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Implicit development of gaze strategies support motor improvements during action encoding training of prosthesis use

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Abstract

Background: Action observation training has been suggested to facilitate motor improvements in the lives of persons with neural injury. Previous studies have shown that for persons with upper limb amputation, matched limb training, where prosthesis users emulate each other, has shown promise above mismatched training where a prosthesis user emulates actions of a person with sound limbs (most commonly that of a therapist).

Objective: The mechanism underlying the matched limb training benefit is unclear. Gaze strategies may reveal unique patterns between matched and mismatched training which could explain improvements in motor function in matched limb training.

Methods: Twenty persons with sound limbs were trained on how to use a prosthesis simulator using matched or mismatched limb training in a single session. Eye movements were recorded during the training phase. Kinematics were recorded as persons performed the task.

Results: Gaze patterns showed differences between the training groups. The mismatched group demonstrated a higher probability of gaze on the path between the start and end of the action, while the matched group demonstrated a significantly higher probability of focusing on the elements of the path of the action and a trend of focusing on the shoulders. Kinematics also revealed overall improvements in motor control for the matched group.

Conclusions: This study proposes a putative mechanism that may explain improvements in matched limb training through shifting gaze strategies. Further work is needed to understand whether implicit visual strategies seen during matched limb training might encourage motor learning during functional training with prostheses.

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none

1. Introduction

Approximately 1.5 million people suffer from limb loss (amputees) with upper limb amputations (ULA) making up 34% of the amputee population¹. Persons with upper limb loss arising from trauma (e.g., effects of accident, injury to blood vessel) are highly prevalent (~92%)^{1,36}. There is urgency in informing upper limb amputees about regaining function with prosthetic limbs². Unfortunately, rejection and non-functional use of prostheses is high³ in both body-powered and myoelectric devices. Body-powered devices utilize a cable system actuated by joint movement while myoelectric devices rely on muscle activation patterns to power the prosthetic device³⁹. For those that use prostheses functionally, use is limited to approximately 50% of daily living tasks (including bimanual tasks)⁴. A recent systematic review of the literature suggests that early technological advancements in upper limb prosthetics do not seem to improve usage patterns⁵.

Low device usage rates may be addressed by tailoring rehabilitation strategies towards more functional outcomes. A review conducted by Cordella and colleagues (2016) found that users desired stable grasps and less visual attention during use. To our knowledge, there has been little research on the most effective rehabilitative techniques between myoelectric or body-powered prosthetic devices. However, one area of potential focus is enhancing rehabilitation methods upon prosthesis fitting⁶. Amputees can improve in some functional measures through rehabilitation, but acquiring skilled use is still a challenge⁷. Wearers of prosthetic devices are able to display typical motor learning patterns with the device, such as motor adaptation notably in early learning, however improvements in motor control may not extend into late learning⁸. While persons using upper limb prostheses can improve speed during motor learning (though at rates not comparable to the sound limb), it comes at great cost to error⁹. The present standard of rehabilitative training involves mimicking of a therapist (normally a person with intact limbs) for “shoulder, elbow, and terminal device control”¹⁰, which facilitates the development of compensatory strategies rather than promoting the development of movements for functional outcomes⁴.

It is possible that gaining functional control with a prosthetic limb is difficult because amputees have little to no cortical action representations of a prosthetic device. This will be a natural impediment to neural encoding of action in therapist-based training, as therapists have intact limbs while the amputee does not. Prior work has reinforced the importance of a motor-based understanding of actions that are observed in activating left parietofrontal circuits for action¹¹. Our prior work shows that when amputees perform actions performed by a prosthesis user (matched imitation) they display the expected left parietofrontal activation during motor planning however, when they emulate an intact hand (mismatched imitation), areas related to visuospatial encoding of actions in the right hemisphere show pronounced activation¹². Actions that are part of an individual’s motor repertoire, such as tool-use, typically recruit left parietofrontal areas. Activation of right parietal and occipital regions in mismatched imitation reveals subjects engaging in abnormal motor planning and resources for visual understanding rather than the appropriate movement patterns for motor control¹². A recent longitudinal training study showed increased neural activation in parietofrontal areas and improved motor performance for matched limb training compared to mismatched training¹⁵. Further, we have identified improved kinematic outcomes, such as

decrease in shoulder motion variability along with greater novel elbow motion variability, to matched limb training compared to mismatched limb training^{13,14}. Thus, participants in the mismatched observation mimic the motor patterns of an intact person while matched observation promoted the generation of new movement patterns that is more efficient for prosthesis use¹³. While the link between parietofrontal and kinematic parameters is seen in literature, it is unclear what mediates this effect.

