The Role of Action Observation in Prosthesis Learning: Final Thesis

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Introduction

After experiencing upper limb loss, amputees must relearn how to execute necessary motor tasks for daily function. Oftentimes, this involves the use of a prosthetic device to act as an extension of the body and replacement of the lost limb. However, prosthetic devices are not intuitive to use. The human brain is hardwired to control our natural limbs, so even experienced prosthesis users find manipulating their device to be mentally and physically effortful as compared to people using their intact limbs (Parr et al., 2018). Attempting to use a clumsy device that is an approximation of the natural human body results in a steep learning curve that can feel impossible for patients to surmount (Hughey & Wheaton, 2016). Even so, there are ways to improve learning outcomes for upper limb prosthesis users, with previous work demonstrating some ideal paradigms. Primarily, people learn to use prosthetic devices more effectively when they are watching someone execute a task and copying it rather than solely having verbal instruction. However, there are still many unknowns about the mechanics of the learning process, such as the neurobehavioral patterns that occur when prosthesis learners attempt to copy someone also using a prosthetic device, versus when learners try to imitate an intact actor. It is important to explore these parameters because they will elucidate the mechanisms of prosthetic learning beyond the measurable kinematic parameters that are often cited.

In experimental paradigms that involve action observation, or an individual watching another person execute an action, gaze-tracking is a common metric for the identification of subject behavioral patterns (Flanagan et al., 2013; Wright et al., 2018). The ability to detect what parts of a scene a subject pays attention to while observing an action indicates what they consider to be the most salient portions of the scene, either consciously or subconsciously. However, this metric has not been extensively applied to action observation in prosthesis learning. Most studies of prosthesis learning focus on learning outcomes, such as task performance efficiency and accuracy (Cuscak et al., 2012; Cusack et al., 2014; Cusack et al., 2016). A single preliminary study has examined gaze positioning in action observation prosthesis learning conditions, including a basic analysis of common gaze locations in matched versus mismatched conditions (Bayani et al., 2019). However, this analysis did not relate gaze patterns back to specific kinematic outcomes. A more thorough analysis will examine how kinematic outcomes are correlated with gaze patterns; this will indicate which elements of a scene are most important to support positive learning outcomes.

Learning to use an upper limb prosthesis is difficult, and many patients misuse their devices, become frustrated, or even refuse the devices altogether (Datta et al., 2014). When used properly, though, prosthetic devices can provide improvements in quality of life to those who are missing portions of their upper limbs. Therefore, it is vital to know the best method to teach amputees how to use their prosthetic devices, and this proper methodology can be discovered and implemented through a better understanding of the cognition behind the prosthetic learning process.

Literature Review

Background

Optimal prosthetic learning, which involves a patient learning how to use a prosthetic device quickly and in a way that restores maximum function, is achievable, but requires purposeful rehabilitation. Therefore, there is a need for an examination of the best strategies for assisting patients with learning to navigate their prosthetic devices, in order to increase overall patient satisfaction, functionality, and quality of life. Prior work has demonstrated the importance of learning by observation, with the best functional outcomes occurring when a patient observes an actor completing a target task in a condition which matches the patient's own, i.e., also using a prosthetic device (Cusak et al., 2014). In order to build a competent understanding of the mechanics of optimal prosthetic learning, it is critical to independently study what happens when we observe others completing an action and what happens when we attempt to use a prosthetic device, and then explore what is currently known about the intersection of those two activities.

Action Observation

When observing another individual completing an action, the brain naturally attempts to understand that action empathetically, putting itself in the perspective of the actor. This is supported by the mirror neuron theory, concerning a parietofrontal network engaged both when completing an action and when observing another individual completing that same action (Rizzolatti & Sinigaglia, 2010). These neurons have been observed most closely in animal models, due to the ability to perform more invasive procedures, such as implantation of electrodes to monitor individual neurons (Rizzolatti & Sinigaglia, 2010).

There are non-invasive methodologies of observing regions of activation in the human brain, and many studies have attempted to understand how we process observing the movement of others. One of these is transcranial magnetic stimulation, or TMS. TMS involves targeted stimulation of a certain region of the brain with a magnetic field. Based on how 'excitable' that region is, or how primed it is to activate, a response associated with that brain region can be measured (Bassolino et al., 2014). Bassolino et al. used this methodology for action observation, where they immobilized subjects' arms and had them either watch a video of someone reaching and grabbing an object, or showed them a static image of that same object and instructed them to imagine grasping it. They then used TMS to stimulate the portion of subjects' motor cortices responsible for moving the immobilized hand, and measured resulting excitability via an electrode on the hand that picked up muscle activation. They found that during the immobilization period, the group that watched someone actually pick up an object had a much smaller drop in excitability as compared to the larger drop in the group that only imagined picking up the object (and a control group). This suggests that even in the absence of mobility, observing someone complete a motion leaves the brain primed to act.

