# Quantifying Prosthetic and Intact Limb Use in Upper Limb Amputees via Egocentric Video: An Unsupervised, At-Home Study

Adam Spiers, *Member, IEEE*, Jillian Cochran, Linda Resnik and Aaron Dollar, *Senior Member, IEEE*

***Abstract*— Analysis of the manipulation strategies employed by upper-limb prosthetic device users can provide valuable insights into the shortcomings of current prosthetic technology or therapeutic interventions. Typically, this problem has been approached with survey or lab-based studies, whose prehensile-grasp-focused results do not necessarily give accurate representations of daily activity. In this work, we capture prosthesis-user behavior in the unstructured and familiar environments of the participants own homes. Compact head-mounted video cameras recorded ego-centric views of the hands during self-selected household chores. Over 60 hours of video was recorded from 8 persons with unilateral amputation or limb difference (6 transradial, 1 transhumeral, 1 shoulder). Of this, almost 16 hours of video data was analyzed by human experts using the 22-category 'TULIP' custom manipulation taxonomy, producing the type and duration of over 27,000 prehensile and non-prehensile manipulation tags on both upper limbs, permitting a level of objective analysis not previously possible with this population. Our analysis included unique observations on non-prehensile manipulations occurrence, determining that 79% of transradial body-powered device manipulations were non-prehensile, compared to 60% for transradial myoelectric devices. Conversely, only 16-19% of intact limb activity was non-prehensile. Additionally, multi-grasp terminal devices did not lead to increased activity compared to 1DOF devices.**

***Index Terms*— End Effector, Human Motion Analysis, Human Manipulation, Prosthetics, Prosthetic Hands, Upper Limb Prosthetics**

## I. Introduction

Understanding and quantifying upper-limb prosthesis usage has traditionally been limited to either written surveys or standardized manipulation tests administered in a clinic or lab. The former tends to be mostly qualitative and rarely provide insight into how devices are being specifically utilized, while also being subject to the inaccuracies of self-reporting on past events. The latter are generally very specific and scripted tasks involving prehensile (grasping) actions, and often ignoring the role of non-prehensile manipulation (such as pushing or clamping), which we consider as a valuable and notable manipulation strategy. Additionally, these tests often do not allow unilateral amputees to use their intact hand, even though this may be their natural preference.

We believe that a more complete view of current upper-limb prosthesis use in ecological contexts will be highly beneficial to general understanding of amputee behavior with currently available terminal devices while also leading to the development of more effective prosthetic devices and therapeutic interventions in the future. The functional benefit of prosthetic devices is of interest to the prosthetist who assigns devices to a patient, the engineer who designs future technical solutions and the person or entity who needs to justify payment for these often expensive systems [1].

In this paper, we present a study of this nature, in which head-mounted video cameras (Fig. 1) were used to record egocentric views of the hand and terminal device of persons with unilateral upper-limb-difference (either congenital or via amputation) as they completed several hours of standard household tasks in their own homes, without an experimenter present. The most manipulation-intensive segments of the resulting video were then analyzed by manually tagging the video files. The output of this process is a log of the type and duration of over 27,000 manipulation tags of varying durations (i.e. not single frames), across eight participants with different terminal devices/levels of amputation. To our knowledge, this is currently the most extensive data-set of unilateral upper-limb prosthesis use.

We analyze this dataset with regard to manipulation tag frequency and duration, providing breakdowns for individual participants and groups. Rather than pursuing a single hypothesis in our analysis, we report and comment on numerous statistical comparisons, with the goal of creating a broad and readily available reference to the many available insights in such work. The 23 findings that we considered most prominent are summarized at the end of the manuscript.

We begin the paper with an in-depth discussion of related work (Section II), followed by a description of our methodology, including video tagging based on our Taxonomy of Upper Limb Intact and Prosthesis use – TULIP, which was first introduced in [2] (Section III). Such tagging produces

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A. J. Spiers is with the Department of Electrical and Electronic Engineering, Imperial College London, London, SW7 2BU, UK (e-mail: a.spiers@imperial.ac.uk).

J. Cochran and A. M. Dollar are with the Department of Mechanical Engineering, Yale University, New Haven, CT 06511, USA. (phone: 203- 432-4380, e-mail: jillian.cochran@yale.edu, aaron.dollar@yale.edu).

L. Resnik is with the Providence VA Medical Center and Brown University, Providence, RI (e-mail: linda_resnik@brown.edu).

numeric records of each manipulation action, which we then use for in-depth statistical comparisons. Section IV describes the data analysis methodology, followed by the results (Section V), and a discussion of the major take-away messages from the analyses (Section VI).

This study was approved by the Yale University Human Subjects Committee, HSC #1408014459 and the U.S. Army Human Research Protection Office (HRPO) EMDS: #5893, Proposal: #13116005.

## II. Related Work

### A. Human Manipulation Studies

#### 1) Prosthesis-User Studies

Researchers have attempted to understand the usage trends of upper-limb prostheses for many decades, in the hopes that insights from such studies will help designers and clinicians to address the challenging technical task of developing effective substitute limbs. This problem, of engineering prosthetic systems, covers topics ranging from the biomechanics of suspension systems to signal processing of myoelectric interfaces.

Traditionally, there have been two major approaches to understanding manipulation strategies in persons with limb difference: asking participants about their daily behavior via self-report questionnaires (Section 'a' below), and measuring participant performance in an instrumented laboratory (Section 'b')

##### a) Self-report Questionnaires

Questionnaires and surveys are an effective way to glean data from large numbers of participants as is clear from the widespread use of this medium in fields such as marketing. A number of questionnaires for upper limb amputees have been published for use as clinical tools, such as the Upper Extremity Functional Scale (UEFS) from the Orthotics and Prosthetics User Survey (OPUS) [3] and the Trinity Amputation and Prosthesis Experience Scales (TAPES) [4]. Additional questionnaires are targeted at lower limb prostheses, such as the Prosthetics Evaluation Questionnaire (PEQ) [5] and the Prosthetic Profile of the Amputee Questionnaire (PPA) [6].

Even prior to the widespread use of the internet (which simplifies survey distribution and user targeting), studies such as [7], [8] collected survey data from dozens to hundreds of amputees, with minimal technical equipment or time demands on the participants, to estimate, for example, the acceptance/rejection rate of prosthetic devices or the numbers of hours the device was used.

More recently, questionnaire studies have been used to gauge a number of factors. The authors of [9]–[11] investigated prosthetic preference, satisfaction and abandonment for various demographics of war veteran. Device rejection was specifically addressed in [12], with over 200 participants, and in [11] with over 800 participants. In [13], an online survey of 54 amputees addressed usage time and reasons for dissatisfaction.

Despite the popularity of this medium, there is evidence that self-reporting questionnaire data can be subject to error [14].

In [8], the authors requested that their participants report the number of hours that they wore their prosthesis during weekends and weekdays. Even assuming that participants were able to recall this duration accurately (which is not guaranteed) we have no further data on how often the devices were actually used for manipulation. Indeed, it could be that certain devices are worn more often because they are lighter and more comfortable, rather than actually affording the user any additional capability. In an interesting study [15], the authors reported how the perception of prosthesis use varied between amputee children and their parents, due to the two groups rating prostheses *'in the context of different functional environments'*. One may also wonder how much context changes between adults of different demographics and lifestyles.

Figure 1: (Top) A head-mounted camera recorded the arms and hands of upper limb amputees as they performed self-selected tasks in their own homes. (Bottom) An example ego-centric frame from the camera.

Chadwell et al. state that, at best, due to errors of self-reporting, such surveys can provide only averaged data on general topics such as device wear times and usage [16]. Acquiring reliable objective data on detailed factors such as relative limb use or grasp type preference is clearly not feasible with this approach.

##### b) Laboratory Based Assessment

An alternative approach to studying the manipulation strategies and capabilities of amputee participants are laboratory or clinical studies. Functional assessment measures aim to numerically score participants on their ability to complete discrete manipulation tasks [17]. One example of this is the SHAP test, which measures the time it takes for participants to pick up and move / use a variety of objects, the varying morphology of which, in theory, require different grasps and arm motions [18]. Other standard outcome measures include the Box and Blocks test [19], The Jebsen-Taylor Test of Hand Function [20] and the Activities Measure for Upper Limb Amputees - AMULA [21].

There has been concern however, that performance of the functional tasks within a laboratory setting do not necessarily translate well to participant behavior outside of the laboratory [16]. For example, in many studies participants are forced to complete tasks using their prosthetic limb, while in daily life those participants may typically perform that same task with their intact limb. One example may be carrying a cup, which a participant could perform with little caution if the cup is empty in a sparse laboratory, compared to if it was filled with hot coffee at a family breakfast table.

Extensive work has also been conducted to quantify the usage of human hands and arms in healthy individuals. Such work often takes place in highly structured motion capture laboratories with simulated activities of daily living, or more abstract tasks (e.g. [22], [23]), or under the supervision of experimenters, which shares some of the limitations of the functional assessment measures mentioned in the last section.

For example, in key work by Santello et al., the joint of angles of participants hands were recorded while the participants grasped real objects or made the motion of grasping imagined or virtual objects [24]. Other studies have used setups that involved picking up objects from fixed locations, while logging motion and contact data [25], [26]. A number of the functional measures discussed earlier have been adapted for use as benchmark tasks in motion capture environments, when accurate joint motion tracking of the participant is an objective. [23], [27]–[29].

### 2) *In-The-Wild/Ecological Manipulation Studies*

As with the functional assessment studies, there have been concerns that laboratory based approaches do not translate well to daily human motion and manipulation in an ecological context that are natural and unstructured. This has led to the development of several wearable technologies to monitor hand motion, though often only limited DOF are recorded [30], or the glove-like devices that cover the sensing surfaces of the hand, but impair tactile sensitivity and influencing natural object interactions [31].

To address this, a major study in this area [32]–[34] aimed to characterize human-motion 'in-the-wild' by using small and portable head-mounted video cameras to capture a wearers hands. In that study, two machinists and two professional housecleaners recorded video data during working hours. Analysis was completed only on the dominant hand, with the resulting proportions of usage largely related to that person's occupation (e.g., a spray bottle was gripped often by one of the cleaners).

In the recent 'Epic Kitchens' dataset [35], a head mounted camera was used to collect egocentric video data from 32 healthy participants as they prepared meals in their own kitchens, the video data was then narrated by the participants to assist with extracting user intention.. The main focus of this work was to provide datasets for automatic hand, object and action detection algorithms [36]. Such efforts have been applied to diagnostic activity monitoring for individuals with Spinal Cord Injury (SCI) [37], [38]. Though this is a promising technology, currently only general hand use can be detected, but not the type of grasp being used.

These methods and arguments may be applied to improving the realism and objectivity of amputee manipulation data, via self-selected tasks in natural and unstructured environments.

In 2018 Chadwell et al. presented their work on continuous activity monitoring of the upper limbs of 4 adult participants (2 unilateral amputees and 2 non-amputees) over the course of one week using wrist worn inertial activity monitors (IMUs) with on-board data logging [16]. This research has since been extended to forty participants [39]. Though these devices do not permit the reconstruction of user arm pose (as in IMU based motion capture suits such as *Xsens www.xsens.com*) and cannot identify grip types, the data provided valuable and objective insight into relative limb use by amputees in daily life.

## B. *Manipulation Taxonomies*

In order to numerically quantify observations of human manipulation, taxonomies are often employed as a method of formalizing/simplifying the space of possible grasps [40]. Such taxonomies date back to 1919, when Schelisinger [41] created such a system to provide insight on the design of artificial upper limbs. A number of other taxonomies are reviewed by Iberall in [42], who was again motived by generating functional goals for the designers of prosthetics and robotic hands.