Gaze behavior during observation could be a potential mechanism that mediates the differences between intact and prosthesis users and may also influence gaze and kinematic patterns during execution. Prior evidence during action execution has demonstrated notable differences in the gaze strategies of prosthesis users compared to users using their anatomic hand³⁷. In this study, prosthesis users directed a significant amount of their attention toward the hand with an associated decrease in time spent attending to the target of the task³⁷. Gaze behaviors, notably time spent on the terminal end of the prosthesis, can decrease in persons with high levels of skill¹⁶. However, this observation is not consistently seen with skill or across training and may depend on a variety of factors (e.g., duration of daily use)^{16,17}. Achieving this high level of skill is a challenge. Persons using a myoelectric prosthesis simulator showed limited ability to use gaze to plan upcoming actions in a task, likely driven by grasp insecurity that was unaffected by practice^{17,37}. During motor execution studies, analyzing gaze patterns suggests a reliance on visual feedback mechanisms requiring greater cognitive resources during the learning process³⁷.

It remains unclear whether different forms of observation-based training can influence gaze patterns during training itself. Prior studies have suggested that the ability to facilitate sensorimotor areas during action observation is contingent upon eye gaze that focuses on the movement of the limb¹⁸. This facilitation is not only evident in cortical areas, but gaze has also been shown to modulate corticospinal excitability suggesting a direct link to motor neurons³⁸. These studies implement explicit paradigms wherein the spatial allocation of gaze is manipulated to facilitate sensorimotor neural areas. However, it may be possible that the spatial allocation of gaze during observation could also develop without guided cuing. Hence, the focal point of the current study is to understand gaze strategies that develop implicitly and without biased cuing during task observation. Research reveals that gaze of body cues can support understanding action intent in others^{19,20} which could be beneficial to understanding of action observation-based rehabilitation outcomes²¹. We postulate that the neurobehavioral improvements seen in matched limb over mismatched limb training^{13–15} are initially driven by implicitly divergent gaze strategies between the two training approaches.

The goal of this work is to identify whether gaze strategies differ between matched and mismatched limb training during observation of matched and mismatched limbs. Findings may reveal a mechanism explaining how varied approaches to action observation training in amputees may differentially facilitate motor outcomes. Specifically, our prior work has demonstrated that decreases in shoulder movement variability are most pronounced in persons with matched limb training^{13,15}, which is vital for control of body-powered prosthetic limbs. Thus, we hypothesize that matched limb training will promote a significantly increased gaze to the shoulders and a focus on the path of the movement compared to the mismatched group. Further, we hypothesize that the matched limb group

will show improved kinematics, such as faster peak velocity of the prosthesis, increased smoothness, decreased upper body variability, compared to the mismatched group.

2. Materials and Methods

2.1 Participants

Twenty right-handed participants with intact upper extremities were recruited for this experimental study and randomly assigned to either the matched ($n_{\text{female}} = 5$, $n_{\text{male}} = 5$) or mismatched training group ($n_{\text{female}} = 5$, $n_{\text{male}} = 5$) (mean age = 24.7 ± 3.39 years, range = 18–34 years). Sample size was based on our previous kinematic studies comparing kinematic outcomes of matched versus mismatched training^{12,13,15}. The Edinburgh Handedness Inventory²² was utilized to confirm right-handedness. Signed informed consent was acquired from all participants according to the procedures set forth by the Institutional Review Board at the Georgia Institute of Technology.

2.2 Materials

Participants performed the experimental task while wearing a prosthesis (also referred to as the Fictive Amputee Model System (FAMS)¹³) that fit over their intact right upper extremity. The FAMS is a prosthesis designed to emulate the type of device an individual with limb loss at the forearm would need to allow for some prehension capabilities. Additionally, the FAMS simulates the altered degrees of freedom and kinematic adaptations that an individual with a transradial amputation would experience as a result of an amputation¹³. The FAMS utilized for this experiment was constructed of 0.25in polypropylene molded for an intact right upper extremity. It has a body-powered design and consisted of a figure of nine harness, northwestern ring placed inferior to C7 slightly towards contralateral side, voluntary opening hook (Vari-Pinch Prehensor™ (V2P™, Mydtral Orthopedic Technologies, Winnipeg), and was secured comfortably with two large pads placed proximally and distally on the anterior forearm with velcro. The device aperture was voluntarily opened with glenohumeral flexion and scapular/biscapular abduction.

Pupil Labs Eye Camera (Berlin, Germany; 200 Hz, binocular) was used to collect gaze path data throughout the experiment. The participant donned eye tracking glasses that featured two pupil cameras which tracked the participant's pupils relative to the world, which recorded what participant saw in their line of vision. To ensure accurate gaze recording, manual marker calibration was used to calibrate the three cameras relative to the 3D workspace that contained the task.