However, this simple action observation versus static image paradigm does not tell the entire story of how we observe the actions of others. Another group attempted to determine what gaze patterns lead to the most excitability, measured again via TMS, when observing an action (Wright et al., 2018). Subjects either observed a static image of a finger and thumb pinching a ball, a video of a finger and thumb pinching a ball with no instructions, or that same video with instructions to look at the ball or look at the actor's hand. Subjects that were instructed to observe the ball had greater excitability in the region of the motor cortex devoted to their own hand as compared to excitability in subjects instructed to observe the actor's hand, those given no instructions, or those viewing a static image. This confirms previous findings in gaze-tracking for action observation, where it has been demonstrated that observers tend to 'reach' the target object for a grasping task with their eyes before the actor physically grasps the object with their hand, in order to predict the mechanical interactions between human and target object (Flanagan et al., 2013). Essentially, we humans are incredibly social creatures, and when we watch someone execute a task, we cannot help but put ourselves in their shoes. Specifically, this empathetic response is strongest when observing an actual video of an action and when paying attention to the object of interest instead of just the actor themselves.

Prosthesis Learning

There are two main types of prosthetic devices: body-powered, where movements in the limb remnant mechanically cause the prosthetic to move, and myoelectric, where electrodes detect flexion in the muscles of the limb remnant and the device translates that signal to into movement (Bayani et al., 2019). The study that I conducted involved the use of a body-powered prosthetic device; however, usage principles for myoelectric prostheses are applicable to body-powered devices.

Prosthetics are quite foreign to the human brain and therefore come with a steep learning curve. One study attempted to demonstrate the specifics of this curve by having subjects complete a disk-moving task with either their intact limb or a fictive amputee modeling system (FAMS) (Hughey & Wheaton, 2016). This FAMS involved a device that immobilized a subject's intact hand and forced them to use what was essentially a pretend hand prosthetic device, where moving the wrist forwards/backwards corresponded to opening and closing the claw on the device. As expected, the group operating with their intact limb completed the task with greater speed and accuracy, and the group using the FAMS was more prone to error and took much longer.

In the interest of further exploring what happens when individuals try to use a prosthetic device, another group used a similar intact limb versus prosthesis comparison for a fine motor task, this time with a gaze-tracking component involved (Parr et al., 2018). Similar to Hughey & Wheaton in 2016, this study found the expected propensity to error in the fictive prosthesis group. Additionally, the subjects using the fictive prosthesis spent much more time looking at the prosthetic hand and the target object than the control group, who would sometimes look at other elements of the scene (like the rest of the workspace, the scientist conducting the experiment, etc.). This suggests that prosthesis use is not only more physically effortful, but mentally effortful, requiring full attention to the most salient elements of a fine motor task, at the expense of naturally letting the eyes and mind wander.

Another group sought to find whether these difficulties with prosthesis use are just associated with the learning process, or whether even experienced users still find prosthetic use effortful (Sobuh et al., 2014). This study involved experienced amputee prosthesis users and intact subjects using a fictive prosthetic device performing the same reach and grasp task. Both groups demonstrated the same gaze pattern observed by Parr et al. (2018), with most attention focused on the target object and the prosthetic device rather than the surrounding scene. This suggests a level of continual discomfort with prosthesis usage, even in experienced users. It is noteworthy that experienced users were initially more successful with the fine motor task (faster speed, fewer errors), but this difference disappeared fairly quickly with training for the intact subjects.

Action Observation in Prosthesis Learning

Some work has been conducted exploring the interaction of prosthesis learning and action observation, attempting to discern whether action observation helps improve prosthesis learning, and, if so, the best way to conduct that action observation. Cusack et al. (2012) attempted to compare neural activation via EEG of amputee prosthesis users and intact subjects while observing the actions of both prosthesis users and intact actors. Intact subjects observing both prosthesis users and intact actors had similar activation in the left parieto-frontal region, as well as amputee subjects observing prosthesis user actors. However, amputee subjects observing intact actors had additional activation in the right parietal and occipital regions, suggesting additional cognitive effort required to translate the observed motion of an intact actor into something that a prosthesis user can execute.

The same group conducted a study involving an element of training, where intact subjects attempted to use a FAMS device, trained on it for three days by either observing an intact actor (mismatched group) or another person using the FAMS device (matched group), and then were tested on device use again (Cusack et al., 2016). EEG and kinematic data (such as movement speed, body positioning, etc.) were both collected on day 1 before the training, and day 5 after the training. The matched group displayed less intense motor cortex activation after training, suggesting that prosthesis use was less effortful for them after training with a matched actor. The mismatched group did not display any significant cortical changes after training; additionally, this group had a much higher variability in kinematic parameters than the matched group. This demonstrates the vitality of therapists and clinicians teaching new amputees how to use prosthetic devices by physically displaying device usage instead of only verbally encouraging patients to complete a task or demonstrating the task with their intact limbs.