A number of manipulation taxonomies were integrated in order to generate the 'GRASP taxonomy of healthy hand', which includes 33 different grasp types [43]. A notable aspect of the GRASP taxonomy is the grouping of all grasps into three major categories of power, precision and lateral/intermediate grasps. In other taxonomies, such as [44], lateral grasps are subsumed into power or precision categories.

Two other taxonomies, the 'modified taxonomy of manufacturing grasps' [44] and 'Human Manipulation Taxonomy' [45] are hierarchically arranged in tree structures embedded within axes of 'gross/detailed tasks' and 'power/dexterity'. In comparison, the GRASP taxonomy resembles a table, where arrangement is dependent on object contact with different parts of the hand (i.e., palm, pad, side) and abduction of the thumb [43].

Many manipulation classification efforts, including the GRASP taxonomy, focus only on prehensile grasping, rather than non-prehensile manipulations that also take place with intact human hands. Our experience working with prosthesis users, revealed that non-prehensile manipulations were highly prevalent in terminal device usage [2].

Though prosthetic devices are often designed to achieve a particular set of grasp types, it is clear that their wearers often find innovative ways to use the mechanical features of their devices to achieve additional manipulation actions, such as the pushing and clamping of objects. Such non-prehensile manipulations were captured in the grasp and force based taxonomies of split-hook terminal device usage use by Belter et al. in [46], which were developed based on head-mounted camera video recordings of a single amputee participant. Though Belter's taxonomies provide insight into the many manipulation strategies of one popular prosthetic gripper, the classifications are dependent on specific mechanical features of the split hook (e.g. the cable anchor, which can be treated as an additional digit, and a proximal clamp feature located between the fingers, which can be used to hold pens). As such, these taxonomies do not generalize well to other terminal devices, such as an Otto Bock Griefer [47] or multi-grasp hands (such as the iLimb range of terminal devices).

Thus, for this work we developed our own manipulation taxonomy that would capture the actions of different levels of unilateral amputees, as they made use of a variety of terminal devices [2].

## III. Methods

### A. Data Collection

Similar to the studies of [32]–[35], we collected ego-centric video data of participant's interactions with the world via an unobtrusive head-mounted video camera (Fig. 1). In our case we used 'GoPro Hero 3+ Silver' and 'GoPro Hero 4+ Silver' cameras. These cameras were appealing for their small size, high-resolution wide angle video capture, secure head-straps and robustness, as they are designed for use during a variety of sports, such as snowboarding. An external USB power bank battery pack was connected to the GoPro Cameras during the experiments in order to extend the battery life from approximately 45 minutes to between 3-4 hours (Fig. 2).

The camera recording was set at 2.7k resolution and 30fps. This provided a good tradeoff between image fidelity, reduced motion blur and file size. At this resolution it was possible for a participant to record up to 2 hours and 30 minutes of video on a single 64Gb micro SD memory card. As a safeguard against a card becoming full in the middle of interesting manipulations, the memory card was changed every 2 hours, either by the experimenter or the participant, depending on whether a participant was local or remote.

Local participants were located within 3 hour driving distance of Yale University. These participants were visited at their homes in person by the experimenter (one of the authors of this paper) who obtained informed consent of study participation and were given a demonstration on how to use the camera and battery pack. The experimenter left the participant's home during data collection, but remained within a 5 mile vicinity of the participant's home in case of technical problems. Typically, visits to local participants were made over 2 days, with up to 4 hours of data collected during each day.


Figure 2: The contents of the equipment 'kit' sent to remote participants via postal courier. The contents are as follows: 1. Head strap and GoPro camera with modified case to allow USB connection 2. Long mini-USB cable for connecting GoPro to Power Bank 3. Power Bank 4. Short micro-USB Cable for re-charging Power Bank 5. USB charger 6. Micro SD cards and organizer / holder (the bottom row is for empty cards which are moved to the top row when they contain data).

Remote participants were located outside of the 3 hour driving radius, but within the USA. These participants completed informed consent electronically, following a conversation with the experimenter, who had emailed all IRB paperwork at least one day beforehand. After informed consent had been obtained, the study equipment was sent to participants via a courier service as a shoe-box sized parcel. Additional documents were included in the parcel (and also sent electronically) which provided detailed instructions on the study equipment, with a focus on completing certain tasks using only one hand (i.e. putting on the head-strap and removing the SD card from the camera).

A pre-paid return label was included in the parcel, so that participants could return the equipment when they had completed the study.

Table 1: Participant information and the length of video recorded / analyzed for each terminal device.

| Participant | Sex | Age | Amputation Level | Terminal Device | Actuation Type | Glove | Total Video Recorded | Video Analyzed |
|---|---|---|---|---|---|---|---|---|
| P1 | M | 49 | TR | System Hand | Body Powered | ✓ | 01:14:00 | 01:14:16 |
| P2A | M | 69 | SD | iLimb Ultra | Myoelectric | ✓ | 03:51:00 | 01:05:24 |
| P2B | | | | EKD Split Hook | Myoelectric | × | 03:48:00 | 01:21:26 |
| P3 | F | 60 | TR | TRS Prehensor | Body Powered | × | 06:17:00 | 01:09:48 |
| P4A | M | 40 | TR | Hosmer Hook | Body Powered | × | 03:54:00 | 01:14:49 |
| P4B | | | | Greifer | Myoelectric | × | 03:55:00 | 01:10:54 |
| P5A | M | 52 | TR | iLimb Quantum | Myoelectric | ✓ | 10:14:00 | 01:21:26 |
| P5B | | | | iLimb Ultra | Myoelectric | ✓ | 01:55:00 | 00:48:02 |
| P5C | | | | System Hand | Body Powered | ✓ | 04:04:00 | 01:10:54 |
| P6 | F | 22 | TR | iLimb Quantum | Myoelectric | ✓ | 05:17:00 | 01:11:09 |
| P7 | F | 44 | TR + PH | Sensor Hand | Myoelectric | ✓ | 08:24:00 | 01:09:48 |
| P8A | M | 60 | TH | Axon Hook | Myoelectric | × | 04:56:00 | 01:26:06 |
| P8B | | | | Michelangelo Hand | Myoelectric | ✓ | 03:35:00 | 01:11:55 |
| | 5M 3F | 49.5 | 6 TR | 7 Anthropomorphic | 4 BP 9 Myo | 8 Gloves | 61:24:00 | 15:35:57 |

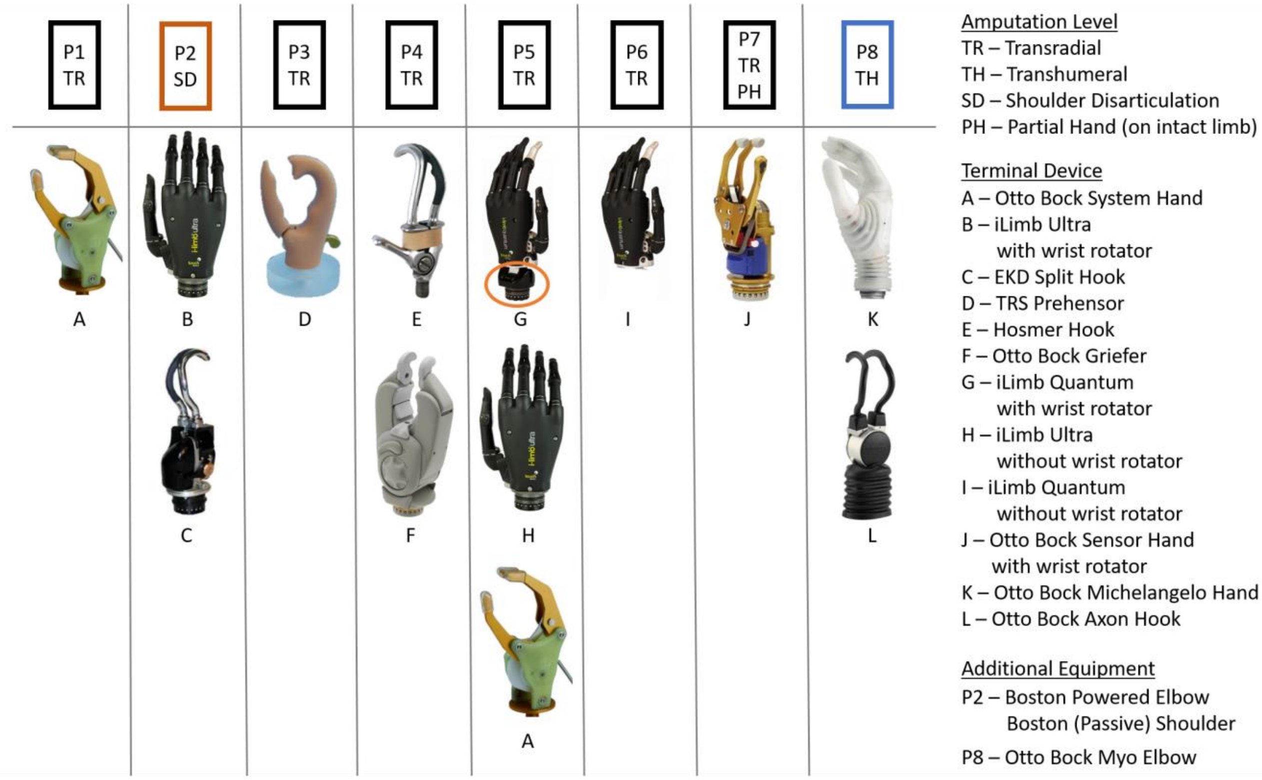


Figure 3: Terminal devices used by the participants during the study. All participants used their prosthetics devices every day, and had done so with their current prosthesis/prostheses for at least 6 months. P2 and P8 are highlight as non-transradial amputees.

In both local and remote cases, participants were shown how to start and stop recording without removing the camera from their head, so that privacy could be granted on-demand. The cameras settings were configured so that red lights would flash on the front and top of the camera when recording was in progress. Additionally, audible beeps would sound when recording began and stopped. Participants were told that they could check if the camera was recording by looking in a mirror for the flashing red lights.

Participant instructions are provided in Appendix B.

### *B. Participants*

Study applicants were recruited via online advertisements on Craigslist, Facebook (targeted ads) and via prosthetists. Participants were selected from applicants based on diversity of age, sex, level of amputation and prosthetic system. All levels of unilateral limb-difference were admissible for the study. Persons with bi-lateral limb difference were not eligible to participant. Furthermore, all upper limb prosthetic devices were eligible for study inclusion. Participants were required to have no mobility or vision issues, as this could influence manipulation behavior and limit comparisons to other participants. Following selection, applicants took part in an initial phone screening, which included discussion of their prosthesis use. All participants were required to have had their current prosthesis for at least 6 months and to have used that prosthesis every day during that time.

The eight applicants who took part in the study are listed in Table 1. The terminal devices used by the participants are shown in Fig. 3. Several participants used more than one terminal device in their daily life. For example, participants P2 and P4 stated that they used their hook devices for yard work and tasks where the terminal device might become wet. Participants with multiple devices were requested to record video with each of their devices.

Of the eight participants, six had transradial (TR) amputation, one had transhumeral (TH) amputation and one had a shoulder disarticulation (SD). Efforts were made to recruit additional participants with TH or SD amputation amputees to diversify the sample, but this unfortunately was not achieved.

Participants were requested to record eight hours of video, but, due to the fact that no experimenter was present during recording, the amount of time actually recorded varied between individuals. For example, Participant 6 was a remote participant and returned the equipment kit with only 2 hours of video recorded. Many remote participants kept the equipment kits for several weeks in order to generate their videos.

Participant 1 had the camera for 2 hours, but frequently turned it off during recording. They terminated the first session early due to a personal commitment and did not respond to subsequent requests for further study sessions.