Kinematics during action execution was recorded using a four (4) Sensor Ascension trakSTAR system (Motion Monitor, Chicago). The planes were defined as follows: the Y-plane extended in a horizontal fashion, the X-plane extended in front of and behind the participant, and the Z-plane extended in a vertical fashion. Four electromagnetic sensors (MotionMonitor, Chicago) were placed: 1) apex of right scapula, 2) midline of right bicep in sagittal plane, 3) right immobile aspect of distal attachment of the prosthesis, and 4) right mobile aspect of distal attachment of the prosthesis. Ten anatomical landmarks were denoted with a stylus, and those locations allowed for digitization of segment lengths using local

coordinate systems and anthropometric assumptions. Those landmarks included: 1) C7/T1 joint, 2) right acromioclavicular joint, 3) right shoulder trigonum spinae, 4) right shoulder angulus inferior, 5) right shoulder angulus acromialis, 6) right shoulder processus coracoid, 7) right elbow medial epicondyle, 8) right elbow lateral epicondyle, landmark on the FAMS approximating the 9) right wrist ulna and 10) right wrist radius. To reduce artifacts in data collection, participants were instructed to refrain from extraneous movements during the task completion component of the experimental design.

2.3 Experimental Setup

All participants were seated in a comfortable arm chair in a well-lit room for the duration of the experiment. A standard script was read aloud detailing the experimental paradigm. The study featured two experimental groups referred to as the matched group and the mismatched group. In the matched group, a participant wearing the body-powered prosthesis viewed a video of a task being performed by a prosthesis user also using a body-powered prosthesis. In the mismatched group, a participant viewed a video of the task being completed by an individual with two intact upper extremities. Participants viewed the task performed in an allocentric perspective to mimic a typical training environment. The participants would then execute the task from the video while wearing the prosthesis. The experiment was comprised of three blocks with each block featuring a video watching and a task completion component. All subjects were instructed with the following script: “We will have you sit and watch a video and then perform the task in the video. In this task, you will start by pressing the green button to your right. After pressing the button take a few seconds before moving your arm and beginning the task. You will then pick up the disc from its location and move it to the designated slot, as denoted by the yellow coloring, and place the disc fully seated in the slot. Then return to the green button and press it before beginning the task again. At the end of your last block press the green button and return to your home base position, seated with your arms rested in your lap.”

2.3.1 Action observation—For the experiment, all participants were seated in a chair centered in front of a table ($0.72\text{m} \times 0.6\text{m} \times 0.45\text{m}$). During action observation, a series of videos were shown on a monitor ($0.4\text{m} \times 0.3\text{m}$) positioned 0.6m from the middle of the chair. Twelve Pupil Labs surface markers were placed along the perimeter of the monitor to allow for the future demarcation of areas of interest. All individuals were instructed to observe the videos on the screen without any instruction on what aspect of the video to focus on, hence, gaze strategies are implicit and without any external influence. Each participant within a training group viewed the same video for three blocks, and the video corresponding to their experimental group, matched or mismatched. Both videos were approximately one minute in length and showed the actor performing 15 movements (trials) per video (Figure 1a). The action consisted of either a sound limb (mismatched) or a body-powered prosthetic limb (matched) reaching to grasp a disc, and move it over a barrier to an open slot opposite the barrier (Figure 1b).

2.3.2 Action execution—Immediately following action observation, participants were asked to perform the same task. A workspace board ($0.6\text{m} \times 0.45\text{m}$) was positioned on the table in front of the participant such that the partition on the board was aligned with the

vertical midline of the participant's torso. The board featured a 0.24m high partition and a 3.8cm diameter circular slot on either side of the partition in which a round disc of the same size was placed. At the lower right hand corner of the table, on which the monitor and board were placed, a circular green button was used to denote the start and end of each movement.

The task itself was divided into five phases: 1) Reach, 2) Grasp, 3) Transport, 4) Placement, 5) Transition. The reach phase encompasses the time when participants release the button, open the terminal device, and then proceed towards the slot on the right to pick up the disc. During the grasp phase, the participant initiated the closing of the terminal device until the disc was securely grasped by the distal attachment. At the start of all trials, a researcher placed the disc into a well so that a portion of the disc was raised above the well and easy to grasp. During the transport phase, the participant lifted and moved the disc up and over the partition. Placement started when the disc hovered directly above and in line with the slot on the left side. Placement was considered complete once the disc was completely seated in the slot. After placement of the disc in the allocated slot, the participant returned to the green button during the transition phase to begin the next movement of the task. A researcher sat in front of the table throughout the task to replenish discs from the end location slot into the starting slot after the completion of each movement. Each block contained fifteen trials in total.