Methods

Data Acquisition

The data analyzed for this study were compiled from previous work conducted by Bayani et al. (2019). In brief, twenty healthy, college-age, right-handed subjects were divided between two groups: matched (n = 10, 5 male/5 female) and mismatched (*n* = 10, 5 male/5 female) training. Subjects completed a task using a FAMS that fit over their intact right upper extremity, immobilizing the limb below the elbow (Figure 1). To mimic natural grasping motions, subjects could voluntarily open and close the device claws via glenohumeral flexion and scapular/biscapular abduction.

Gaze-tracking data and kinematic positioning data were recorded during experimentation. During action observation, subjects donned a Pupil Labs gaze-tracking system that featured one world-view camera and two pupil-view cameras, which recorded subject gaze location in real-time. Additionally, during task execution, body positioning was recorded by a four-point system consisting of Ascension trakSTAR™ electromagnetic tracking units. The sensors were placed on the apex of the subject's right scapula, midline of the right bicep, and the mobile and immobile aspects at the terminal end of the FAMS device.

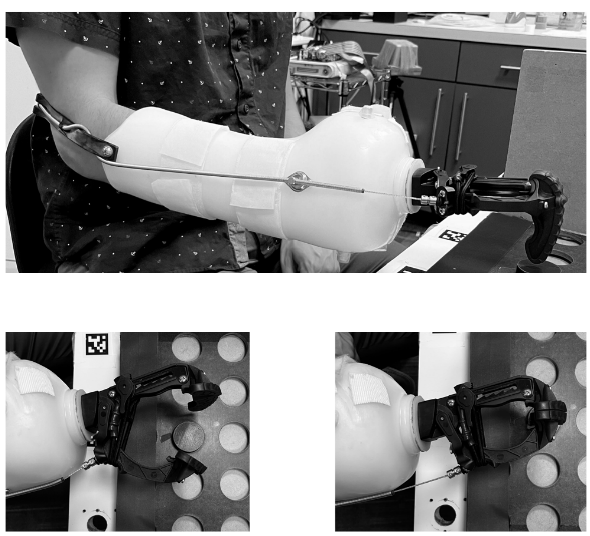

Figure 1: FAMS device. *Top:* Subject wearing FAMS on right upper limb in experimental setup. *Bottom Left:* Open FAMS aperture. *Bottom Right:* Closed FAMS aperture.

Experimentation consisted of three blocks, each containing an action observation component and a task completion component (Figure 2). The 1.5-minute video displayed an actor completing 15 trials of a movement task, where they used their own right arm to transport a disc from their right side to their left. In the video for the matched training group, the actor completed this task with a FAMS fitted over their intact upper right extremity; in the mismatched training group, the actor completed this task with their own intact upper right extremity. After observing this video, subjects then completed the same task 15 times per block, using the FAMS to transport a 3.8cm diameter disc from the right to the left; after each trial, a researcher reset the disc to its original position while the subject returned to the rest position. Subjects were instructed to ensure that the FAMS went over the 0.24m high center partition between the left and right sides of the experimental workspace.