### *C. Video Selection*

It was necessary to select a limited number of videos to analyze for each participant, due to the length of time involved in video tagging (an estimated 30 minutes/1 minute of video). The ~15.5 hours of video presented in this manuscript required over 450 hours of human analysis.

The GoPro cameras automatically segmented the recorded videos into files of length 11min 38sec (Hero 3 model) or 11min 48sec (Hero 4 model), with exceptions in length for the last segment, which is shorter in duration. We believe that this to be

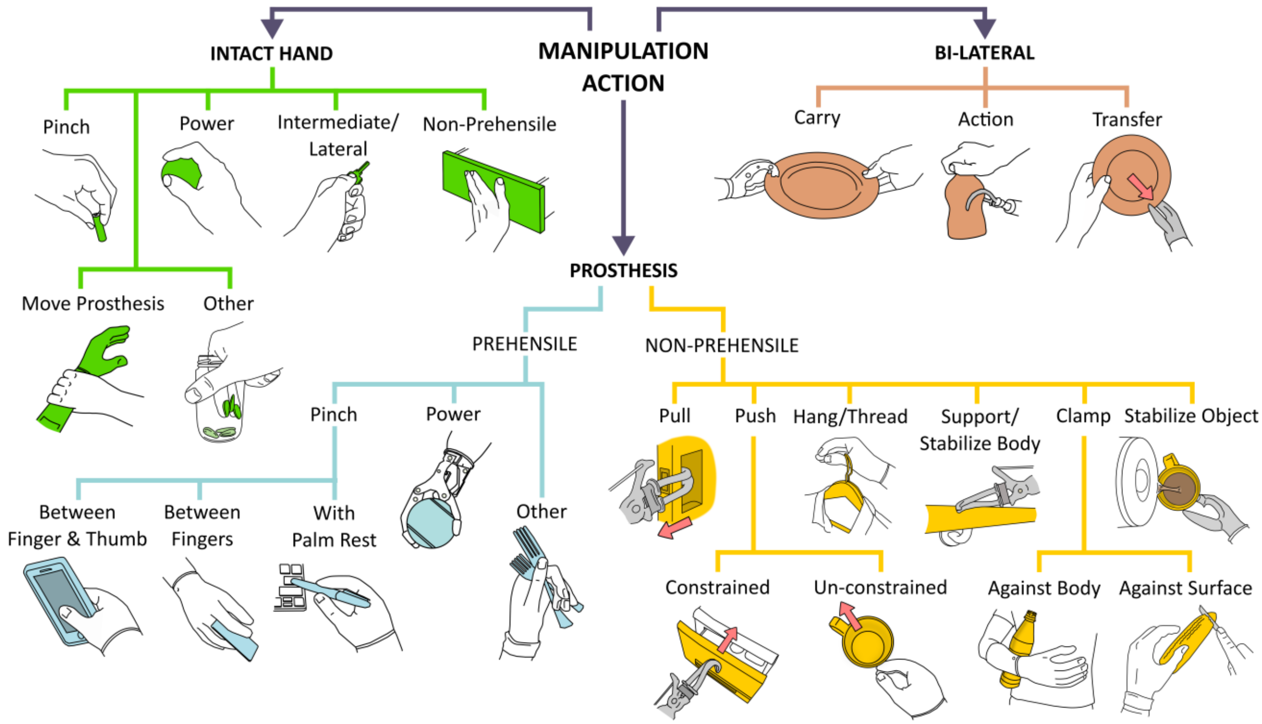


Figure 4: The Taxonomy of Upper Limb Intact and Prosthetic limb use (TULIP). Each of the manipulation tags is described in the appendix.

a software failsafe against longer recording sessions being lost by camera damage during extreme sports activities (a major use case of these devices). We used this automatic segmentation of the video files as a way of breaking up the raw data. Additional segmentation of the video into separate files also occurred whenever the participants started or stopped the recording.

Members of the study team watched all video files (sometimes at increased playback speed), and selected files for in-depth analysis. This was achieved by first noting the contents of each video (e.g. chopping tomatoes, sweeping, loading a washing machine). Videos for each subject were then prioritized for analysis based on their contents with the goal of analyzing roughly equivalent video time for all participants (as shown in Table 1). The videos that included events most related to activities of daily living (ADLs) were selected as the first priority because they are important for independence. Such tasks included preparing food and drink, house-hold cleaning and doing laundry. The second priority were videos that included intricate manipulation tasks that were not necessarily ADL related. Examples include dismantling and packing a quadrotor drone, installing a towel rail in a bathroom, and trimming a bush using hand shears. The third priority were non-sedentary videos, i.e. those that did not consist of a participant just watching television, browsing on their smartphone or reading. These videos included typing on a computer, practicing golf putting (indoors) and petting a dog.

Files that consisted of mostly sedentary activities (e.g. watching television or browsing the internet on a smartphone) were generally ignored. Though we asked participants to keep sedentary activities to a minimum, this did not always occur as, with no experimenter present, some participants continued their daily routines (such as watching the news on television at a particular time).

There was sufficient content in these three categories that no purely sedentary videos were included in the analysis. Note that, if a video contained 30 seconds of washing dishes and 11 minutes of watching television then it was not classed in the highest priority group.

We attempted to keep the length of analyzed videos relatively consistent between participants, as shown in Table 1.

### *D. Unilateral Prosthesis-Use Manipulation Taxonomy*

In order to numerically analyze and compare the manipulation actions of the various participants, a unifying method of categorizing manipulation tasks was required. As already discussed in Section II.A, a taxonomy was required to encapsulate the manipulation strategies of participants with a variety of amputation levels, who were using a variety of terminal devices. These devices vary significantly in both form and function, as illustrated in Fig. 3. For example, P1 and P6 both have anthropomorphic devices, but these vary from 1-DOF body-powered actuation (an Otto Bock SensorHand Speed with cosmetic glove) to a 5DOF multi-grasp myoelectric control (an iLimb Quantum).

While observing the video files of the first three participants, notes were made on the manipulation tactics of the unimpaired and impaired limb for a variety of tasks. These notes led to 22 manipulation ‘tags’ that were grouped into 4 categories to create the *Taxonomy of Upper Limb Intact and Prosthetic Limb Use (TULIP)*, shown in Fig. 4. This taxonomy was first presented in [2] under the name ‘Unilateral Prosthesis User Manipulation Taxonomy’.

The categories of TULIP are as follows:

1. Intact Hand
2. Prosthetic Device – Prehensile


Figure 5: A screenshot from the custom video player software (top). Logged tags are shown in the playback progress bar. A hardware midi interface (below) is used to precisely control video playback and tagging.

3. Prosthetic Device – Non-Prehensile
4. Bi-lateral

A description of each manipulation tag is provided in the Appendix A of this paper.

### E. *Custom Video Tagging Software*

To facilitate the manual identification of manipulation tags in the videos, custom video tagging software was created in C++ using the *openFrameworks* (OF) library. One novel aspect of this software was the integration of a physical midi-controller (a Korg NanoKontrol 2 – www.korg.com) as a tangible interface. Normally intended for eight-track audio mixing with compatible software, the NanoKontrol device offers dedicated transport controls (play, pause, stop, fast-forward and rewind buttons) which were augmented by assigning additional buttons to frame-by-frame video stepping, or jumping between existing tags. The NanoKontrol 2 features 24 additional push-buttons (in eight groups of three) that were assigned to the various manipulation tags. These were labelled on the midi device using a label-maker. Additional knobs and sliders were used to adjust parameters such as video playback speed. Together, these tangible controls allowed the video tagger direct, parallel and precise access to multiple controls when tagging videos. We believe this considerably improved the speed and robustness of video tagging compared to manual methods (in [32], which involved taggers writing tag details manually in a spreadsheet).

The video tagging software interface is shown in Fig. 5. This consisted of a large video display window, a text region (which described information such as video frame number and time step), and a visual timeline in the form of a progress bar. The user enters a manipulation tag by pressing the corresponding button at the start of the tag, and the 'tag end' button at the end of the tag. Recorded tags are visually indicated on the progress bar with different colors and vertical positions.

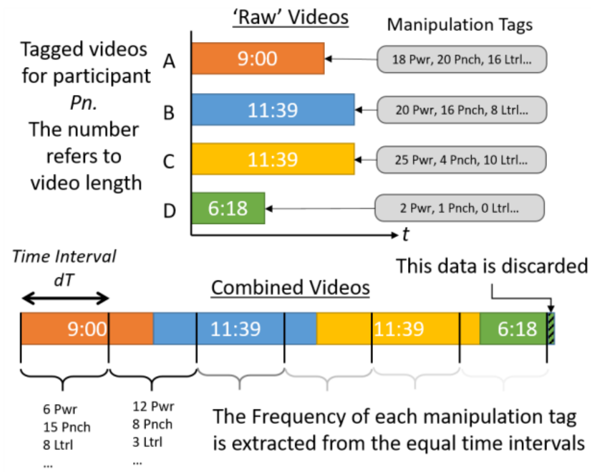


Figure 6: The method for dividing and re-sampling the analyzed data from raw videos into equal time intervals for statistical analysis.

As the user tags the video, a .csv log file is created of the tag type and start / end frame numbers. These log files may be loaded back into the video tagging software for further editing or loaded into software such as MATLAB for analysis.

## IV. Data Analysis

### A. *Statistical tools*

In order to effectively analyze the frequency and duration of manipulation actions performed by the participants, a number of decisions were made regarding data structure and statistical tools. These will be described in this section.

#### 1) *Time Interval Determination*

For each observed manipulation action, the video tagging process recorded the manipulation tag type (from those listed in the taxonomy – Fig. 4) and start/end times. For statistical analysis of this data, we considered the frequency of the individual tags for each study participant over the full length of their recorded videos.

Limiting this frequency measure to a single average value however would not allow for consideration of such factors as variance with respect to time. Variance can capture how some manipulation actions may occur specifically during certain tasks (e.g. folding clothes while doing laundry), while others actions are more general (e.g. carrying small objects in a pinch grasp).

As such, the recorded tags were considered over discrete intervals of the combined video files. More specifically, each participant's raw data consisted of multiple video files of different lengths (as discussed in Section III.C), which have been tagged. These videos files (and associated tags) were combined together to create a continuous data file and then re-sampled into equal time intervals. This method is illustrated in Fig. 6. Data that did not make up a full interval, at the end of the combined videos, was discarded. This meant that less than one interval of data was discarded per participant.

For each time interval we recorded the frequency (tags/min) of each manipulation action. The length of the time interval, *dT*, therefore affected the number of frequency measures that were available for statistical analysis. For example, if 60 minutes of video data is segmented with $dT$ = 10 minutes, we would have 6 frequency measures per tag. Conversely if $dT$ is 20 minutes then we would have only 3 measures. In the interest of having a large number of frequency measures for statistical analysis, a smaller time interval was the best choice.

Appendix C provides boxplots illustrating how the frequency of manipulation tags vary for different time interval sizes. The data in Appendix C is constructed from grouped manipulation tags for all participants. As the time intervals grow larger, the number of outliers decreases. Relatedly, the scatter plot Appendix C (bottom) shows how the standard deviation of the frequency of grouped tags decreases with increasing interval size. Note that the standard deviations shown are averaged over all participants. Therefore, in contrast to our earlier statement, larger time intervals are more favorable for statistical testing in that it is easier to differentiate between two groups of participants when both groups have smaller standard deviations.

After considering these results, we selected five-minute intervals to balance the number of frequency measures and spread of the data. Interval sizes larger than five minutes only had marginal reductions in the standard deviation (Fig. 7 bottom). Furthermore, P5B provided 48 minutes of video data (Table 1); segmenting that video data into five-minute segments results in 9 frequency measurements. Using a larger interval size would result in fewer than 9 frequency measures for P5B, which is unfavorable for statistical testing.