2.4 Data Preprocessing

Eye tracking and kinematic data were extracted from the Pupil Capture (Pupil Labs), and from MotionMonitor respectively. All data was initially preprocessed using MATLAB R2015b (Natick, MA) before transferring to R (the R Foundation for Statistical Computing, Vienna) for statistical analysis.

2.4.1 Eye Tracking: Distinct, non-overlapping AOIs were defined by using surface markers on the workspace. Borders delineating the different AOIs were determined post-hoc and after visualization of gaze data. AOIs were the actor's ipsilateral shoulder, contralateral shoulder, upper trajectory, and lower trajectory. The ipsilateral shoulder represents the shoulder that contained the FAMS (right shoulder). The contralateral shoulder was the shoulder opposite of the FAMS (left shoulder). The shoulders were included as the FAMS is opened with glenohumeral flexion and scapular/biscapular abduction. The upper trajectory was defined as the area above the barrier and encompassed the trajectory of the disc but does not incorporate shoulders. The lower trajectory was defined as the straight trajectory across the barrier from the start to the end point of the movement but does not incorporate shoulders (Figure 1). Furthermore, we ensured that the point of grasp (i.e., start) and placement (i.e., end) were not incorporated in either trajectory AOI since subjects' gaze always attended to those areas during the start and end of the task. Eye movements within an AOI was expressed as a binary value, inside (1) or outside (0) the AOIs across time. The amount of time gaze fell within areas of interests (AOI) during this observational period were extracted from the Pupil Labs software and analyzed offline. The probability of gaze to fall within a particular AOI at each movement phase during video observation was calculated by dividing the number of times gaze fell within the AOI by the total number of time points. Continuous gaze data was divided into three different phases of the actor's

movement: reach to grasp, transport to placement, and transition to return home. These phases are distinct from the action execution data for two reasons: our emphasis was on continuous gaze data not on singular, near discrete events (such as grasp or placement) and execution and observation data points are separate with no intention to assume correlation between the two.

2.4.2 Kinematics: Inspection of continuous displacement and velocity of the terminal device revealed a sharp change in displacement and velocity was present in the first 5% of each trial which reflects the terminal device bouncing off of the home button. The last 10% of the data represented the transition phase. To ensure that data did not contain movement artifacts (e.g. bouncing motion after pressing home button) that are not relevant to the specifics of the task, the first 5% of the kinematic data was removed from analysis and the last 10% of kinematic data was removed for all blocks and all subjects. All descriptive statistics used for analysis were extracted using the *normfit* function of MATLAB. The average peak height and peak velocity of the terminal device was determined by calculating the mean of all trials for each block. Movement smoothness was calculated as a measure of the velocity of the terminal device during reach, grasp, transport, and placement. To quantify movement smoothness, spectral arc length used³⁵. Spectral arc length utilizes a Fourier transform to quantify the speed profile variability over the course of the movement trajectory and has been shown to be highly sensitive in detecting functional changes in movement smoothness in clinical populations and during motor learning²³. An amplitude threshold of 0.05, maximum cut-off frequency of 20Hz, and a zero padding index of 4 was applied. The maximum displacement of the shoulder along the y-axis and the standard deviation of the shoulder along the y-axis for each movement were used to calculate peak lateral trunk movement and variability of lateral trunk movement for every movement respectively.

2.4.3 Performance Measures: From the kinematic data, movement time was defined as the time from the initiation of reach to the end of the transition phase. Video recordings were used to quantify the number and type of errors that were committed across all 45 trials. Errors were placed into 5 categories: grasp error, drop during transport, partition hit, placement error, and drop at destination. During reach & grasp, failure to fully secure the disc within the terminal device was considered an error. During transport, loss of the disc due to insecure grip or terminal device impact on the partition were categorized as errors during transport. Lastly, placement error due to lack of precision during placement or a drop at the destination due to insecure grip was categorized as errors during placement.

2.5 Statistical Analysis

All statistical analyses were performed using RStudio 2009–2016 version 1.0.136. A linear mixed effect model with maximum likelihood was used to determine the contribution of the fixed effects (Group and Block). To account for baseline difference in gaze and kinematic behavior, a null model, containing only the random effect of Subject, was created using the *lme* function in R. Additional models incorporating one of the fixed effects and a combination of the fixed effects were created to determine the main and interaction effects respectively. A likelihood ratio test was used to compare the null model from models that incorporated the fixed and random effect by using the *anova* function in R. Chi-square

statistics from the *anova* function in R were used to compare differences between factors. Post-hoc pairwise comparisons were calculated using the *multcomp* and *lsmeans* package, which applies a single-step method using Tukey-HSD adjustment. A $p\text{-value} < 0.05$ was considered significant. As this is a preliminary study, we also identified significant trends ($0.05 < p < 0.10$) in the data. A Cohen's d calculation using G*Power was used to assess effect size for two-sided t-test results.