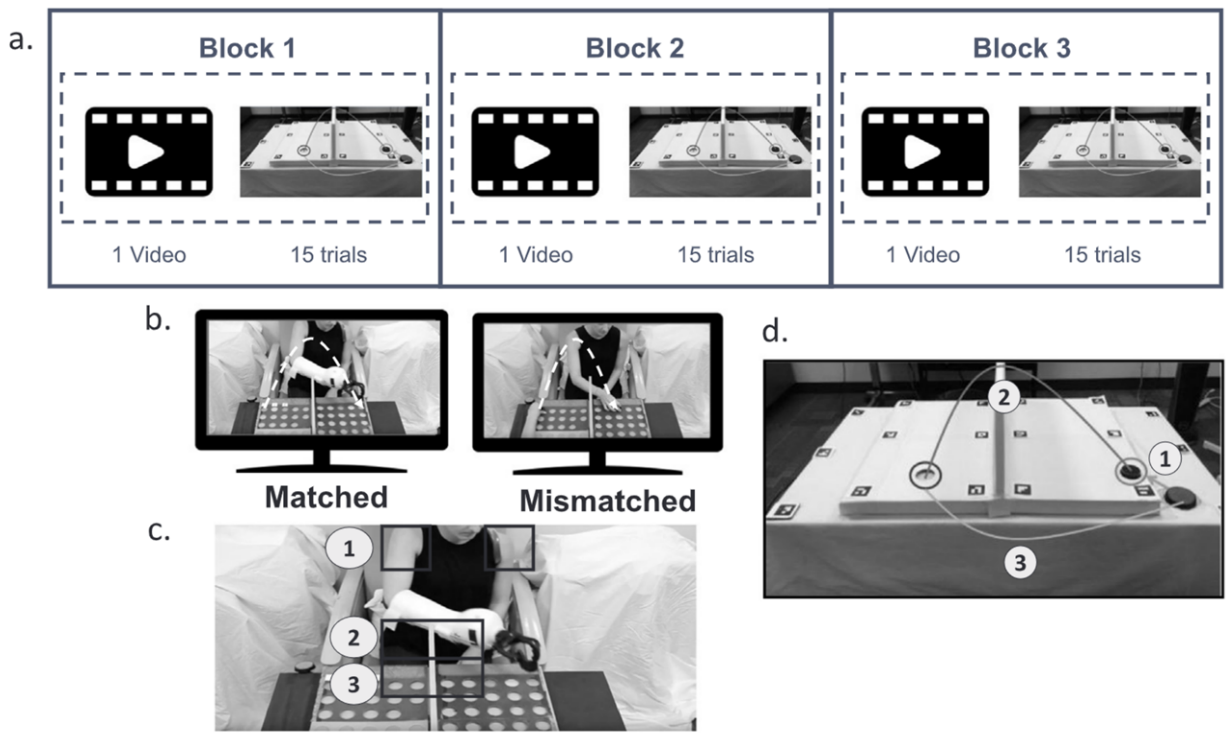

Figure 2: Experimental setup (Bayani et al., 2019). a) Experimental timeline, consisting of three blocks. Each block began with one viewing of a video, followed by 15 executions of the task. b) Two training conditions. The Matched condition consisted of viewing a video of an actor using the FAMS; the Mismatched condition involved the actor using their intact limbs. c) Three primary areas of visual interest during action observation, including 1. actor's shoulders, 2. actor's upper movement trajectory, and 3. actor's lower movement trajectory. These AOIs were consistent across groups. d) Three primary phases of subject movement: 1. reach and grasp, 2. transport, and 3. return to home. Phase 2, transport, was the primary phase of interest for this study.

Preprocessing

After experimentation, areas of interest (AOIs) were created post-hoc using Pupil Lab's PupilPlayer surface creation capability. The primary AOIs labeled for the action observation phase were the actor's ipsilateral (right) shoulder, their contralateral (left) shoulder, upper movement trajectory, and lower movement trajectory (Figure 2.c). The ipsilateral and contralateral shoulders were combined to create one general 'shoulder' AOI. During this phase, two subjects were discarded due to corrupted gaze-tracking data, leaving n = 9 subjects for both the matched and mismatched training groups.

After the creation of AOIs, the primary metric of interest was subject attention to each AOI during action observation. During each time point, subject gaze was either on (1) or off (0) of a certain AOI. This binary metric was extracted by PupilPlayer for each AOI within each block within each subject across the entire observation period. The final probability of gaze on AOI for each trial was determined by dividing the number of time points with gaze on AOI by the total time points in an individual trial.

Examination of the kinematic data revealed sharp changes in position and velocity at the beginning of each trial, related to a 'jerk' as the subject moved the FAMS from the starting position. Additionally, the ending of each trial showed similar sharp changes related to the conclusion of a trial and transition into the next stage. Accordingly, the first 5% and last 10% of data from each trial were discarded to examine only activity during the majority of the transportation movement.

For each trial, several descriptive statistics were generated using *normfit* in MATLAB. Primarily, peak height and peak velocity of the terminal end of the FAMS were extracted from the electromagnetic position sensors. Lateral trunk displacement was quantified by examination of the movement of the shoulder along the y-axis. Finally, movement smoothness was determined via spectral arc length, which utilizes a Fourier transform to quantify the variability in velocity profile over the course of a movement.

Canonical Correlation Analysis

To determine the relation between areas of significant visual attention and kinematic outcomes during training for the matched and mismatched groups, canonical correlation analysis was used within each subject. Canonical correlation analysis, or CCA, is a statistical tool that examines the interaction of two sets of variables, exploring how they vary together as predictors of overall outcome (Wang et al., 2020). More specifically, CCA intakes two matrices, each composed of a set of variables with the same number of observations, and via co-decomposition of the two matrices, determines the relative weight of each variable to its set and the overall correlation between the two sets. For this instance, the two variable sets are visual data, consisting of gaze probability on the three AOIs (shoulder, upper trajectory, and lower trajectory), and kinematic data, consisting of peak FAMS height, peak FAMS velocity, movement smoothness, and lateral trunk variability. The CCA algorithm is executed within each subject, with the 45 trials (15 trials/3 blocks) used as the observations of each variable. At this stage, one more subject within the matched group was discarded due to incomplete and unrecoverable visual data, yielding a matched group size of n = 8.

