which was further altered to include a BNO055 (Bosch Sensortech, Germany) inertial measurement unit (IMU) in its base. Altogether the device weighed 550 g. The open-source files for the simulated prosthesis can be found online [14]. The prosthesis extended distally from the user's intact hand, resulting in an increased effective limb length of 26 cm, which was necessary to ensure unimpeded prosthesis wrist motion. The wrist splint restricted biological wrist flexion/extension and radial/ulnar (R/U) deviation of the participant, but allowed wrist rotation. The prosthesis was controlled using a Myo Armband (Thalmic Labs, Kitchener, ON) on the user's forearm. EMG signals from contraction of the user's forearm muscles corresponding to wrist flexion/extension were mapped to open/close of the hand or radial/ulnar deviation of the wrist (up/down in this configuration) depending which joint was being controlled. EMG singals were converted to mean absolute values with a window size of 40 steps (approximately 200 ms), in accordance with standard myoelectric control paradigms [15]. A button activated by the user's thumb was used to give the switching signal. A button was used rather than myoelectric co-contraction to achieve cleaner, clearer control signals, thereby reducing inadvertent switches which would make the system more difficult to learn. Electrical power and computation of the control software were provided externally; cables were managed to be as unobtrusive as possible in terms of weight and restricted motion. The prosthesis functioned in three distinct modes: Fixed Wrist (FW), Sequential Switching (SS), and Automatically Levelling (AL). In FW mode, which mimics a prosthesis with no wrist DOF, the prosthesis allowed hand control only; both wrist rotation and R/U deviation were fixed in a neutral position. For the sequential switching mode, which mimics conventional myoelectric switching control strategies for a 1 DOF wrist, the user could switch between directly controlling the terminal device or R/U deviation of the wrist; wrist rotation was fixed in a neutral position. The automatically levelling mode also allowed the user to switch between wrist R/U deviation and hand control, but the wrist also worked autonomously to maintain the hand orientation in the method described in the next section.

B. Automatic Levelling Method

The integrated IMU in the base of the terminal device enabled the AL functionality. The IMU uses a fusion of accelerometer and gyroscope data to compute a "Gravity Vector" (GV), which consists of the x, y, and z components of the acceleration due to gravity experienced by the IMU, separate from other accelerations [16]. The gravity vector and relevant angles are depicted in Fig. 2. "Automatic Levelling" consisted of two separate sub-functions: "Flexion Levelling" and "Rotation Levelling". Flexion Levelling aimed to keep the angle θ constant (set to whatever angle it was when Flexion Levelling was engaged), and was active whenever AL was engaged *and* the user was *not* controlling the wrist. Rotation levelling aimed to keep the angle ϕ at a constant 180°, and was active whenever AL was engaged. Both Flexion Levelling and Rotation Levelling operated on separate PID loops, each of which updated at a minimum rate of approximately 200 Hz. The PID loops were tuned by hand to give reasonable settling times; rotation settled to within +/- 5° error from an 80° disturbance within about 600 ms; flexion settled to within +/- 5° error from a 50° disturbance within about 580 ms. For rotation, the (k_p, k_i, k_d) values were (0.32, 0.06 μs^{-1}, 8.79 ms); for flexion they were (0.29, 0.42 μs^{-1}, 8.00 ms).

C. Experiment Design

Twelve able-bodied people participated in the study, each providing written informed consent prior to participating. There were three female and nine male participants, with average age 25.3 years (SD 7.5 years), average weight 73.2 kg (SD 7.4 kg), average height 170.7 cm (SD 10.0 cm). All participants were right-handed, with normal or corrected-to-normal vision, and performed the task using their right hand.

Our outcome measures were based a study conducted by Valevicius et al. [17], which focused on quantifying movement patterns for able-bodied persons on two tasks: the Cup Transfer task, and the Pasta-Box task. The Cup Transfer Task involved moving two cups full of beads across the mid-line, using first a top-grasp and then a side-grasp, and returning the cups to the starting position using the same method. The Pasta-Box task involved transferring a box of pasta from a low side table to a series of higher shelves, and finally returning the pasta box to the side table. In Valevicius et al., both of these tasks were studied using a Vicon Bonita 12-camera motion-capture setup to record upper body joint angular kinematics in 20 able-bodied participants. For a full description of the experiment setup and task descriptions,