2.5.1 Eye Tracking: Two subjects were removed from the study due to corrupted data. To determine if there is a significant difference in probability between subjects in the matched ($n = 9$) or mismatched ($n = 9$) group, Phase (reach to grasp, transport, and return to home) and AOI (upper trajectory, lower trajectory, contralateral shoulder, and ipsilateral shoulder) were also included as additional factors in gaze analysis. After initial visualization of eye movement data, the probability of gaze to fall within the contralateral shoulder and ipsilateral shoulder were not significantly different from one another ($t = 0.312$, $p = 0.989$). Hence, probabilities from the contralateral and ipsilateral shoulder were collapsed into a single shoulder AOI. We employed two analytical approaches. First, we ran four different models to determine the main effect of Group (matched, mismatched), Block (1, 2, 3), Phase, and AOI along with the interaction effect of $\text{AOI} \times \text{Group}$. Second, we separated the data by AOI and analyzed the main and interaction effect of Group, Block, and Phase.

2.5.2 Kinematics: We examined the main effects of Group and Block and the interaction of $\text{Group} \times \text{Block}$ for peak height, peak velocity, smoothness, peak lateral trunk movement, and variability of lateral trunk movement and time of movement.

2.5.3 Performance measures: For movement time, we determined the main effects and interaction effects of Group and Block. From the errors, the main effect and interaction effect of the error type, Group, and Block were calculated to determine if training affected and observation affected performance.

3 Results

3.1 Eye Tracking

3.1.1 Gaze Across AOIs—To evaluate the differences in gaze strategies during matched and mismatched observation, we calculated the probability of gaze to fall within a particular AOI. There was a main effect of Phase ($\chi^2(2) = 12.013$, $p = 0.002$), AOI ($\chi^2(2) = 415.62$, $p < 0.0001$), and an interaction effect of $\text{AOI} \times \text{Group}$ ($\chi^2(5) = 503.87$, $p < 0.0001$) (Figure 2). Participants in the matched group had a significantly greater probability of viewing the upper trajectory compared to the mismatched group ($t(16) = -3.417$, $p = 0.0063$, $d = 0.312$). There was a trend for subjects in the matched group to view the lower trajectory less compared to mismatched ($t(16) = 2.567$, $p = 0.084$, $d = 0.147$). The matched group demonstrate a trend towards a greater probability of watching the shoulders more compared to the mismatched group ($t(16) = -2.553$, $p = .88$, $d = 0.224$). Across AOIs, probability of gaze to fall within the lower trajectory was significantly higher than the upper trajectory ($t(16) = 14.92$, $p < 0.001$, $d = 0.499$) and the shoulders ($t(16) = 20.332$, $p < 0.001$, $d = 0.537$) in the mismatched group. Furthermore, the mismatched group had a significantly greater

probability of viewing the upper trajectory compared to the shoulders ($t(16) = 3.944$, $p < 0.001$, $d = 0.729$). Subjects in the matched group had a greater probability of viewing the upper trajectory ($t(16) = 6.314$, $p < 0.001$, $d = 0.261$) and the lower trajectory compared to shoulders ($t(16) = 8.935$, $p < 0.001$, $d = 0.333$).

3.1.2 Observation across movement phases—To determine gaze patterns during observation differed based on the task-related features or movement phase during observation, we analyzed the probabilities of gaze to fall within a particular AOI by phase and separated the data into lower trajectory, upper trajectory, and shoulder AOIs. In this approach, we were interested in the main effect of Group, Block, and Phase along with the interaction effect of Group and Phase within a single AOI (Figure 3).

Lower trajectory: There was a main effect of Block ($\chi^2(2) = 63.156$, $p < 0.001$) and Phase ($\chi^2(2) = 9.6751$, $p = 0.008$) and an interaction effect of Phase $\times$ Group ($\chi^2(5) = 28.086$, $p < 0.01$). The probability of gaze to fall within the lower trajectory during reach and grasp ($t(16) = 3.515$, $p = 0.005$, $d = 0.274$) and transport ($t(16) = 3.971$, $p < 0.001$, $d = 0.296$) was significantly higher than home in the mismatched group. There was a trend towards greater probability of gaze to fall within the lower trajectory in transport compared to reach and grasp in the matched group ($t(16) = -2.598$, $p = 0.079$, $d = 0.181$) (Figure 3a).