After determining the weightings for each parameter within each subject, as well as the correlation between parameter sets within each subject, these can be combined across subjects within a group to explore trends within the two training groups. First, the average weighting for each parameter and correlation coefficient within the two groups was examined to determine the heaviest-weighted parameters, and how those different between the matched and mismatched groups. Then, to explore the distribution of the parameter weightings within each group, a measure of kurtosis was employed, which indicates the tendency of data to either cluster at either the tails or the peak of a frequency distribution. The kurtosis of the normal distribution is 3; distributions with larger spread have a kurtosis of greater than 3 and tightly clustered distributions have kurtosis of less than 3 (Kalner, 2018).

Results

Parameter Distribution

Within the matched and mismatched groups, different combinations of parameters came together with different weightings to produce the observed correlation within each group (Figure 4). In general, the matched group had a tighter correlation between visual and kinematic parameters, with an average correlation coefficient of R^2 = 0.49 across the 8 subjects; the mismatched group displayed a lesser correlation between parameter sets, with an average correlation coefficient of R^2 = 0.37.

Additionally, the two groups displayed different patterns of spread among observations of variable weightings within subjects (Table 1). Generally, the mismatched group had higher kurtosis, or a larger variety of weightings for each variable. On average, the kurtosis for any given parameter within the matched group was 1.91; for any parameter within the mismatched group, it was 2.34.

Visual Variable Weightings

The three visual variables correspond to attention on the three areas of interest; namely, the actor's upper trajectory, lower trajectory, and shoulders. Within each of the two groups, a variety of parameters came together to produce the observed correlation (Figure 4). In general, the most significant variable for both the matched and mismatched groups was the actor's lower trajectory, with an average weighting of 0.736 in the matched group and 0.740 in the mismatched group. In the matched group, there was a significant difference in variable weightings between the upper and lower trajectory AOIs based on a post-hoc two-sample t-test (p = 3.9e-4). In the mismatched group, the lower trajectory was more heavily weighted than the upper trajectory (p = 0.029) and the shoulder AOIs (p = 0.0094).

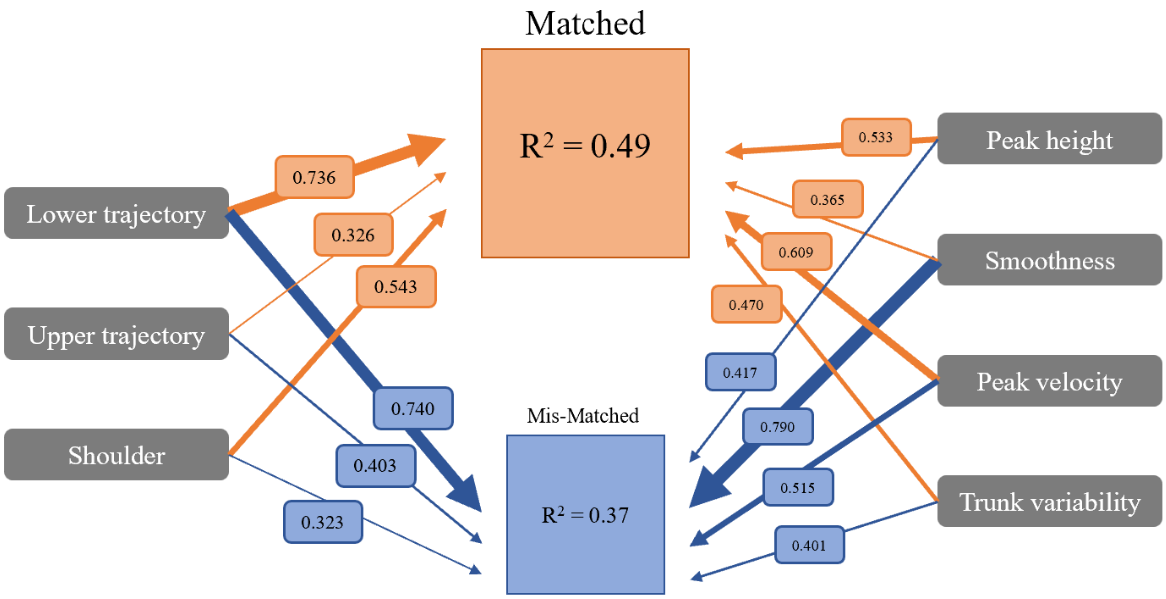

Figure 3: Combinations of parameters for two groups. Visual variables are on the left; kinematic variables are on the right, and the average correlations for the matched and mismatched groups are in the middle. Arrow weightings correspond to the average contribution of each parameter to overall patterns (parameter weighting). The average weighting for each parameter within the two groups is listed on each arrow.

Between the two groups, the primary difference in visual weightings was attention to the actor's shoulder (Figure 5). The mismatched group's outcomes had less of an emphasis on observation of the actor's shoulders, with a weighting of 0.323; the matched group had much more of an emphasis on observation of the actor's shoulders, with a weighting of 0.543. A post-hoc two-sample t-test was conducted to search for a significant difference between the two weighting means; a significance threshold of $p < 0.05$ was not achieved ($p = 0.150$), but the overall trend indicated a higher weighting for the shoulder AOI within the matched group.