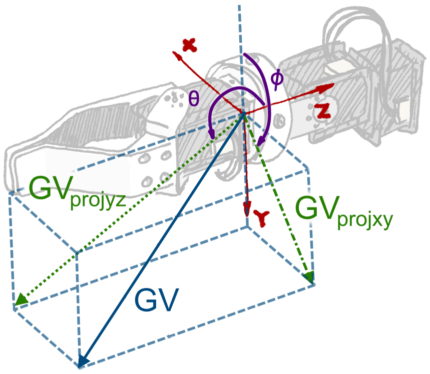

Fig. 2: The IMU provided the Gravity Vector (GV), from which the angles ϕ and θ were calculated, using the projections of GV on the x-y and z-y planes. Flexion Levelling kept the angle θ constant; Rotation levelling kept the angle ϕ = 180°.

refer to Valevicius et al. [17]. For this experiment, the setup was modified from this original work in two ways:

1) The side table was moved 26 cm to the right and 26 cm back, to accommodate for the additional length of the simulated prosthesis. Participants were instructed to stand at a comfortable distance to the task table while performing the task with the simulated prosthesis.
2) The cups used were made of stiff plastic rather than compliant paper, since the emphasis in this study was on wrist control conditions rather than force modulation control.

All other task specifications are identical to the specifications in [17]. Marker positioning was consistent with the cluster-based marker model used in Boser et al. [18]; markers for the right hand and forearm were mounted on the simulated prosthesis in analogous locations. A depiction of the tasks is shown in Figs. 3 and 4. A demonstration of the tasks performed with the fixed-wrist and automatically-levelling conditions is given in the accompanying video.

Participants were first familiarized with the prosthesis by allowing approximately five minutes of unstructured play, wherein they could stack cups, balls, and various other small objects. For the first few minutes of this time, or until the participant felt comfortable with the system, the prosthesis was operated in the SS mode. For the last few minutes of the training session, the participant was familiarized with the AL mode. Only once the participant agreed that they felt sufficiently capable did the experiment trials begin.

Each participant performed three blocks of trials (one block each for FW, SS, and AL) for each task. The order that the interventions were tested by each participant was varied; twelve participants were studied so that each of the six possible orders of interventions was tested twice. Everyone began with the Cup Transfer task, and after completing all Cup Transfer trials took a ten-minute break before conducting the Pasta-Box trials. For each task type, the experimenter explained and demonstrated the format of the task, and the participant performed one or more practice trials until they felt comfortable with the task. A practice trial was also allowed at the beginning of each block of trials to familiarize the user with that particular control mode. A block consisted of enough trials to represent ten usable trials, with a maximum of fifteen attempts. All participants had at least nine usable trials for each block. Reasons for mistrials were recorded, and only mistrials caused by participant error (incorrect task execution, spilled or dropped items) are reported. Data collected during the trials included x, y, z marker position, EMG signals, IMU gravity vector components (x,y,z), switching signals, and position, velocity, and load data from the prosthesis servomotors. Motion-capture data (8-camera OptiTrack) were collected at a rate of 120 Hz, while all other data were collected at approximately 200 Hz. No time-series analyses were conducted in this work, so the data rate disparity is inconsequential. Participants also filled out a qualitative survey at the end of the session. The survey prompted participants to score each of the control modes in four categories (intuitiveness, effectiveness at the Cup Transfer task, effectiveness at the Pasta-Box task, and reliability) using a visual analogue scale (VAS) from 0 to 5. Intuitiveness was probed by asking "How easy was each control mode to learn?"; Effectiveness was determined by the question "How well did each control mode perform the cup transfer task?", or "pasta task" as appropriate; and Reliability was discerned through asking "How often did you find the arm moved in a different way than you wanted or expected?". The participants also indicated an ordinal rank of their preference to use each control mode for each task.

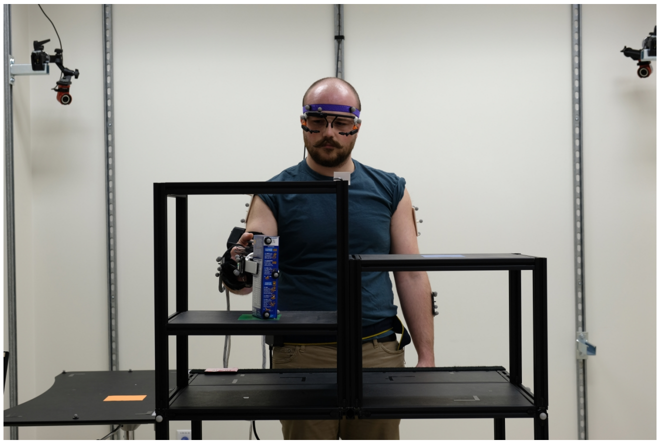

Fig. 3: Depiction of the task setup for the Pasta-Box task. Participants move a box of pasta from the low side table to a middle shelf, then a high shelf, and back to the side table.