#### 2) *Test Statistics*

To detect significant differences in the frequency and duration of various grasp and manipulation tags, we used a combination of parametric and non-parametric hypothesis tests, which we performed using MATLAB 2017a with the Statistics and Machine Learning toolbox.

Most parametric tests assume that the residuals of the data being tested have a normal distribution. The residuals are calculated by subtracting each of the observed frequency measures from the estimate of the true frequency value, (the mean of the frequency measures). When the residuals have a normal distribution, a histogram plot of the residuals will appear bell-shaped and centered around zero. The resulting significance of the test may be inaccurate if this assumption of normality is not met. A *Kolmogorov-Smirnov test* was used *(via the MATLAB command kstest)* to determine if the two sets of tag frequency measures or duration measures being compared had residuals that were not normal. If so, a non-parametric version of the t-test was used, otherwise, a parametric t-test was employed.

When comparing frequency or duration of one manipulation tag versus another for each participant, we use a paired t-test. In the cases where residuals are not normal, the *Wilcoxon Signed Rank test* (the non-parametric alternative to a paired t-test) was used (via the MATLAB command *signrank*). Given that the frequencies of the two types of tags being compared were collected from the same section of video, we do not assume that the frequencies or durations of the two tag types are independent from one another.

Welch's t-test was used when comparing tag frequencies or durations from groups of similar participants against one another. In this context a sample consists of all of the tag frequency measures for a particular type of manipulation tag, from all subsections of video, from a group of like participants. Unlike Student's t-statistic, Welch's t-statistic does not pool the variance of the two samples being compared. If the residuals of the data are not normally distributed, meaning that assumption of the t test has been violated, a *Mann Whitney U-test* (the non-parametric alternative to a two sample t test) was used (via the MATLAB command *ranksum*).

Other statistical tools were explored during this analysis with similar end results, which provides greater confidence in the validity of these results. The Shaprio-Wilk test was used in place of the Kilmorogov-Smirnov test and permutation testing in place of the Wilcoxon Signed Rank and Mann Whitney U tests. Most hypotheses that had significant results under one set of tests showed the same significance under an alternate set of tests. Permutation testing was not used due to the long computation times.

## V. Results

In Section V.A we present an overview of total tag counts and frequency (tags/min) the recorded manipulation actions, both for individual participants and in groups, arranged by various characteristics. In Sections V.B-V.C we perform statistical hypothesis testing on this data in within-subjects and between-subjects cases. In Section V.D, we present an overview of the results of tag duration analysis (i.e. the length of different manipulation tags). Section V.E performs statistical hypothesis testing on the duration data.

### A. *Cumulative Tag Count Overview*

In this section we provide general observations on cumulative manipulation tag frequencies.

#### 1) *Grouped Manipulation Tags Overview*

Fig. 8 (top) provides an overview of tag frequency results (i.e. how many times each type of manipulation was used) for each participant in terms of prehensile and non-prehensile manipulations for both the intact and prosthetic limb.

In Fig. 7 (bottom), this data is shown as a proportion of all manipulations for each individual (i.e. the various manipulation types sum to 100% in each case). The bars of Fig. 7 were ordered into groups based on amputation level and device actuation (body powered vs. myoelectric). Note that the 'Proximal to Elbow' (PE) group includes participants with transhumeral amputation (P2) and shoulder disarticulation (P8). This data is also reflected in Table 2, which provides the proportional comparisons between the numbers of recorded tags for each individual.

A few trends are immediately apparent, such as the dominance of intact hand manipulations, as compared to those with the prosthesis. The prosthesis was, on average, only used for 19% of all recorded manipulations, with a range of 33% to 6% across individual participants.

Subjects with transradial amputation and body-powered devices (TR-BP) used their prosthesis the most (28% of

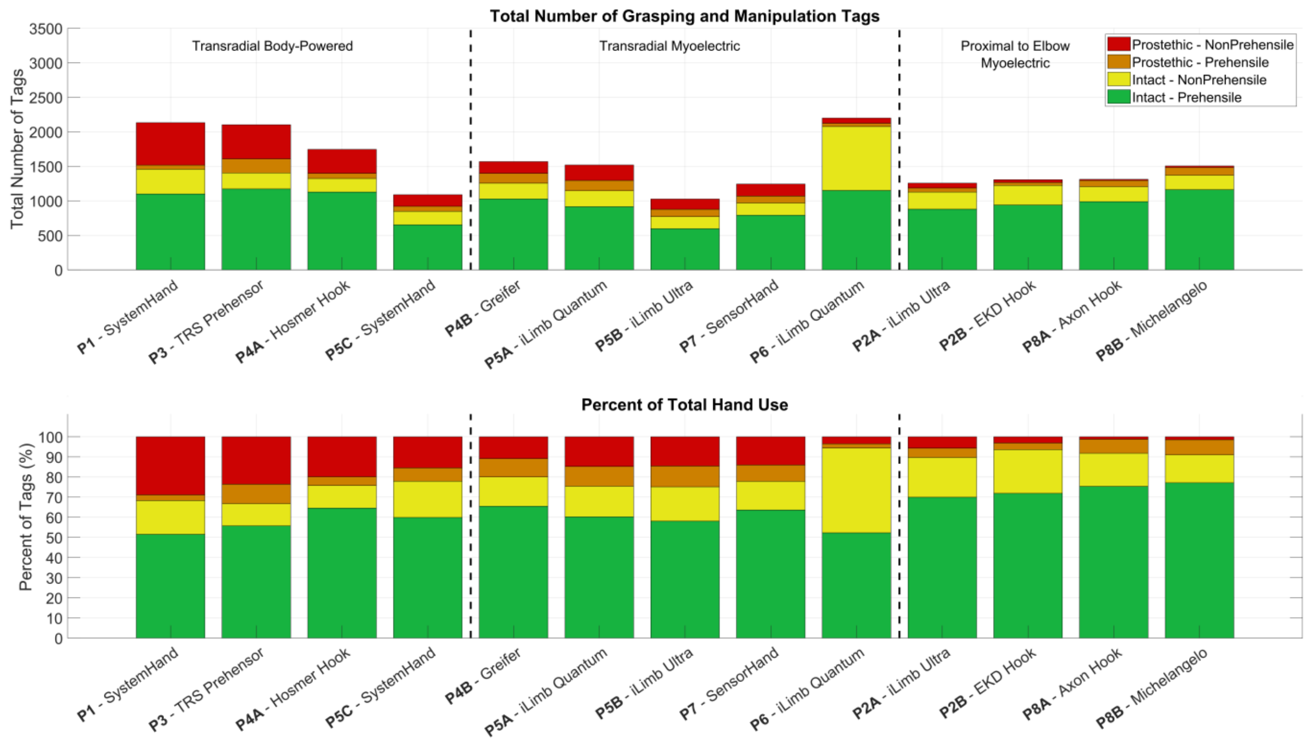


Figure 7: The top bar plot displays the total number of grasping and manipulation tags recorded for each participant. The bottom bar plot presents the proportion of hand use for each case. The bars are grouped based on amputation level and device actuation, to highlight trends.

manipulations), with 79% of those prosthesis actions consisting of non-prehensile manipulations. Conversely, transradial myoelectric device users (TR-Myo) used their prosthesis for 19% of manipulations. Though the majority of those manipulations (60%) were non-prehensile, this proportion is less than the body powered device users.

Proximal to Elbow (PE) amputees (all of which had myoelectric devices) displayed far less prosthesis use, at only 8% of all manipulation actions. For PE participants, non-prehensile manipulations made up only 34% of prosthesis use, meaning that the prosthesis was primarily used for prehensile functions. However, the affected limb was used in a greater proportion of non-prehensile manipulations than the intact limb (34% vs. 20%).

Participants at all amputation levels had very similar ratios of prehensile to non-prehensile use with their intact limb (20-25%). All participants (with the exception of P8A) demonstrated a higher proportion of non-prehensile manipulations with their prosthesis than non-prehensile manipulations with their intact limb ($p<1\times10^{-5}$). This indicates that the grasping function of a prosthesis is not utilized in the same way as the grasping function of an intact hand.

These observed differences in limb use could be attributable to a number of factors including, but not limited to, prosthesis weight, strength, speed, control complexity, and lack of haptic feedback and proprioception [48], [49]. Persons with amputation often learn to accomplish many tasks solely using the intact hand, given the reduced capabilities of their affected limb [50].

Additionally, we observed that our subjects rarely dropped items with their prosthesis, indicating that they were familiar with device limitations and did not attempt activities that they were not proficient in. In total, we observed less than 10 item drops over the entire 61 hours of recorded video.

Table 2: Cumulative tag counts (over all analyzed data for each individual), averages tag counts (by participant group and overall) and individual and group proportions of limb use and prehensile / non-prehensile manipulation per limb. Shading is used to highlight higher percentages. The group average shading is calculated independently of the individual participant shading.

| | | I - TR Body Powered | | | | II - TR Myo | | | | | III- Prox to Elbow Myo | | | | Group Averages | | | Overall Averages |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | P1 | P3 | P4A | P5C | P4B | P5A | P5B | P6 | P7 | P2A | P2B | P8A | P8B | I | II | III | |
| Total Tags | Intact Pre | 1099 | 1172 | 1127 | 652 | 1027 | 915 | 596 | 1150 | 791 | 879 | 939 | 988 | 1161 | 1012.5 | 895.8 | 991.75 | 961.2 |
| | Intact Non-Pre | 358 | 232 | 196 | 196 | 228 | 231 | 175 | 924 | 177 | 248 | 284 | 216 | 209 | 245.5 | 347 | 239.25 | 282.6 |
| | Pros-Pre | 60 | 203 | 75 | 72 | 143 | 149 | 106 | 47 | 101 | 58 | 43 | 91 | 113 | 102.5 | 109.2 | 76.25 | 97.0 |
| | Pros-NonPre | 615 | 495 | 347 | 168 | 170 | 224 | 149 | 76 | 174 | 71 | 40 | 16 | 22 | 406.25 | 158.6 | 37.25 | 197.5 |
| Percentages | All Pros / All Manipulations | 32% | 33% | 24% | 22% | 20% | 25% | 25% | 6% | 22% | 10% | 6% | 8% | 9% | **28%** | **19%** | **8%** | **19%** |
| | Intact NonPre / All Intact | 25% | 17% | 15% | 23% | 18% | 20% | 23% | 45% | 18% | 22% | 23% | 18% | 15% | **20%** | **25%** | **20%** | **22%** |
| | Pros Non-Pre / All Pros | 91% | 71% | 82% | 70% | 54% | 60% | 58% | 62% | 63% | 55% | 48% | 15% | 16% | **79%** | **60%** | **34%** | **57%** |