Table 1: Kurtosis for each parameter within each group.

	CC	Shoulder	Lower	Upper	Height	Velocity	Sig trunk	Smooth
Matched	1.75	2.23	1.69	1.86	1.88	2.24	1.95	1.71
Mismatched	2.85	1.84	2.75	1.90	2.10	1.70	1.55	3.99

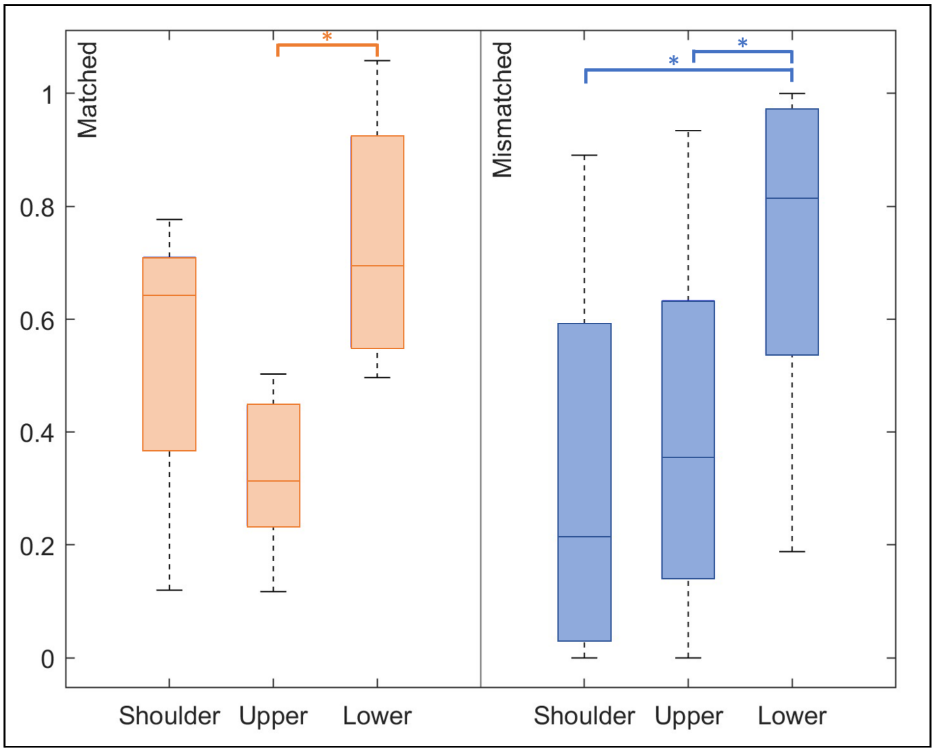

Figure 4: Weightings of gaze on AOI for subjects in the matched (left) and mismatched (right) training groups. The Y-axis represents the spread of weightings as observed across all subjects within a group.

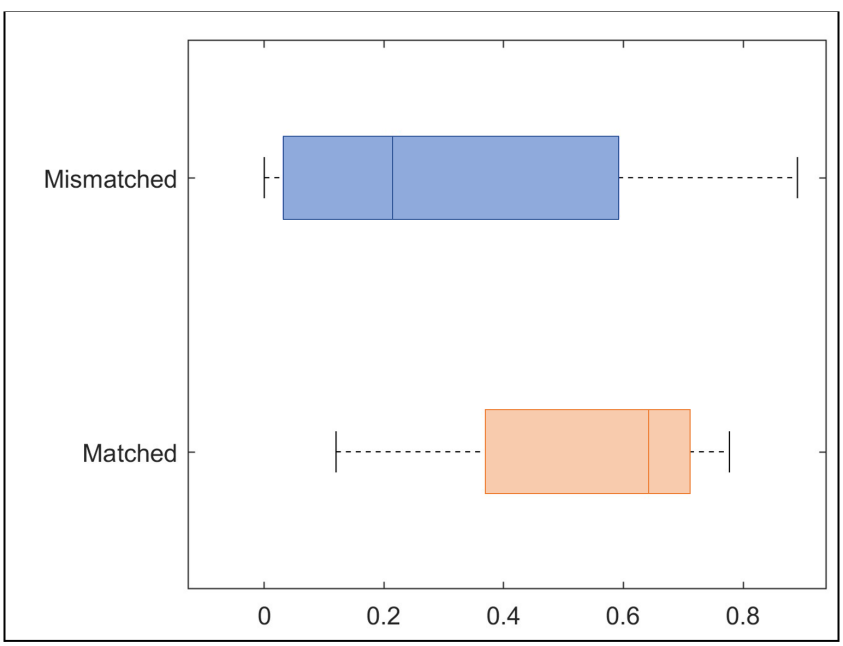

Figure 5: Distribution of weighting for shoulder AOI in matched and mismatched groups.