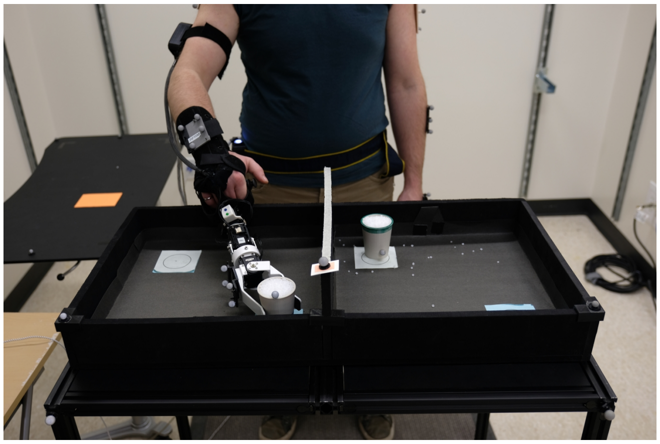

Fig. 4: Depiction of the task setup for the Cup Transfer task. Participants move a cup filled with beads across the box, over a barrier and back again, using both a top and side grasp.

D. Data Analysis

Mean maximum angles for trunk flexion/extension, trunk ipsi/contra-lateral bend, trunk axial rotation, shoulder flexion/extension, shoulder internal/external rotation, and shoulder ad/ab-duction were explored in this study. Shoulder and trunk angle metrics were drawn from the motion-capture data. The pelvis, thorax, and right-upper-arm motion tracking data was manually cleaned to ensure trunk and shoulder angle metrics would not be affected by occluded or mislabelled markers. Hand data, while not included in this analysis, was also cleaned since hand velocity was used as an indicator for trial beginnings and endings. Cleaning involved constant, linear, cubic, or pattern-based interpolation across gaps in marker position data, assessed on a case-by-case basis to provide the most reasonable marker trajectory. The maximum angle for each degree of freedom was averaged across trials for each participant. Performance metrics included the time of task completion, the number of switching signals given by the participant, and the number of participant-caused mistrials. Mean differences for all continuous data (mean maximum angles, time of trial completion, switch counts, mistrial counts, and VAS scores) were calculated using paired two-sample t-tests across the three tested conditions (FW vs AL, SS vs AL, FW vs SS), with $\alpha = 0.05$. A Bonferroni correction was made for three comparisons, making $\alpha = 0.0167$. For the ordinal preference ranking, a Mann-Whitney U-test was conducted, with $\alpha = 0.05$.

III. RESULTS

The mean maximum angle for each trunk and shoulder movement is plotted on a per-participant basis for the Cup Transfer task in Fig. 5, and for the Pasta-Box task in Fig. 6. The total range of motion can be inferred by considering both pairs of angles for a degree of freedom (i.e. max flexion + max extension = range of motion). The data for the normative (N) study [17] is plotted as well. While not directly comparable to our results with a simulated prosthesis, the data from this study is provided alongside our results to indicate that our results are within reasonable expectations. The points for individual participants are connected by lines to facilitate discernment of trends across the interventions tested in this study. The various performance metrics are plotted in Fig. 7, including average trial time, number of control switches, and number of participant-caused mistrials. Time of trial start was defined as the first time the hand velocity rose above 5% of its peak velocity, and time of trial end was defined as the last time the hand velocity fell below 5% of peak velocity, based on the marker position data. The results of the qualitative survey presented at the end of the session are summarized in Fig. 8. For all measures in Fig. 8, higher scores indicate better performance. Error bars in all figures represent ± one standard deviation. The results of the statistical analyses for all comparisons are provided in Table I.