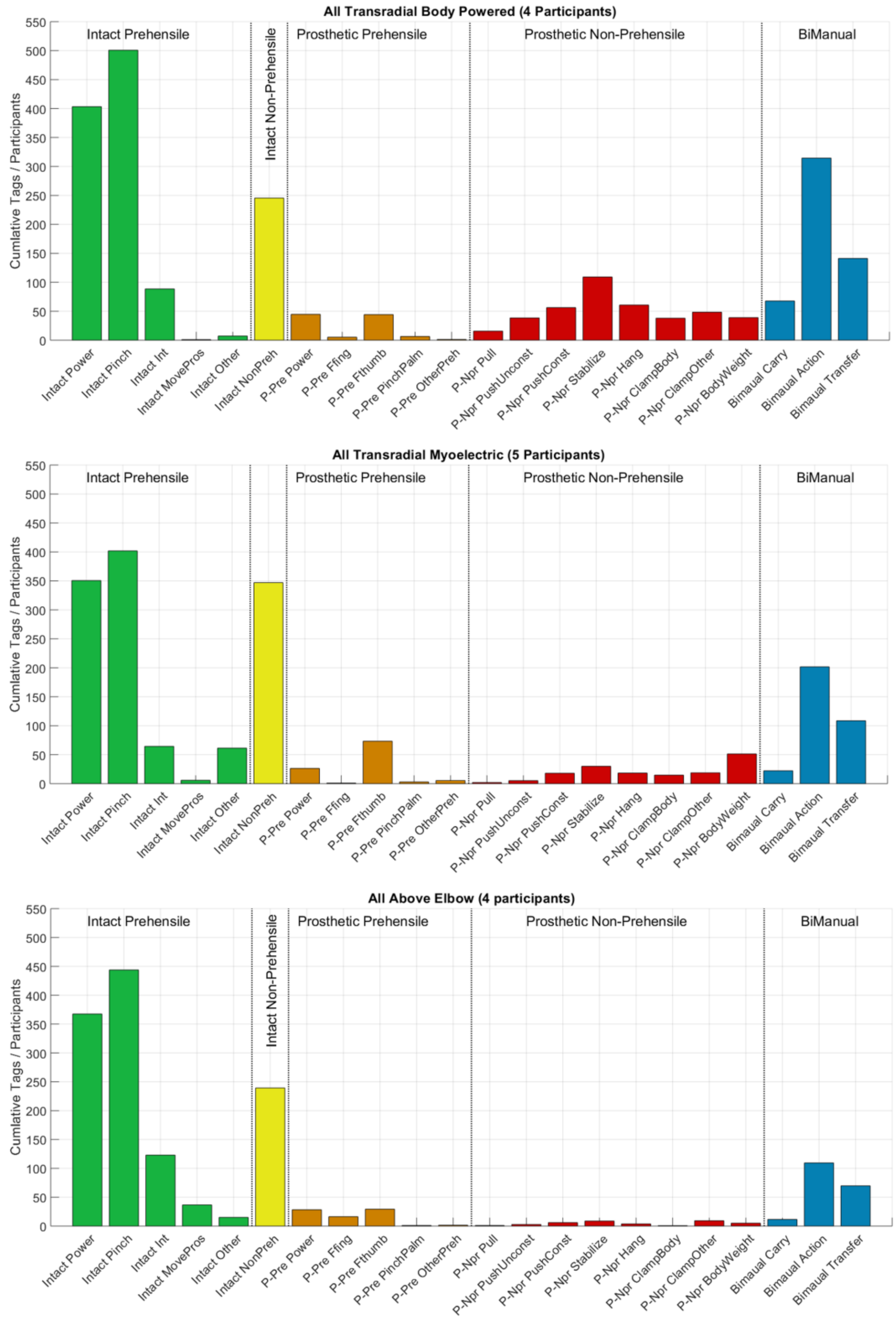


Figure 8: All average cumulative tags for three groups of participants. The number of tags was counted for all participants in a group and then divided by the number of participants in that group.

Instead of displaying total numbers of manipulation tags, Table 3 and 4 show the median tag frequency (tags/min) for the intact hand and prosthesis, for each participant. On average participants performed 16.4 tags/minute (Interquartile Range: IQR = 8.3) with the intact hand and 3.9 (IQR = 2.5) with the prosthesis.

A ratio of intact limb vs prosthetic manipulations is also provided for each participant. By observing the group averages in Table 3, we see that the prosthesis is used only 24% as frequently as the intact limb. This ranged from 6-54% between individual participants.

Both Table 2 and Table 3 show that the most active users of their prosthetic devices were P3 and P1 (33% and 32% of all manipulations, 54% and 43% ratio of limb use frequency). Both

Table 3. Median frequency (manipulation tags/min) of the intact hand and prosthesis us for each participant. The ratio indicates prosthesis tag frequency / intact hand tag frequency. A ratio of 1.0 would indicate that both hands are used with equal frequency. The shading corresponds to the value of the ratio, with darker shading indicating more equal limb use.

| Frequency (Tags/Min) | Participant | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2A | 2B | 3 | 4A | 4B | 5A | 5B | 5C | 6 | 7 | 8A | 8B | Average |
| Intact | 19.2 | 17 | 13 | 18.2 | 17.7 | 16.5 | 13.4 | 16 | 11.9 | 24.6 | 13.4 | 13.6 | 18.2 | 16.36 |
| Prosthesis | 8.3 | 2 | 1.1 | 9.8 | 5.9 | 3.6 | 5 | 4.8 | 3.2 | 1.7 | 2.2 | 0.8 | 1.9 | 3.87 |
| Ratio (I/P) | 0.432 | 0.118 | 0.085 | 0.538 | 0.333 | 0.218 | 0.373 | 0.300 | 0.269 | 0.069 | 0.164 | 0.059 | 0.104 | 0.236 |

P3 and P1 have congenital TR limb absence and make use of single DOF body powered devices (see Fig. 3 and Table 1). Considering in particular the high general activity level of P1 (in Fig. 7 and Table 2) it is interesting that over 90% of their prosthesis use was non-prehensile.

P6 is notable for both their high level of activity (Fig. 8) and their unusually low utilization of their prosthesis (6% of all manipulations in Table 2), compared to the other TR amputees in our subject pool (20-33%). Indeed, in Table 2, their manipulation breakdown is closer to that of an above-elbow amputee participant. It is worth mentioning that P6 has congenital limb difference and did not use a prosthesis during childhood and adolescence. Instead, they learned to complete tasks unilaterally or with their residual limb (without a prosthesis) and only received their first prosthetic as a young adult.

This may explain why their results appear as outliers with particularly frequent use of the intact limb (Table 2 also illustrates unusually high non-prehensile use of the intact limb for P6).

Table 4 illustrates median tag frequency values for a number of participant groups, beyond the three major groups that were included in Table 2 (which are also marked here as A, B and C). A major topic of discussion in the prosthetics community has been whether multi-grasp hands provide a benefit to manipulation over 1DOF devices [51]. This may be considered by comparing groups iii vs. iv for TR myoelectric device users, though it must be noted that only participant P4B used a 1DOF myoelectric device. The frequencies indicate an equal frequency of prehensile manipulations but a slight increase of non-prehensile manipulations with the multi-grasp terminal devices. Compared to the body powered 1-DOF TR users (group i), both myoelectric groups had slightly higher prehensile grasps (0.2 tags/min increase) but much lower non-prehensile manipulations (difference of 3.2-3.4 tags/min). We may also note that bi-manual manipulations were highest for group i, but higher for 1-DOF myoelectric users than multi-DOF myoelectric users.

Comparison of multi-grasp terminal devices with 1DOF hook devices for PE amputees is achieved via groups vii and iix, which each include 2 participants. In this case it is much clearer that the multi-grasp terminal devices were associated with increases in all aspects of prosthesis use.

### 2) *Separate Manipulation Tags Overview*

Further individual manipulation tag breakdown by groups of participants is provided in Fig. 8, where the total number of tags for each group was divided by the number of participants in that group, to provide a bar plot of average number of tags per participant.

Once again, we can observe the dominance of the intact limb, with a similar breakdown of grasp types across the three groups of participants. Precision/pinch grasps are the most used grasp type, closely followed by power grasps. This is contrary to the earlier findings of [33], which determined a power grasp to be most common grasp, followed by a precision grasp. However, the head-mounted video data in [33] was collected data from two housekeepers and two machinists, who were actively working during the study. Indeed, the authors highlight that the frequent use of cleaning products, including a power-grasped spray bottle, biased the data towards specific tasks and away from the more diverse interactions of daily life.

Non-prehensile manipulations are the third most used intact hand tag, which surprisingly, are higher in occurrence than intermediate grasps. As previous work on in-the-wild human manipulation (e.g. [32], [43]) has focused only on grasps, we

Table 4: Median Frequency (manipulation tags/min) across five conditions (columns) for different groupings of participants (rows). The shading of each of the frequency columns is conditionally formatted, with higher numbers represented as darker colors. Groups labelled A, B and C are the same groups as were presented in Table 2. Abbreviations TR: Transradial, PE: Proximal to Elbow, TH: Transhumeral, SD: Shoulder Disarticulate, BP: Body Powered

| Group | Description | Participant Group | | | Median Frequency (tags/min) | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Amputation | Actuation | DOF | Intact Prehensile | Intact Non-prehensile | Prosthetic Prehensile | Prosthetic Non-prehensile | Bimanual |
| i | **All BP (A)** | TR | BP | 1-DoF (All) | 13.2 | 3 | 1.2 | 5.4 | 7.4 |
| ii | **All Myo (B)** | TR | Myo | 1-DoF & Multi-DoF | 11.6 | 3.2 | 1.4 | 2.2 | 4.8 |
| iii | TR Myo 1-DOF | TR | Myo | 1-DoF | 11.8 | 2.2 | 1.4 | 2 | 5.2 |
| iv | TR Multi-Grasp | TR | Myo | Multi-Dof | 11.2 | 4 | 1.4 | 2.2 | 4 |
| v | All TR | TR | BP & Myo | 1-DoF & Multi-DoF | 12.2 | 3 | 1.2 | 3 | 5.2 |
| vi | **All PE (C)** | PE | Myo | 1-DoF & Multi-DoF | 11.6 | 2.3 | 0.8 | 0.2 | 2.3 |
| vii | PE 1-DOF | PE | Myo | 1-DoF | 11 | 2.4 | 0.6 | 0.2 | 1.2 |
| iix | PE Multi-Grasp | PE | Myo | Multi-Dof | 14.2 | 2.2 | 1 | 0.4 | 3.2 |
| ix | All SD | SD | Myo | 1-DoF & Multi-DoF | 11 | 3.2 | 0.6 | 0.6 | 2.4 |
| x | All TH | TH | Myo | 1-DoF & Multi-DoF | 12.2 | 2.2 | 1 | 0 | 1.6 |

Table 5: List of hypotheses tests for tag frequency and proportion testing within participants. Results are given in Table 6.

| Hypothesis Number | Variable 1 | Variable 2 | Frequency or Proportion |
|---|---|---|---|
| FW-1 | All intact use | All prosthesis use | Frequency |
| FW-2 | Intact prehensile | Intact non-prehensile | Frequency |
| FW-3 | Prosthesis prehensile | Prosthesis non-prehensile | Frequency |
| FW-4 | Intact prehensile | Prosthesis prehensile | Proportion |
| FW-5 | Intact non-prehensile | Prosthesis non-prehensile | Proportion |
| FW-6 | Intact power | Intact pinch | Frequency |
| FW-7 | Prosthesis power | Prosthesis pinch | Frequency |
| FW-8 | Intact power | Prosthesis power | Proportion |
| FW-9 | Intact pinch | Prosthesis pinch | Proportion |
| FW-10 | Prosthesis pull | Prosthesis push | Frequency |
| FW-11 | Prosthesis pinch between fingers | Prosthesis pinch between finger and thumb | Frequency |
| FW-12 | Prosthesis push unconstrained objects | Prosthesis push constrained objects | Frequency |
| FW-13 | Prosthesis clamp against body | Prosthesis clamp against other | Frequency |
| FW-14 | Bimanual carry | Bimanual action | Frequency |
| FW-15 | Intact prehensile | Prosthesis prehensile | Frequency |

feel that the importance and reliance on these non-prehensile manipulations may have been overlooked by the manipulation community in general.

Regarding prehensile prosthesis use, the distribution between power and precision grasps is equal for TR body powered device users and PE amputees, though a preference is shown for pinch grasps by TR myoelectric device users.