Additionally, two subjects in the mismatched group did not have any visual attention on the upper trajectory or shoulder, resulting in a weighting of 1.0 on the lower trajectory AOI and weightings of 0.0 on the upper trajectory and shoulder AOIs.

Kinematic Variable Weightings

The four kinematic variables were peak FAMS height, peak FAMS velocity, movement smoothness, and trunk position variability. Within the matched and mismatched groups, a variety of parameters influenced the overall outcome (Figure 6). In the matched group, there were no significant differences between the weightings of any of the kinematic parameters, based on a post-hoc two-sample t-test. Within the mismatched group, smoothness was weighted more heavily than peak height ($p = 0.036$) and trunk variability ($p = 0.0154$).

Between the two groups, the primary difference in kinematic weightings was movement smoothness (Figure 7). On average, smoothness was weighted much more highly in the mismatched group, with a weighting of 0.790, than the matched group, with a weighting of 0.365. A post-hoc two-sample t-test was conducted to determine significance, and there was observed significance between the two groups ($p = 0.012$).

Discussion

Both the matched and mismatched groups displayed relatively similar patternings of variable weightings, with some notable exceptions, while learning to use the FAMS. The two groups were executing the same task in relatively similar training conditions, so this was as expected. However, the matched group displayed a tighter correlation between kinematic and visual variables; additionally, there was generally a smaller variety of variable weightings within the matched group. This indicates that there was less overall variability in how the matched group approached learning how to use the FAMS device, as there was more of a certain, streamlined pathway for translating observed actions into kinematic results. The matched group was better able to copy the physical actions of their observed actor than the mismatched group, because the shoulder motions required to operate the FAMS device were very particular. The mismatched group, in the absence of specific instruction and example on how to open and close the device aperture, were forced to learn by doing rather than observing, leading to a greater variety in parameter outcomes. This is further evidenced by previous observations that FAMS learners in mismatched groups displayed heightened right parietal and occipital activation over matched groups, indicating that FAMS usage is more effortful in the absence of a matched teacher (Cusack et al., 2012).

In the matched group, observation of the actor's shoulders was weighted more highly than in the mismatched group. In the context of the differences between the two groups, this was expected. Operation

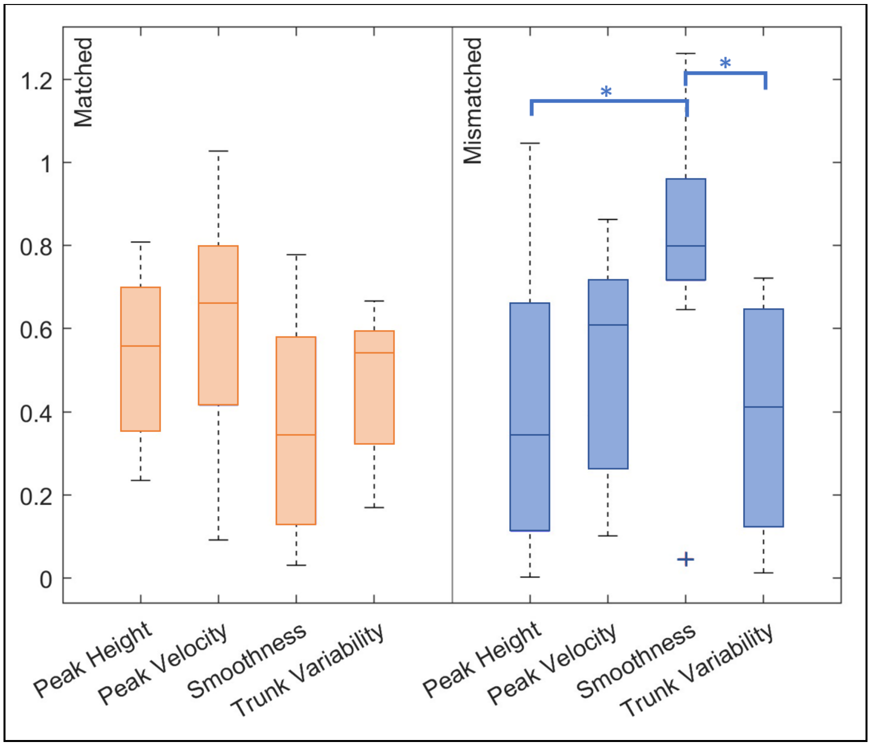

Figure 6: Weightings of kinematic parameters for subjects in the matched (left) and mismatched (right) training groups. The Y-axis represents the spread of weightings as observed across all subjects within a group.