IV. DISCUSSION

A. Kinematic Analysis

1) Cup Transfer Task: The kinematic results from the AL and SS conditions never significantly differed from one another in this task. In the instances where FW differs from AL and SS (trunk flexion and contralateral bend; shoulder flexion, abduction, internal and external rotation), FW always displays a greater mean peak angle. This is indicative of compensatory movements in performing the top-grasp of the cup. Without R/U deviation, the participant had to raise their elbow in order to bring the prosthesis down vertically on the cup and ensure the terminal device did not interfere with the cart barriers. This compensation was exacerbated by the length of the simulated prosthesis; since the height of the table was not altered from the original study, participants needed to raise their arm 26 cm higher than they otherwise would have in order to perform the top-grasp. For the Cup Transfer task, there is evidence supporting the use of a directly controllable wrist allowing R/U deviation, but no evidence to support the use of a continuously adapting wrist as opposed to a conventional sequential switching system.

2) Pasta-Box Task: For the Pasta-Box task, the only significant differences between the tested control modes existed in shoulder flexion and internal/external rotation, and abduction. In shoulder flexion, the average maximum flexion angle for the AL condition was less than that of both the FW and SS conditions, and for abduction it was less than the FW condition. Less shoulder flexion and abduction in the AL case indicates that the participants didn't need to raise their arm as high in order to place the pasta box onto the shelf, suggesting less compensatory movement. The fact that the maximum flexion angle for all control modes was lower than that for the normative data set was likely due to the increased length of the simulated prosthesis, which enabled the participants to place the box on the shelf without raising their arm as much as they otherwise would have. That the mean maximum flexion angle was significantly different between the AL and SS cases suggests that this difference is a result of the adaptive wrist angle. The FW condition induced more internal rotation and less external rotation than AL and SS most probably because users were unable to set the wrist ulnar/radial deviation angle to a suitable position (which was possible in the AL/SS cases). Less internal rotation and more external rotation indicates arm movements with more reach away from the body in the AL and SS cases as compared to FW, which displays more close-to-the-body movement. AL induced less internal rotation than SS, indicating that while setting an initial deviation angle helped, adaptation of that angle throughout the task may have had some benefit as well.

Overall, it appears that for the Pasta-Box task that there was little difference between all conditions in terms of movement strategies at the trunk and shoulder level. Differences in internal and external rotation support the advance setting of an appropriate deviation angle, and the reduced shoulder flexion suggests that an adaptive wrist angle may reduce compensatory movements for vertically-oriented tasks.