For non-prehensile manipulations with the prosthesis, it may be seen that transradial body-powered device users performed more manipulations than other groups (as was highlighted in Table 2). In comparison, the quantity of various manipulation types is less for TR myoelectric users and even less for above-elbow amputees, all of whom used myoelectric devices.

### B. *Within-Subjects Hypothesis Testing: Manipulation Frequency*

This section details the statistical comparison of one manipulation tag type (such as an *intact limb power grasp*) or a tag group (such as *intact limb grasps*, to which the intact power grasp belongs) to another tag or group of tags for each participant. Hypothesis testing (the methods of which are discussed in IV.A) was completed for all 13 participant cases (from Table 1) individually resulting in 13 distinct $p$ values for each of the 15 hypotheses (195 significance values in total). Because these statistical values are distributed among many different groupings, and therefore do not involve the repeat comparisons of the same two groups, a correction factor (such as Bonferroni correction) was not implemented. Table 5 describes all 15 hypothesis comparisons and Table 6 shows the resulting statistically significant findings for each comparison and participant. We intend that such a statistical look-up table can be used as a reference tool for further comparison of the participants in this study, beyond what will be discussed in this manuscript.

The following sections discuss several of the results, especially those for which the result was similar across many participants. Due to limitations of space, not every comparison may be discussed, but all have been included in Table 6 for completeness.

When reporting metrics to represent the value and size of the frequency data, the average median and the average interquartile range (IQR) will be used. Note that the median may not be in the center of the IQR because the data is skewed. Only those participants for whom the difference was significant will be included in the average metrics reported.

#### 1) *General Intact Limb vs. Prosthesis Use*

As expected, all participants use their intact hand more frequently than their prosthesis (Table 5, FW-1). This was previously illustrated in Fig. 7, Table 2 and Table 3.

#### 2) *Intact Limb vs. Prosthetic: Specific Grasp Comparison*

Given that the intact hand is used more frequently than the prosthesis, the following analysis compares the *proportion* of related tags (instead of pure frequency values) between the intact and affected limbs. In these calculations, the denominator is the frequency of all tags for the limb in question.

For example, Variable 1 is the number of prehensile grasps with the intact hand over the total number of intact hand tags.

Table 6: Statistical results of hypothesis testing within subjects for tag frequency and proportion. The hypothesis number corresponds to the description in Table 4. The number of stars indicates the level of significance (as defined in the legend on the left). Green shading indicates significance in the direction of variable 1 and blue shading indicates significance in the direction of Variable 2. As an example, Hypothesis 1 for Participant 1 indicates that the frequency of all intact limb use was greater than prosthetic use by a highly significant amount *(p<0.0005)*.

| Key |
|---|
| ✕ $p \geq 0.05$ |
| ★ $p<0.05$ |
| ★★ $p<0.005$ |
| ★★★ $p<0.0005$ |
| Var 1 > Var 2 |
| Var 2 > Var 1 |

| Hypothesis | P1 TR / BP | P2A SD / Myo | P2B SD / Myo | P3 TR / BP | P4A TR / BP | P4B TR / Myo | P5A TR / Myo | P5B TR / Myo | P5C TR / BP | P6 TR / Myo | P7 TR / Myo | P8A TH / Myo | P8B TH / Myo |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| FW-1 | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ |
| FW-2 | ★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ✕ | ★★★ | ★★★ | ★★★ |
| FW-3 | ★★★ | ✕ | ✕ | ★★ | ★★★ | ✕ | ✕ | ✕ | ★ | ✕ | ✕ | ★★ | ★★ |
| FW-4 | ★★★ | ★ | ★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★ | ★★★ | ✕ | ★★ | ✕ | ✕ |
| FW-5 | ★★★ | ★ | ★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★ | ★★★ | ✕ | ★★ | ✕ | ✕ |
| FW-6 | ★★★ | ✕ | ✕ | ✕ | ✕ | ✕ | ★★ | ★ | ★★★ | ✕ | ✕ | ★ | ✕ |
| FW-7 | ★★★ | ✕ | ✕ | ✕ | ★ | ★★ | ★ | ✕ | ★ | ✕ | ★ | ✕ | ✕ |
| FW-8 | ★★★ | ✕ | ★ | ✕ | ✕ | ★★★ | ✕ | ✕ | ✕ | ★ | ★★★ | ✕ | ✕ |
| FW-9 | ★★★ | ✕ | ★ | ✕ | ✕ | ★★★ | ✕ | ✕ | ✕ | ✕ | ★★★ | ✕ | ✕ |
| FW-10 | ★★★ | ★ | ✕ | ★★★ | ✕ | ★ | ★★ | ★ | ★★★ | ★ | ★ | ✕ | ✕ |
| FW-11 | ★★★ | ★★★ | ★ | ★★★ | ★ | ★★★ | ★★ | ✕ | ★★ | ★ | ★★ | ✕ | ★★ |
| FW-12 | ★★★ | ✕ | ✕ | ✕ | ✕ | ✕ | ★★★ | ✕ | ★ | ✕ | ✕ | ✕ | ✕ |
| FW-13 | ★★★ | ★ | ★ | ★ | ★ | ★ | ✕ | ✕ | ✕ | ★ | ✕ | ✕ | ✕ |
| FW-14 | ★★★ | ★★ | ★★ | ★★★ | ★★ | ★★★ | ★ | ★★ | ★★ | ★★ | ★★★ | ★★ | ★★★ |
| FW-15 | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ |

Table 7: List of hypothesis tests for between-subjects (group) comparison regarding tag frequency. FB refers to Frequency data between subjects. The results of these tests are provided in Table 8.

| Hypothesis Number | Group 1 | | | Group 2 | | |
|---|---|---|---|---|---|---|
| | Amputation | Actuation | DOF | Amputation | Actuation | DOF |
| FB-1 | TR | BP & Myo | 1-DoF / Multi-DoF | PE | Myo | 1-DoF / Multi-DoF |
| FB-2 | TR | BP | 1-DoF | TR | Myo | 1-DoF / Multi-DoF |
| FB-3 | TR | BP | 1-DoF | TR | Myo | 1-DOF |
| FB-4 | TR | Myo | 1-DoF | TR | Myo | Multi-DoF |
| FB-5 | PE | Myo | 1-DoF | PE | Myo | Multi-DoF |
| FB-6 | TR | Myo | 1-DoF | PE | Myo | 1-DoF |
| FB-7 | TR | Myo | Multi-DoF | PE | Myo | Multi-DoF |
| FB-8 | SD | Myo | 1-DoF / Multi-DoF | TH | Myo | 1-DoF / Multi-DoF |

Variable 2 is the number of prehensile grasps with the prosthesis over total number of prosthesis tags. Variable 1 may then be compared against Variable 2, to complete hypothesis FW-4. This was completed for the following tags or groups of tags: Prehensile, Non-prehensile, Power and Pinch as indicated by Table 5 and 6, for hypothesis FW-4, FW-5, FW-8 and FW-9. These four hypotheses compare proportions instead of raw frequency values. For all TR participants (apart from P6), prehensile grasps form a higher proportion of intact hand usage than prehensile grasps with their prosthesis (80%, IQR = 13%, 34%, IQR = 25%).

Relatedly, for all TR participants' (excluding P6) the proportion of manipulations with the prosthetic that are non-prehensile (66%, IQR = 25%) are higher than the proportion with the intact hand (19%, IQR = 12%).

The use frequency is likely a direct result of a prosthetic hand's general lack of dexterity and tactile feedback, small grasp aperture, and slow grasping rates, compared to the healthy hand. There is more uncertainty associated using a prehensile grasp with the prosthesis than the intact hand, though this does vary between different terminal devices (Fig. 1). There is also the additional cognitive and physical demands of providing a grasp signal or body powered cable exertion, in comparison to the near-effortless control of a healthy limb.

### 3) *Prosthetic Prehensile vs. Non-Prehensile Manipulations*

All TR participants appeared to use prosthetic non-prehensile manipulations more frequently than prosthetic prehensile grasps. Hypothesis FW-3 of Table 6 provides the p values for each participant and illustrates that this observation was statistically significant for each body-powered device user but not significant for any of the myoelectric device users.

P8 is the only participant who exhibited the opposite trend, using prehensile grasps significantly more frequently than non-prehensile manipulations with both of their prosthesis. As a reminder, P8 is a TH amputee.

Overall, these results refine the trend originally suggested in [2] that TR amputees with body-powered devices used non-prehensile manipulations more often than prehensile grasps with their prosthesis.

### 4) *Prosthetic Non-Prehensile Manipulations*

Hypothesis testing on each participant revealed that eight of nine TR participants pushed objects significantly more frequently than pulling them (hypothesis FW-10). One potential reason for this difference is that some subjects were not using prostheses with slender fingers, thereby prohibiting them from using handles to pull open drawers with the prosthesis. However, this difference could also be related to lack of a wrist that could allow the subjects to orient the device for inserting fingers into a handle and/or getting a suitable device orientation for pulling.

Table 8: Significance results of hypothesis testing between subjects for tag frequency. The hypothesis number corresponds to the description in Table 7. The number of stars indicates the level of significance (as defined in the legend on the left). Orange shading indicates significance in the direction of Group 1 and lilac (patterned) shading indicates significance in the direction of Group 2.

| Key |
|---|
| × $p \geq 0.05$ |
| ★ $p<0.05$ |
| ★★ $p<0.005$ |
| ★★★ $p<0.0005$ |
| Group 1 > 2 |
| Group 2 > 1 |

| Hypothesis | Intact Prehensile | Intact Non-Prehensile | Prosthesis Prehensile | Prosthesis Non-Prehensile | Bimanual |
|---|---|---|---|---|---|
| FB-1 | × | × | ★★ | ★★★ | ★★★ |
| FB-2 | × | × | × | ★★★ | ★★ |
| FB-3 | × | × | × | ★★★ | × |
| FB-4 | × | ★★ | × | × | × |
| FB-5 | ★ | × | × | × | ★ |
| FB-6 | × | × | ★★ | ★★★ | ★★★ |
| FB-7 | ★ | ★ | × | ★★★ | × |
| FB-8 | × | × | ★ | ★★★ | × |

## C. *Between-Subjects Hypothesis Testing: Manipulation Frequency*

In this section we attempt to discern differences in frequency of use between groups of similar participants. These groups were defined by several variables including level of amputation, prosthesis actuation, and prosthesis DoFs. We compare these groups across 5 categories: intact prehensile, intact non-prehensile, prosthetic prehensile, prosthetic non-prehensile and bimanual.

Table 7 displays a list of groups tested against one another in statistical comparison.

It is important to remember that several of the participants make use of multiple devices, and so could fall into two opposing groups for the same variable, or the same group twice. For instance P5 provided video data using a myoelectric iLimb Quantum (P5A) and a body-powered Sensor Hand (P5C). P5A is grouped into the TR myoelectric device group, and P5C is in the TR, body-powered device group (see hypothesis FB-2 in tables 7 and 8). Such occurrences violate the statistical assumption that the two groups being compared were sampled independently from one another. Given the small number of participants, this is unavoidable.