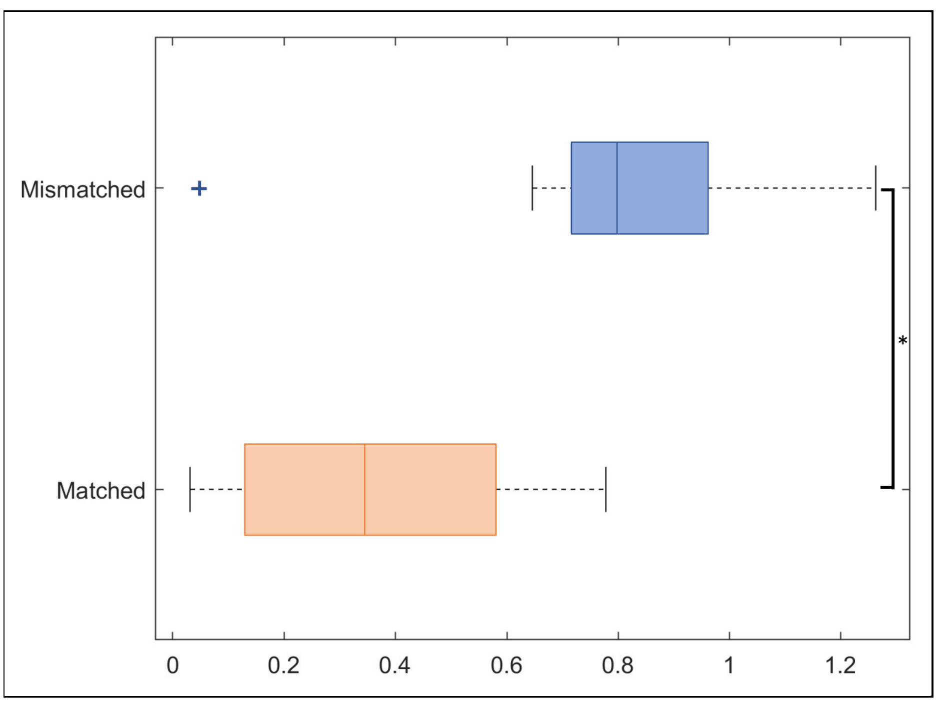

Figure 7: Distribution of weighting for movement smoothness in matched and mismatched groups.

of the FAMS occurs primarily via shoulder movements, so observation of the way that a successful FAMS user is moving their shoulder is crucial for comprehension of how to operate the device. The high weighting of observation of shoulder within the matched group indicates that time spent observing the actor's shoulder was an indicator of overall performance in the task; that is, if a subject in the matched group did not observe the actor's shoulders as closely, they were less likely to be successful in their completion of the task. On the other hand, for the mismatched group, the actor's shoulders were not relevant to the task they were learning to complete, as the actor was simply picking up a disc with their intact limb.

Additionally, within the mismatched group, movement smoothness was highly related to overall subject outcomes, much more so than within the matched group. Within the context of this work, this emphasis on smoothness was unexpected in the mismatched group. A potential explanation for this observation may be that in the absence of a matched actor to observe, the mismatched group emphasized spatial coordination of the device, which is indicated by movement smoothness. In contrast, the matched group was able to evaluate the movement of the prosthetic device as compared to a skilled actor, so this smoothness parameter was less crucial in the presence of a more objective movement goal. Also, this high weighting does not indicate that the mismatched group had particularly high smoothness as compared to the matched group; in fact, preliminary analysis of this same data revealed no effect of the subject training group on movement smoothness (Bayani et al., 2019).

A primary limitation of the current work is the small sample size present in both groups. Though there were originally ten subjects per group, only 9 in the mismatched group and 8 in the matched group were usable for this study. The limited sample size hindered the robustness of observed trends.

In future research, an important consideration would include different action phases. In this study, the only phase considered for kinematic parameters was transportation of the disc, with the very beginning (grasp) and end (placement) of the movement truncated. Observation of kinematic parameters in phases such as reach-and-grasp and return to home after placement could further elucidate differences in how matched and mismatched training impact action planning, instead of just movement execution.

Additionally, there are other FAMS devices available to simulate the experience of amputation, such as a partial hand prosthesis controlled by wrist abduction (Alterman et al., 2022). Conduction of a similar study with a focus on the mechanics of a different joint would provide a more complete picture of the adaptive nature of the whole upper limb, instead of just movement of the shoulder.

Conclusion

When portions of upper limbs are lost, persons with new amputations must re-learn how to exist within the world. This involves training patients on prosthetic devices that aim to replace limb functionality; however, these prostheses are difficult to use and are often taught poorly. It has been established that the most effective method of teaching prostheses involves having patients observe a teacher who is also using a prosthetic device, but the reasons why are unclear. This work elucidated the differences between patients who learn how to use a prosthesis by observing a matched actor as opposed to those watching a mismatched actor. Specifically, those in the matched group had a more streamlined learning process with higher correlation between visual and kinematic variables; the mismatched group experienced a more chaotic learning process with lower correlation between visual and kinematic variables. This suggests that the route to prosthesis learning is more obvious in the presence of a matched teacher, which serves to further emphasize the importance of a matched protocol being the default in a rehabilitation setting.

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