Upper trajectory: There was a main effect of Group ($\chi^2(1) = 7.9048$, $p = 0.005$), Block ($\chi^2(2) = 13.671$, $p = 0.001$), and Phase ($\chi^2(2) = 11.201$, $p = 0.004$) along with an interaction effect of Phase $\times$ Group ($\chi^2(5) = 29.034$, $p < 0.001$). In the mismatched group, there was a significantly greater probability for subjects to view the upper trajectory during the reach and grasp phase compared to the home phase ($t(16) = 2.932$, $p = 0.035$, $d = 0.224$). In the matched group, the probability of gaze to fall within the upper trajectory was significantly greater during the transport phase compared to the reach and grasp ($t(16) = -2.855$, $p = 0.044$, $d = 0.182$) and the home phase ($t(16) = 3.255$, $p = 0.013$, $d = 0.182$). Furthermore, the matched group had a greater probability of viewing the upper trajectory compared to the mismatched group in the transport ($t(16) = -4.040$, $p < 0.001$, $d = 0.416$) and home phase ($t(16) = -2.826$, $p = 0.048$, $d = 0.362$) (Figure 3b).

Shoulders: The shoulder AOI showed a significant main effect of Block ($\chi^2(2) = 29.034$, $p < 0.012$) but no interaction effect of Phase $\times$ Group ($\chi^2(5) = 5.070$, $p = 0.407$) (Figure 3c).

3.1.3 Observation across blocks—To evaluate the relative contribution of practice, we further examined the interaction effect of Block $\times$ Group in the lower trajectory ($\chi^2(5) = 78.043$, $p < 0.001$), upper trajectory ($\chi^2(5) = 23.5$, $p < 0.001$), and shoulders ($\chi^2(5) = 14.648$, $p < 0.012$) (Figure 4).

Lower trajectory: In the mismatched group, the probability of gaze to fall within the lower trajectory was significantly lower in the third block compared to the first ($t(16) = 3.552$, $p = 0.004$, $d = 0.214$) and second block ($t(16) = 3.376$, $p = 0.007$, $d = 0.207$). In the matched group, the probability of gaze to fall within the lower trajectory in first block was significantly greater than the second ($t(16) = 4.938$, $p < 0.001$, $d = 0.287$) and third ($t(16) =$

7.775, $p < 0.001$, $d = 0.549$) blocks. Furthermore, the third block was also significantly lower than the second block in the matched group ($t(16) = 2.837$, $p = 0.041$, $d = 0.364$) (Figure 4a).

Upper trajectory: There was a significant increase in probability between the first and third block for the matched group ($t(16) = -3.108$, $p = 0.021$, $d = 0.179$). Unique to the upper trajectory, a significant difference between groups were found in the third block ($t(16) = -3.372$, $p = 0.009$, $d = 0.345$) and a trend in the first block ($t(16) = -2.564$, $p = 0.10$, $d = 0.412$) (Figure 4b).

Shoulders: Lastly, there was a significant increase in probability at the shoulders between the first and third block for the matched group ($t(16) = -2.937$, $p = 0.03$, $d = 0.078$) (Figure 4c).

3.2 Kinematics

-Peak height: The peak height the terminal device achieved demonstrated a main effect of Block ($\chi^2(2) = 10.503$, $p = 0.005$) and an interaction effect of Block $\times$ Group ($\chi^2(5) = 18.677$, $p = 0.002$) (Figure 5a). The matched group showed a significant decrease in peak height on the third block compared to first block ($t(18) = 3.923$, $p < 0.001$, $d = 0.25$) and second block ($t(18) = 3.260$, $p = 0.011$, $d = 0.25$). No significant differences were detected for the mismatched group.

3.2.1 Peak velocity: Peak velocity of the terminal device showed a significant main effect of Block ($\chi^2(2) = 57.701$, $p < 0.001$) and an interaction effect of Block $\times$ Group ($\chi^2(5) = 89.579$, $p < 0.001$) (Figure 5b). In the mismatched group, the peak velocity in the second block was significantly greater than the first block ($t(18) = -3.457$, $p = 0.005$, $d = 0.307$). The matched group showed differences across multiple blocks. Subjects reached greater peak velocities in the second block ($t(18) = -5.691$, $p < 0.001$, $d = 0.5$) and the third block ($t(18) = -8.875$, $p < 0.001$, $d = 0.736$) compared to the first block. These differences were also present between in the second and third block in the matched group ($t(18) = -3.088$, $p = 0.017$, $d = 0.295$).

3.2.2 Peak lateral trunk movement: A significant main effect of Block ($\chi^2(2) = 70.224$, $p < 0.001$) and an interaction effect of Block $\times$ Group ($\chi^2(5) = 80.774$, $p < 0.001$) was found for peak lateral trunk movement (Figure 5c). In the mismatched group, subjects exhibited significantly less peak lateral trunk movement by the third block ($t(18) = 3.802$, $p = 0.001$, $d = 0.283$) and a trend towards less lateral trunk movement by the second block ($t(18) = 2.470$, $p = 0.09$, $d = 0.211$) compared to the first block. Subjects in the matched group exhibited significantly less lateral trunk movement by the second block ($t(18) = 5.514$, $p < 0.001$, $d = 0.198$) and the third block ($t(18) = 8.101$, $p < 0.001$, $d = 0.277$) compared to the first block. There was also a trend towards a smaller peak lateral trunk movement between the second and third block ($t(18) = 2.500$, $p = 0.083$).