### 1) *Level of Amputation*

In agreement with [52], as a group, we observed TR participants used their devices more frequently than PE participants (hypothesis FB-1). Statistically, TR participants used prehensile grasps more frequently with the prosthesis than PE participants (1.2 tags/min, IQR = 1.6 vs. 0.8 tags/min, IQR = 1.1). Subjects with TR amputations also used non-prehensile manipulations with their prosthesis significantly more frequently than subjects with Proximal to Elbow (PE)

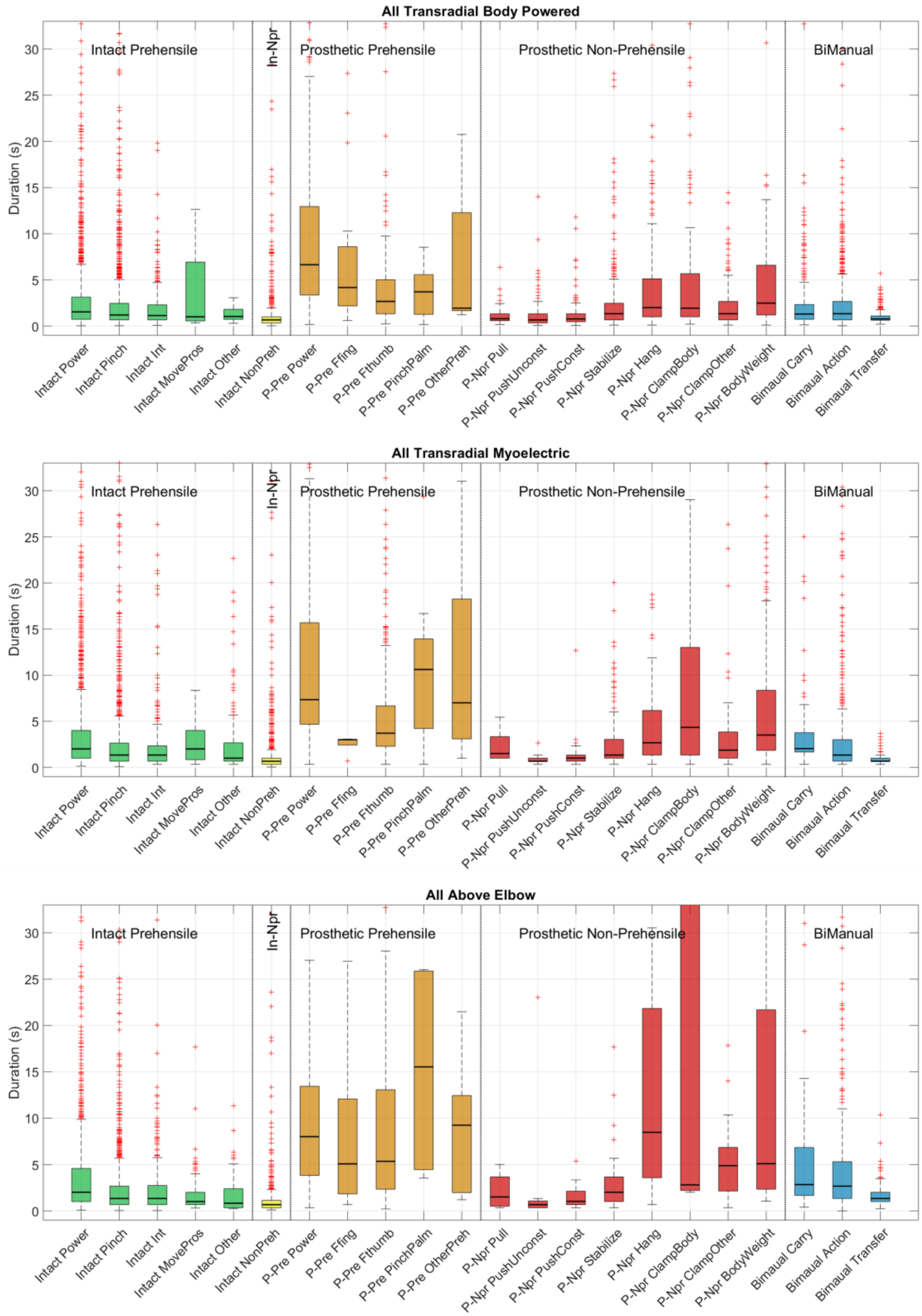


Figure 9: The duration of different manipulation activities for different groups. For the Proximal to Elbow (PE) group, the upper limit of the Non-prehensile Clamp to Body box is 52 seconds and the upper whisker is 68.41 seconds.

amputation (3.0 tags/min, IQR = 3.7 vs. 0.2, tags/min IQR = 0.80). This is reflected in Table 2 and in Table 8 (hypothesis FB-1). Again, this could relate to level of arm mobility.

Participant 6's grasp breakdown (Fig. 7) resembles that of the participants with PE amputations, rather than other TR participants with myoelectric devices. Despite this trend, the grouping of P6 with the other TR amputee participants for hypothesis testing does not cause any of the trends to reverse. As previously mentioned, P6 was born with limb difference and only recently began using a prosthesis. As such, P6 is generally adept at using their intact hand exclusively for many tasks.

When comparing prosthesis use by P8A/B (TH) to P2A/B (SD) (hypothesis FB-8), P2 uses non-prehensile manipulations significantly more frequently than P8 (*p=2.9e-4*). This is somewhat surprising, as transhumeral amputees still generally have use of the glenohumeral joint, which permits upper arm mobility compared to amputees with shoulder disarticulation. However, the additional weight of TH or SD level prosthesis, combined with possible movement restriction from the socket implies that neither participant may have been able to flex their shoulder as easily as TR amputees. This may be key to ease of positioning and exerting forces with the prosthesis, for non-prehensile actions.

*2) Device Actuation*

Comparing TR subjects based on device actuation method (as indicated by hypothesis FB-2) reveals that those with body-powered devices used non-prehensile manipulations with the prosthesis significantly more ($p= 1.3e\text{-}8$) frequently than those with myoelectric devices (5.6 tags/min, IQR = 6.0 vs. 2.0 tags/min, IQR = 2.0).

It is reasonable to assume the inclusion of three multi-grasp devices in the myoelectric device category within the TR participants may skew the results of hypothesis FB-2. However, hypothesis FB-3 compares the TR participants who have 1-DoF body-powered devices to those with 1-DoF myoelectric devices, the difference in frequency of non-prehensile manipulations remains significant ($p=1.6e\text{-}5$).

If we consider the frequency of use of each type of non-prehensile tag, the TR subjects with body powered devices use pull, push constrained objects, push unconstrained objects, and stabilize objects significantly more frequently than the TR subjects with 1-DoF myoelectric devices ($p=3.4e\text{-}5$, $1.1e\text{-}3$, $6.3e\text{-}6$, $8.2e\text{-}5$). Indeed, participants with body powered devices would often stabilize objects such as plates or a stack of folded clothes on top of the prosthesis, usually on the radial side of the hand while the thumb is abducted. Hypothesis testing on the frequency of the remaining non-prehensile manipulation types (hang, clamp against body, clamp against other, and support body weight) resulted in $p > 0.05$. Fig. 8 shows the average number of tags for the three groups of participants. Note that these specific statistical tests use the groupings of FB-2 in Table 7, but as categories of manipulation are limited to only non-prehensile tags for the above significance calculations, these results are not presented in Table 8.

*3) Device DOF*

Lastly, we compared tag frequency in participants using myoelectric devices with 1-DoF to those with multi-DoF. In TR participants with myoelectric devices (hypothesis FB-4), there were no significant differences between 1-Dof and multi-Dof device users for prehensile prosthesis use ($p=0.33$) or non-prehensile prosthesis use ($p=0.72$). The same was true for the participants with PE amputations (prehensile $p=0.078$, non-prehensile $p=0.10$, table 7 hypothesis FB-5).

Yet, if we compare TR subjects with 1-DoF devices to those with multi-DoF devices across each type of non-prehensile manipulation, an interesting difference is highlighted. In TR subjects using myoelectric devices, those with multi-DoF devices used the non-prehensile hang manipulation significantly less frequently than 1 DoF myoelectric users ($p=2.9e\text{-}4$). Perhaps the users of multi-Dof devices avoided hanging objects from their prostheses due to the fear of damaging these expensive systems.

*D. Tag Duration Overview*

During the video analysis process, both the type and duration of each manipulation action were recorded. In contrast to the method used to analyze frequency of use, analyzing duration did not require dividing the video into five-minute intervals to extract multiple measures of tag duration.

Multiple measures of tag duration are needed in order to calculate variance, which is necessary for statistical testing. Each tag included a measure of duration of a particular tag type. Given that most tag types were recorded multiple times over the course of the full length of their recorded videos, we can determine the variance of duration for each tag type without segmenting the video data. Some manipulations actions were used sparingly, providing only a few measures of duration for those tag types. Only tag types that occurred five or more times were included in this analysis. Tables 9, 10 and 11 display the hypothesis and results for the statistical testing and indicate the cases for which there is insufficient data.

An overview of the duration of different tag types for the three major participant groups is provided in the boxplots of Fig. 10. Note that this data has a large number of outliers, due to the large number of tags that were processed (see Table 2).

The boxplots show roughly equal duration information for manipulations with the intact limb cross all groups, which is to be expected.

In [2], which used a small set of this current data, we reported that prehensile manipulations generally had a longer duration with the prosthesis than with the intact limb. This statement continues to be true for all user groups. This suggests that the device is often used as a clamp, with objects being secured or carried in the same grasp. One example of this was noted when observing the videos of P1, who would hold an object in their prosthetic limb while walking around their house, using the intact limb to open doors and perform other operations.

For TR myoelectric users the prosthetic pinch grasps between fingers (as opposed to the more common finger and thumb) stand out as having a particularly short duration. However, this was quite a rare manipulation for this group (as shown in Fig. 9) and is in fact only possible with prostheses with specific gloves (such as that used by P1). As such, this outlier is more likely to reflect sparsity of data than TR users performing this manipulation particularly quickly.

Non-prehensile manipulations were generally shorter for the TR body-powered group. More fundamental non-prehensile manipulations (pulling, pushing and stabilizing), had similar durations for all groups, though pulling took longer with myoelectric devices. It is possible that participants may have pulled on objects more slowly and gently with their myoelectric devices due to fragility concerns. Actions of hanging, clamping and leaning one’s body weight took longer for myoelectric and PE users. Some of these manipulations are used to stabilize or carry objects, thus they last longer than momentary tasks such as pulling.

Table 9: Hypotheses used for within-subjects statistical testing of tag duration data. DW refers to Duration data Within subjects. The results of these tests are given in Table 10.

| Hypothesis Number | Variable 1 | Variable 2 | Quantity |
|---|---|---|---|
| DW-1 | All intact use | All prosthesis use | Duration |
| DW-2 | Intact prehensile | Intact non-prehensile | Duration |
| DW-3 | Prosthesis prehensile | Prosthesis non-prehensile | Duration |
| DW-4 | Intact prehensile | Prosthesis prehensile | Duration |
| DW-5 | Intact non-prehensile | Prosthesis non-prehensile | Duration |
| DW-6 | Intact power | Intact pinch | Duration |
| DW-7 | Prosthesis power | Prosthesis pinch | Duration |
| DW-8 | Intact power | Prosthesis power | Duration |
| DW-9 | Intact pinch | Prosthesis pinch | Duration |
| DW-10 | Prosthesis non-prehensile transport | Prothesis non-prehensile other | Duration |
| DW-11 | Prosthesis support body | Prosthesis non-transport non-prehensile | Duration |
| DW-12 | Bimanual carry | Bimanual action | Duration |

Bi-manual manipulations followed a similar trend as other categories, with the body-powered group performing these actions most quickly (and most often, as illustrated in Fig. 9) followed by the TR myoelectric and the PE group.

These observations will be further discussed in the following statistical analysis of the duration data.

### *E. Within Participant Hypothesis Testing: Duration*

The duration data for the tags was analyzed using the same statistical tools as those used to analyze tag frequency. As previously mentioned (in Section IV.A.2), parametric statistical tests assume that the residuals of the data have a normal distribution. We test this assumption using the Kolmogorov-Smirnov test. If the residuals are not normal, the non-parametric version of the t-test, the Mann Whitney U test is used to detect significant differences in duration of various tag types otherwise Welch's t-test is used.