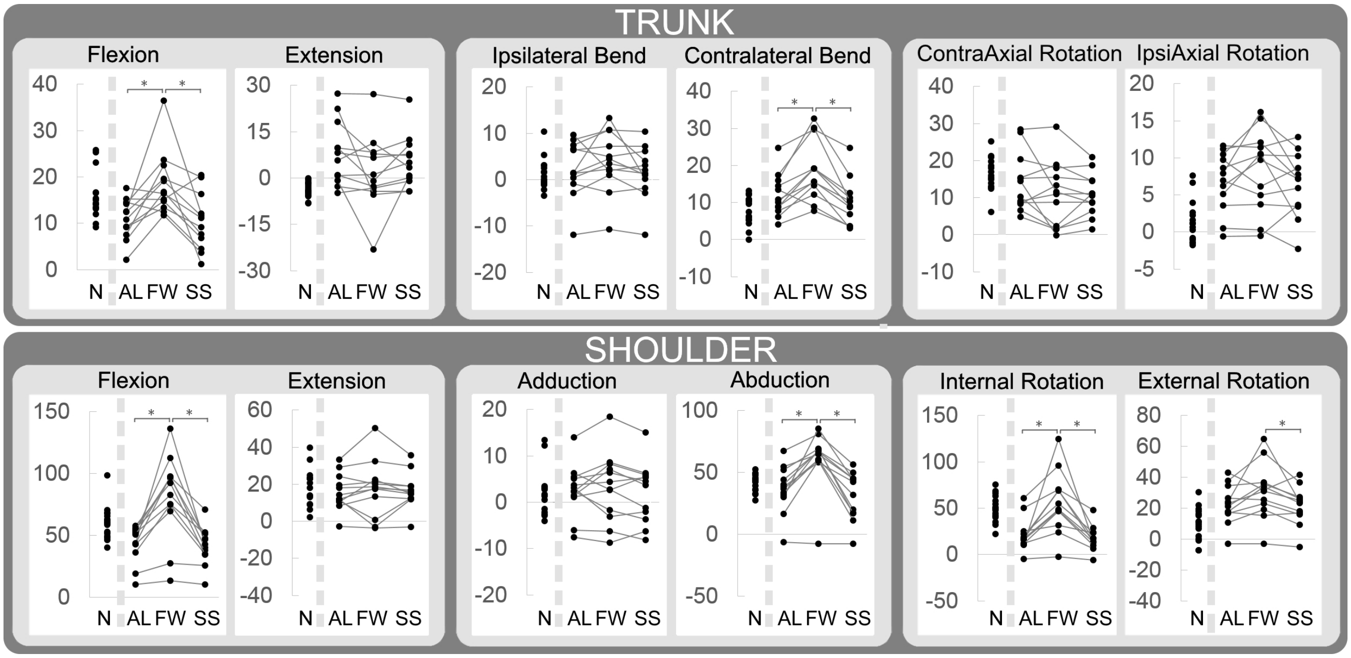

Fig. 5: CUP TRANSFER TASK: Mean maximum angles (in degrees) for each participant. Normative (N) data were collected in a separate experiment [17]. Lines joining individual participants indicate trends across the three control modes tested in this study. While participants are plotted individually, significance was determined based on the average of the group using pairwise two-sample t-tests, α = 0.0167 for Bonferroni correction.

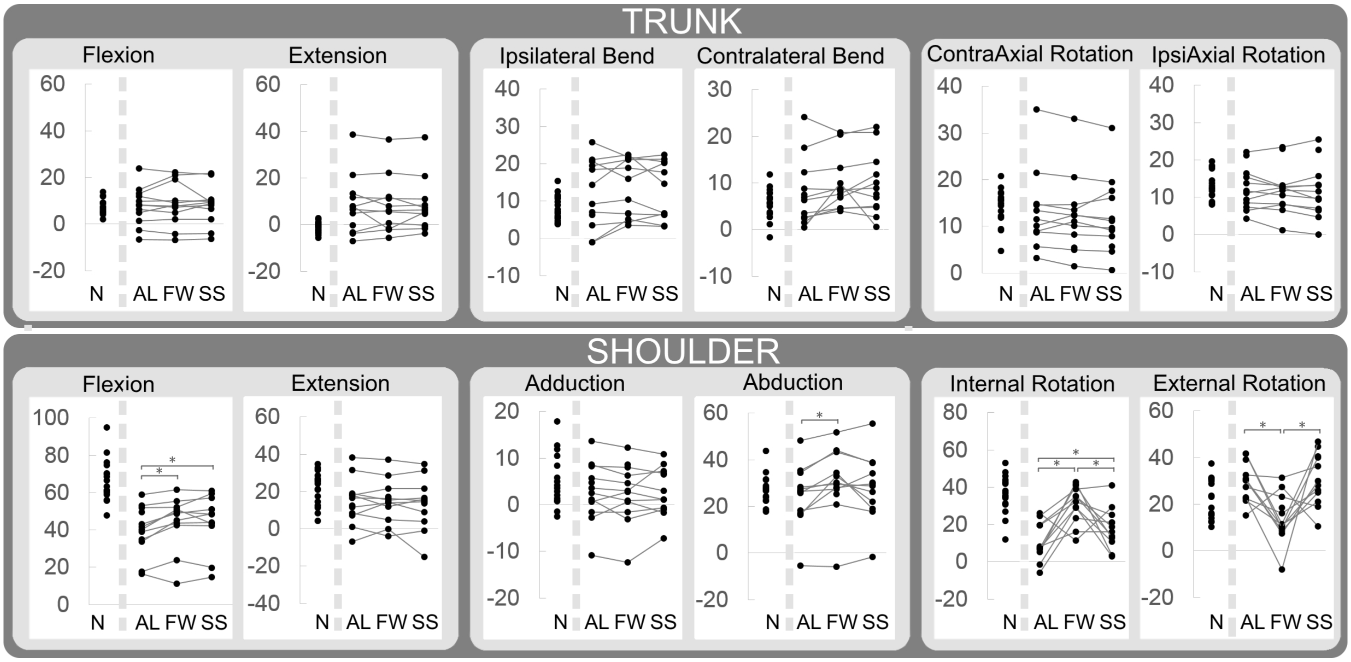

Fig. 6: PASTA-BOX TASK: Mean maximum angles (in degrees) for each participant. Normative (N) data were collected in a separate experiment [17]. Lines joining individual participants indicate trends across the three control modes tested in this study. While participants are plotted individually, significance was determined based on the average of the group using pairwise two-sample t-tests, α = 0.0167 for Bonferroni correction.