3.2.3 Variability in lateral trunk movement: A significant main effect of Block ($\chi^2(2) = 28.254$, $p < 0.001$) and an interaction effect of Block $\times$ Group ($\chi^2(5) = 34.764$, $p < 0.001$). In the mismatched group, the third block had significantly less trunk variability

compared to the first block ($t(18) = 4.164, p < 0.001, d = 1.00$). In the matched group, the first block was significantly greater compared to the second block ($t(18) = 3.894, p < 0.001, d = 0.347$) and 3 ($t(18) = 3.003, p = 0.0227$).

3.2.4 Smoothness: There was a significant main effect of Block ($\chi^2(2) = 12.257, p = 0.003$) but no main effect of Group or interaction effect for the smoothness of movement (Figure 5d). Subjects exhibited greater smoothness in the second block ($t(18) = -2.731, p = 0.017, d = 0.253$) and third block ($t(18) = -3.268, p = 0.003, d = 0.238$) compared to the first block.

3.3 Performance measures

3.3.1 Movement times: There was a main effect of Block ($\chi^2(2) = 275.5, p < 0.0001$). Movement time decreased from the second to third block ($t(18) = 12.845, p < 0.001$), from the first to third block ($t(18) = 17.360, p < 0.001$), and from the second to third block ($t(18) = 4.411, p < 0.001$) in both the matched and mismatched group.

3.3.2 Errors: We determined the differences in errors by group, block, and error type. There was no main effect of Block or Group nor was there an interaction effect. However, there was a main effect of error type ($\chi^2(4) = 11.314, p < 0.0233$). Bonferroni post-hoc revealed significantly greater placement errors than grasp errors ($t(17) = 2.926, p = 0.0302$).

4. Discussion

We sought to identify a potential mechanism that could explain neuromotor benefits of matched over mismatched limb training for prosthesis users seen in prior studies^{13–15} with eye movements as the primary outcome of interest. Findings reveal that gaze patterns significantly differentiate matched versus mismatched trained groups. Gaze in the mismatched group primarily attended to the start and endpoints of the action, while the matched group focused on the path of the prosthesis action and the shoulders. Kinematic results suggest a progressive improvement in motor control (peak height, peak velocity) specific to the matched limb group. A mechanistic visual encoding difference leveraged in matched limb action observation training may facilitate task-specific kinematic improvements in a single session.

The reliance on observation remains a potent tool to support the goals of motor rehabilitation. Through observation followed by execution, studies have shown greater rehabilitative outcomes along with an associated increase in brain regions involved in action understanding²⁵. This present study not only supports the importance of observation, but the specificity of the observed action. In our study, matched observation facilitated differential gaze patterns specifically during the transport phase of the observed action. Continuous matched observation followed by practice resulted in the allocation of gaze away from the lower trajectory and towards the upper trajectory across trials. Specific to prosthesis use, matched observation may be necessary to promote accelerated changes in kinematic patterns through differential gaze patterns. It is specifically relevant during the movement phase that is associated with the greatest amount of grip insecurity, the transport phase, which requires constant monitoring of grip security and clearing the barrier. While there were no significant

differences between groups within a single block in all kinematic parameters, what should be noted is the rate of change in the matched group across trials in the matched group. This may suggest that the motor learning seen in prior matched observation studies with prostheses¹⁵ may arise initially through changes in gaze. The dependence on gaze, neural activity, and kinematics during action observation has been supported by numerous studies. Increases in motor evoked potentials (MEPs) were evident during action observation and strengthened based on the location of gaze^{18,26,38} with congruent observation facilitating greater kinematic similarity in execution and observation²⁷. Gaze pattern during observation also demonstrate similar gaze dynamics (i.e., fixation duration) and spatial location (i.e., contact points) compared to execution^{20–21}. Furthermore, the proactive nature of gaze is lost when the observer's hands are restricted, which further supports the link between gaze and motor programs along with its ability to modulate motor resonance^{18,28,29}.

It is additionally notable that a significant trend was seen for gaze patterns at the shoulder AOI such that the shoulders were viewed more in the matched than the mismatched group. While this effect did not depend on the phase of the action, it did significantly increase over block duration. This may suggest a visual strategy related to the actuation of the prosthesis, which is opened by shoulder flexion and bicipital abduction. It is perhaps consistent with the use of focused vision on parts of seen action when joint control is most vital²⁴. More needs to be understood about the role of gaze on body segments during action, specifically actions that require atypical patterns of motor control such as with prostheses.

The link between oculomotor patterns and neural activity lie heavily on the rich structural and functional interconnections between areas involved in oculomotor control and motor/premotor areas. The anterior intraparietal (AIP) sulcus, an area recruited during the extraction of grasp affordances contains reciprocal connections to and from the lateral intraparietal (LIP)³⁴. The LIP is not only responsible for the coordination of saccades and the visual response but also has been implicated in attention and intention. Premotor areas, such as the frontal eye fields (FEF), also receive projections from LIP neurons and facilitate in visuomotor behavior during prehension^{33, 35}. In addition to the structural relationships between areas involved in gaze and grasp, neuroimaging and neural recording studies solidify the interdependencies between gaze and the activation of neural areas. Premotor areas have been shown to be modulated by the direction of gaze and whether or not gaze is fixated on end-points of action^{30–31}. For example, the robust brain activation in premotor areas (i.e., F5c), an area also associated with mirror neurons, was highly dependent on the location of gaze relative to the action³¹. Furthermore, neuromodulatory techniques, such as TMS to primary motor cortex, cause a delay in predictive gaze patterns and further supports the neurophysiological link between gaze and a specific motor program during observation²⁹.

While many of these studies measure the dependence of neural activation and behavior to gaze, very few studies harness gaze to improve kinematic or neural outcomes nor do they examine its impact on motor learning. It could be possible to maximize the amount of motor resonance in the observer by capitalizing on gaze training to promote task specific gaze behaviors but also facilitate visuomotor learning¹⁸. With the number of studies that show the dependency of neural activation and behavior on gaze, gaze training may be a potential

avenue to promote “retraining” or “re-learning”¹⁸. A study conducted by James & colleagues (2013) revealed accelerated improvement in motor performance when subjects’ motor control was constrained based on gaze behavior (i.e., gaze-contingent motor channeling or GCMC). Neurally, GCMC subjects exhibited greater attenuation of prefrontal activation paired with activation of the posterior parietal cortex, which is an indicator of task internalization and expertise development³². Explicit implementation of specific gaze patterns, which can vary based on the task demands, may have the power to facilitate proper neural activation patterns and promote the development of effective motor control strategies.

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Implications

This study suggests that the kinematic improvements in matched limb training may arise through shifting gaze strategies during the observation component of training. However, it is yet to be determined if matched observation accelerates or facilitates development of explicit gaze strategies. The relative contribution of explicit or implicit strategies is of interest for future research. The current study suggests a value of matched limb training to encourage implicit visual strategies to support motor outcomes with upper limb prosthesis. Future work to examine the modulation of participant's spatiotemporal location of gaze during the task may shed light on the mechanisms of motor learning for prosthetic users.

Highlights

- We sought to understand the role that gaze behavior plays on action observation
- Persons trained by observing a prosthesis user (matched) or sound limb (mismatched)
- Matched training shows gaze focused on task-specific control of user and prosthesis
- Gaze in matched observation may facilitate kinematic performance with prostheses

Figure 1.

Task methodology. Subjects performed three blocks with each block containing an observation period prior to execution of that same task (a). Subjects were placed into two groups: mismatched observation or matched observation (b). The dotted lines show the path of disc transport during observation (b). Areas of interests (AOIs) were created to encompass shoulders (1), lower trajectory (2), and upper trajectory (3) (c). The task included a reach and grasp phase (1), a transport phase 2), and a return to home phase (3) (d).

Figure 2.

The mean probability of gaze ($\pm$ S.E.) to fall within an area of interest (AOI) for all subjects. Horizontal lines below the bars represent significant differences (*) or trends (-) between groups. Brackets across AOIs represent significant differences (*) or trends (-) between the matched (black brackets) and mismatched (gray brackets) groups.

Figure 3.

The mean probability of gaze ($\pm$ S.E.) to fall within the lower trajectory (a), upper trajectory (b), and shoulder (c) across movement phases: reach & grasp, transport, and home.

Significant differences (*) and trends (–) across phases are denoted with black and gray brackets above each line for the matched and mismatched conditions respectively. Gray shaded regions represent significant differences between groups.

Figure 4.

The mean probability of gaze ($\pm$ S.E.) to fall within the lower trajectory (a), upper trajectory (b), and shoulder (c) across blocks. Significant differences (*) and trends (–) across phases are denoted with black and gray brackets above each line for the matched and mismatched conditions respectively. Gray shaded regions and gray dotted lines represent significant differences and a trend towards significance between groups respectively.

Figure 5.

Mean kinematic measures (± S.E.) across all subjects in the mismatched and matched group across all three blocks. Black and gray brackets represent significant difference (*) and trends (-) across trials in the matched and mismatched condition respectively.