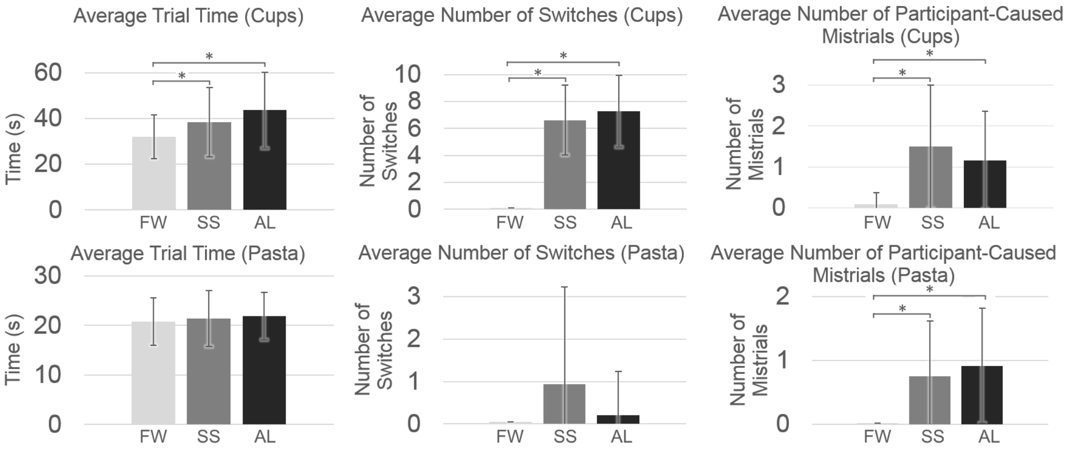

Fig. 7: Performance metrics for each of the control conditions. Columns represent the average across all participants. Error bars indicate one standard deviation. Significance determined using paired two-sample t-tests with α = 0.0167 for Bonferroni correction.

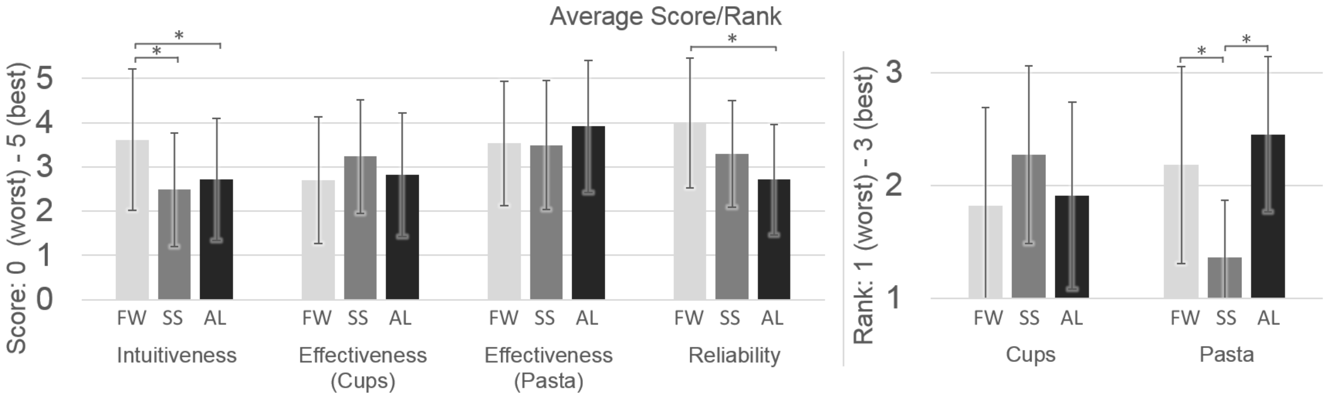

Fig. 8: Qualitative user feedback about various performance aspects of the prosthesis control modes. Columns represent the average across all participants. Error bars indicate one standard deviation. For all measures, a higher score indicates better performance. Significance determined using paired two-sample t-tests (α = 0.0167 for Bonferroni) for the continuous scores, and a Mann-Whitney U-test for the ordinal rankings (α = 0.05).

B. *Performance Metrics*

Each of the measures presented in Fig. 7 represents an indication of the performance of the prosthesis with a particular control mode. Of course, these are only a few of the many possible ways of examining prosthesis performance, and each has its limitations in what it is able to show. From the trial time plots, we can see that there was no difference between the modes in completion of the Pasta-Box task, and a slight trend in favour of FW and against AL for the Cup Transfer task. In terms of switching, the FW control condition by nature of its definition had the least number of switches. Those control modes that do involve switching seemed to perform equally well on the Cup Transfer task, but AL trended toward outperforming SS on the Pasta-Box task. Only one participant used the direct wrist control afforded by SS during the movement portions of the Pasta-Box task, requiring many switching signals. All other participants used it in the same manner as the FW, which gave rise to the large variance seen here. The number of participant-caused mistrials was much less for the FW condition than for the other two conditions. This may suggest that cognitive effort normally spent on the task must be put into wrist control, or that erroneous wrist movements may have caused errors. All of these measures suggest that the most rudimentary control system is the simplest to use. Both control schemes that allowed direct wrist control required more conscious thought, though AL did require less switching than SS on the Pasta-Box task while still allowing a change in R/U deviation angle.

C. *Qualitative Measures*

Equally important to how well a person uses a prosthesis is how a person feels about using their prosthesis. To this end, the qualitative survey was given to discern people's intuitions about the device (see Fig. 8). From these results we see that people felt that all control conditions were equally effective at the tasks, but differences existed in terms of perceived intuitiveness and reliability. The FW control scheme was felt to be the most intuitive, and involved the least complexity

TABLE I: p-values for all comparisons. Paired two-sample t-tests were conducted on all continuous data, with Bonferroni correction for three comparisons leading to α = 0.0167. For ordinal data (rankings), Mann-Whitney U-tests were conducted with α = 0.05.

Metric	FW vs AL	FW vs SS	AL vs SS
Cups Trunk Flex.	**0.0022***	**0.0022***	0.3347
Cups Trunk Ext.	0.0312	0.0832	0.1562
Cups Trunk Cont. Bend	**0.0005***	<<**0.0167***	0.0567
Cups Trunk Ipsi. Bend	0.1249	0.0394	0.1526
Cups Trunk Cont. Rotn	0.0674	0.4872	0.0631
Cups Trunk Ipsi. Rotn	0.0658	0.0696	0.3275
Cups Shldr Flex.	<<**0.0167***	**0.0001***	0.2432
Cups Shldr Ext.	0.2721	0.3843	0.1499
Cups Shldr Add.	0.2947	0.0611	0.3244
Cups Shldr Abd.	<<**0.0167***	<<**0.0167***	0.0842
Cups Shldr Int. Rotn	**0.0008***	**0.0004***	0.0851
Cups Shldr Ext. Rotn	0.0259	**0.0122***	0.2618
Cups Trial Time	**0.0006***	**0.0120***	0.0711
Cups No. of Switches	<<**0.0167***	<<**0.0167***	0.0993
Cups No. of Mistrials	**0.0058***	**0.0058***	0.2583
Pasta Trunk Flex.	0.2383	0.3968	0.3253
Pasta Trunk Ext.	0.3203	0.3387	0.3846
Pasta Trunk Cont. Bend	0.0247	0.4324	0.0359
Pasta Trunk Ipsi. Bend	0.1319	0.2024	0.3586
Pasta Trunk Cont. Rotn	0.0856	0.2986	0.0663
Pasta Trunk Ipsi. Rotn	0.3279	0.1887	0.2165
Pasta Shldr Flex.	**0.0049***	0.2898	**0.0009***
Pasta Shldr Ext.	0.4587	0.1603	0.1071
Pasta Shldr Add.	0.3353	0.3097	0.4440
Pasta Shldr Abd.	**0.0032***	0.1781	0.0185
Pasta Shldr Int. Rotn	**0.0002***	**0.0069***	**0.0073***
Pasta Shldr Ext. Rotn	**0.0011***	**0.0047**	0.3358
Pasta Trial Time	0.0593	0.2696	0.2888
Pasta No. of Switches	0.0533	0.0934	0.1537
Pasta No. of Mistrials	**0.0024***	**0.0060***	0.3190
Intuitiveness	**0.0084***	**0.0005***	0.1490
Effectiveness (Cups)	0.3977	0.0494	0.1698
Effectiveness (Pasta)	0.0640	0.4215	0.0521
Reliability	**0.0043***	0.0360	0.0173
Rank (Cups)	0.8181	0.2501	0.3421
Rank (Pasta)	0.5353	**0.0385***	**0.0035***

of control, compared to AL and SS. AL and SS performed equally well in this category. The FW control scheme was scored as significantly more reliable than AL. The control mode preferred by the participants differed depending on the task at hand. Though not significant, for the Cup Transfer task SS tended to be preferred, likely because AL was too unreliable and FW forced compensation to perform the top grasp. For the Pasta-Box task however, SS was least preferred, likely because of the perception that having direct wrist control was "useless", as one participant put it, for this particular task. This sentiment seems to generalize to the other participants as well, since all but one used the SS control in the same manner as FW. This has important implications, since it demonstrates that people will tend to use compensatory movements for simple tasks even when wrist control is available, if control of the wrist requires a switching signal.

Altogether, these results indicate that people feel that the FW control condition was the simplest to use and the most reliable, but lack of R/U deviation made it less preferred for the Cup Transfer task. People felt that the AL scheme was at times unreliable, and was the most difficult to learn, but in the structure of the Pasta-Box task it proved helpful. SS was viewed as the most reliable scheme that allowed R/U deviation for the Cup-Transfer task, but as an unnecessarily complicated control scheme when it came to the Pasta-Box task.

D. Study Limitations

A limitation of this study was the use of a simulated prosthesis with able-bodied people: particularly, one that positioned the prosthesis distally to the user's hand, increasing the overall limb length by 26 cm. While this was necessary to allow unimpeded prosthesis wrist motion, the extra length introduced additional body compensations in the Cup Transfer task, and may have made some compensations unnecessary even for the FW condition in the Pasta-Box task since it extended the participant's reach. Another limitation was the short duration in which the participants interacted with the system. The intuitiveness scores, time of trials, and other performance metrics indicate that AL may take more time to learn to use than the FW system. It is possible that with further learning performance may change. Future studies should involve participants affected by upper limb amputation to reduce ambiguities introduced by the simulated prosthesis, and allow sufficient training time to ensure learning effects are reduced. Additionally, use of a button rather than myoelectric co-contractions for the switching signal limits generalization of these results to a fully myoelectric system.

E. Discussion Summary

While the performance of the AL system is promising, there are still some limitations including lack of reliability and ease of use. For a person to accept a prosthesis that is making some decisions and movements on its own, the prosthesis must be especially robust and predictable. The PID loop in this tested system, while capable of keeping the hand reasonably level, did still have perceptible lag and overshoot. A more sophisticated control system, perhaps by means of cascading PIDs or neural network tuning might be able to bring the reliability of the system up to a more reasonable level, which should be done prior to further study. Ease of use is more difficult to prescribe a solution for. It is possible that future machine learning techniques may be able to predict a prosthesis-user's next move and automatically switch to the appropriate control scheme [19]; in the near term, the most expedient possible way to improve the use is to allow a longer training period. The kinematic analysis especially indicates that the use of an automatically levelling wrist of the present form may not provide benefit for tasks involving a predominantly horizontal plane. The true usefulness of an automatically levelling wrist in reducing compensatory movements appears to exist in tasks involving large vertical motions, such as in placing or reaching for objects on high shelves.

V. CONCLUSION

In this study, we aimed to evaluate the effect an automatically levelling wrist system might have on a person's interaction with their prosthesis, measuring that effect in a number of different ways. In terms of the movement strategies used by the participants, it seemed that for the Cup Transfer task AL and SS perform equally well, while the FW condition involved more compensation. For the Pasta-Box task, FW and SS were used in a similar manner, but differences in shoulder flexion indicate AL may have contributed to the reduction of compensatory movements. The performance metrics indicated that the FW system was simplest to use and easiest to learn. AL and SS were approximately equally difficult to use, with a trend in trial length and intuitiveness scores indicating AL may take more time to learn. Participants preferred to use the sequential-switching method on the Cup Transfer task, as it was less awkward than FW, and more reliable than AL. For the Pasta-Box task, participants equally preferred AL and FW.

In order to provide people affected by upper-limb amputation with artificial limbs that give meaningful benefit to their lives, care must be taken to ensure that the prostheses are easy to use and do not force compensatory movements; our results suggest that an automatically levelling wrist, if designed robustly and intuitively, may provide one part of the control scheme for such a limb.

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