Similar to the hypotheses testing in Section A, hypothesis testing was completed for each of the 13 'participant' cases across 12 hypotheses. The twelve comparisons are listed in Table 9, the first nine of which are the same as those in Table 4. However, instead of analyzing the frequency of use of each manipulation tag, we are now analyzing the duration of each tag. The resulting degree of statistical significance associated with each participant for each comparison is shown in Table 10.

#### *1) Intact Limb vs. Prosthesis Duration*

Overall all participants used the prosthesis for grasps and manipulations that are significantly longer (hypothesis DW-1) than those performed with the intact hand (3.2 s, IQR = 6.0 vs. 1.2 s, IQR = 2.1). This was the case for both prehensile grasps (hypothesis DW-4) and non-prehensile manipulations (hypothesis DW-5) across all participants. Users of voluntary open body powered devices must expend energy to open their device but not to keep it closed. In myoelectric users, they must provide the control signal to open or close the device but do not to keep it in a same position. The slow closing rate of a terminal device is a common complaint among users of myoelectric prostheses [13]. Given the additional effort or time required to actuate the terminal device as compared to the intact hand, it is not surprising that participants use the prosthesis for fewer, more lengthy grasps than the intact hand.

On average prehensile grasps with the prosthesis were significantly longer in duration than those with the intact hand (prosthesis 5.1s, IQR=8.0, intact 1.5s, IQR=2.4s, hypothesis DW-4). As mentioned in Section D, participants often grasped an object with the prosthesis for several minutes while transporting it between rooms, leaving their intact hand free to complete any other tasks that require more dexterity. Power and pinch last 10.7 s (hypothesis DW-8) and 5.5 s (hypothesis DW-9) longer with the prosthesis than the intact hand, respectively.

Non-prehensile manipulations were on average 5.4s longer with the prosthesis than the intact limb (hypothesis DW-5). This is somewhat surprising given most non-prehensile manipulations do not require actuation of the hand though some require movement of the arm. A case study concerning an experienced body-powered prosthesis user found that the impaired arm approached the object much more slowly than the intact arm during a reaching task [53]. Many non-prehensile manipulations require the participant to move their hand in space and exert forces in arbitrary directions. Given the lack of proprioception within the terminal device it may be more difficult and require more time to accurately position the arm

Table 10. The result of within-subjects statistical testing based on manipulation tag duration. Table 9 describes each hypothesis. The entries in green represent those for which the median of variable 1 is larger than the median of variable 2. The entries in blue exhibit the opposite trend. Entries that are blank indicate that one of the two types of tags being compared was recorded either five times or fewer, so the statistical test was not completed.

| Key | |
|---|---|
| × | $p \geq 0.05$ |
| ★ | $p<0.05$ |
| ★★ | $p<0.005$ |
| ★★★ | $p<0.0005$ |
| Insufficient Data | |
| Var 1 > Var 2 | |
| Var 2 > Var 1 | |

| | Participants | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hypothesis | P1 | P2A | P2B | P3 | P4A | P4B | P5A | P5B | P5C | P6 | P7 | P8A | P8B |
| DW-1 | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ |
| DW-2 | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ |
| DW-3 | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★ | ★★★ | ★★★ | ★★ | ★ | ★★★ | × | × |
| DW-4 | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ |
| DW-5 | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ |
| DW-6 | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | × | ★★★ | ★★★ | ★ | ★★★ |
| DW-7 | ★★★ | × | × | ★★★ | ★ | ★★ | ★★★ | ★ | × | ★★★ | ★★ | × | ★ |
| DW-8 | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★ | ★★★ | ★★★ | ★★★ | ★★★ |
| DW-9 | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ |
| DW-10 | ★★★ | ★★ | | ★★★ | ★★★ | ★★★ | × | | ★ | ★★★ | ★ | | |
| DW-11 | ★★★ | | × | ★★★ | ★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★ | ★★★ | | |
| DW-12 | × | × | × | × | × | × | ★★★ | × | × | ★ | ★ | ★ | × |

and complete the manipulation especially if the subject is relying on visual feedback [53]. The manipulation action ‘Hang/thread through’, which is sometimes used to transport objects with the prosthesis (e.g. hanging a grocery bag or clothes hanger on the device), could also contribute to longer manipulation times, since it is used almost exclusively by the prosthesis.

### 2) *Intact Limb Tag Duration*

Across all participants, prehensile grasps with the intact hand were significantly longer in duration than non-prehensile manipulations with an average difference of 1.9 s, (Table 9 & 10 hypothesis DW-2). This difference is expected in that manipulation actions such as pushing and pulling objects are usually performed quickly in comparison to prehensile actions, which may involve the use of an object for a task (e.g. after pinch grasp is established on a pen, the participant may then write with the pen). For most participants the intact hand performed power grasps significantly longer (4.0s) than pinch grasps (2.6s) (hypothesis DW-6). Power grasps such as the medium wrap mentioned in a [33] are well suited for long grasping times and are often used when transporting objects, which could contribute to this difference in duration.

### 3) *Prosthesis Tag Duration*

Similar to the trend observed with the intact hand, most participants (11 of 13 cases) used significantly longer prehensile grasps than non-prehensile manipulations with the prosthesis (hypothesis DW-3). The spread of the duration of the grasps was much wider for the prosthesis than the intact hand within each participant. For instance, the average interquartile range of the duration of prehensile grasps with the intact hand is 2.4s while it is much greater for the prosthesis at 8.0s.

Power grasps are often more stable for a prosthesis than pinch grasps, so it is reasonable that power grasps were used for significantly longer periods of time than pinch grasps for 9 of 13 cases (hypothesis DW-7). In terms of the non-prehensile manipulations participants tended to use *hang/thread-through* and *clamp-against-body* to transport objects between rooms. These non-prehensile actions tended to last significantly longer than other non-transport non-prehensile manipulations including *pull, push, clamp against other, and stabilize* (transport 3.5s, non-transport 1.2s, hypothesis DW-10). Supporting one’s body weight also tended to last longer than the other non-transport non-prehensile manipulations (support body 4.2s, non-transport 1.3s, hypothesis DW-11).

## F. *Between Participant Analysis: Duration*

Similar to the previous analysis between participants, we compared duration of tag types between groups of like participants using the five main types of tags: intact prehensile, intact non-prehensile, prosthetic prehensile, prosthetic non-prehensile and bimanual use. Again, subjects are grouped based on amputation level, powering of the device, and device DoFs. The groups comparisons in this analysis are the same as those listed in Table 7. Table 11 displays the results of significance testing for each comparison.

Table 11. Significance results of hypothesis testing on tag durations, between groups of subjects. The hypothesis number corresponds to the equivalent hypothesis description in Table 7 with DB-1 referring to Duration testing Between subjects. The number of stars indicates the level of significance (as defined in the legend on the left). Green shading indicates significance in the direction of variable 1 and blue shading indicates significance in the direction of Variable 2.

| Key |
|---|
| × $p \geq 0.05$ |
| ★ $p<0.05$ |
| ★★ $p<0.005$ |
| ★★★ $p<0.0005$ |
| Var 1 > Var 2 |
| Var 2 > Var 1 |

| Hypothesis | Intact Prehensile | Intact Non-Prehensile | Prosthesis Prehensile | Prosthesis Non-Prehensile | Bimanual |
|---|---|---|---|---|---|
| DB-1 | ★★ | ★★ | ★★★ | ★★★ | ★★★ |
| DB-2 | ★★★ | × | ★ | ★★★ | × |
| DB-3 | ★★★ | ★★ | × | ★★★ | × |
| DB-4 | ★★★ | ★★★ | ★ | × | × |
| DB-5 | ★★★ | ★★★ | × | × | × |
| DB-6 | × | × | ★★★ | ★ | ★★★ |
| DB-7 | × | × | × | × | ★★★ |
| DB-8 | ★★★ | × | ★ | × | ★ |

### 1) *Level of Amputation Effect on Duration*

Those with TR amputations used shorter prehensile grasps (difference in medians=2.0s), non-prehensile manipulations (difference in medians=1.1s) with the prosthesis and bimanual tasks (difference in medians=1.0s) than those with PE amputations (Table 7 & 11 hypothesis DB-1). In general, the participants with PE amputations used their prosthesis for fewer yet longer grasps and manipulations.

### 2) *Device Actuation*

In the TR participants, those with body-powered devices used more non-prehensile manipulations with the prosthesis but with significantly shorter durations than those with externally powered devices (hypothesis DB-2). On average the participants with body-powered devices used non-prehensile manipulations lasting 1.3 s and those with externally powered devices, 2.0s. Similar to the results based on frequency, this difference between body powered and myoelectric devices was not solely dependent on 1 DoF vs. multi-DoF devices. Even among TR subjects with 1 DoF devices, those with body-powered devices (1.3s) use significantly shorter non-prehensile manipulations than those with 1 DoF externally powered devices (1.9s, table 7 & 11 DB-3).

### 3) *Device DoF*

For TR subjects using myoelectric devices, those with 1-DOF devices used longer duration prehensile grasps with their intact hand and shorter prehensile grasps with their prosthesis than participants with multi-DoF devices (hypothesis DB-4).

There were no significant differences in terms of duration of non-prehensile use with the prosthesis between TR subjects using 1-DoF myoelectric devices and those using multi-DoF myoelectric devices.

For PE amputees, there are no significant differences between 1 DoF and multi-DoF prosthesis users’ duration of prehensile grasps or non-prehensile manipulations with the prosthesis (p>0.05 hypothesis DB-5). When the PE participants use 1 DoF devices, they tended to use significantly longer prehensile grasps and non-prehensile manipulations with their intact hand than when they use multi-DoF devices ($p_{prehensile}$=6.5e-13, $p_{non\text{-}prehensile}$=3.0e-5).

## VI. Conclusions and Future Work

We present a summary of major findings, organized as numbered bullet points below.

### *A. General Affected vs. Intact Limb Use*

1. Prostheses were used on average for only 19% of all recorded manipulations, across all participants. This value ranges between 6%-33% for individual participants (Table 2).
2. Prostheses were used on average only 24% as frequently as the intact limb, measured in terms of manipulations/minute (Table 3). This ranged from 6%-54% between individual participants.
3. Transradial amputees with body-powered devices (TR-BP) used their prosthetic for 28% of all manipulations. Transradial myoelectric device users (TR-Myo) use their prosthetic for 19% of manipulations. Proximal to Elbow amputees (PE) used their prosthetics (all of which were myoelectric) for 8% of tasks (Table 2).
4. Intact hand manipulation breakdown was similar across all participant groups. The most used manipulation actions, in descending order, were precision grasp, power grasp, non-prehensile manipulation and intermediate grasp (Fig. 8). Previous work (e.g. [33], [43]) did not consider non-prehensile manipulations in their data analysis, so the fact that non-prehensile manipulations occur more often than intermediate grasps is a new and interesting finding.
5. TR amputees use their prostheses more often than above-elbow amputees (FB-1).
6. Prosthesis use was uncharacteristically low for P6, a TR amputee whose data resembled more the behavior of an PE amputee. This may be related to the participant not using a prosthetic until they were an adult, despite congenital limb difference (Fig. 8, Table 2 and 3).

### *B. Non-prehensile Manipulation with Prostheses*

7. For TR-BP users, 79% of prosthesis usage is non-prehensile. This reduces to 60% for TR-Myo users and 34% for PE amputees (Section 5.A.1 and Table 2).
8. Non-prehensile manipulation accounts for 20-25% of intact hand use across all groups. This is much less than non-prehensile use with prostheses (Section 5.A.1 and Table 2).
9. All TR participants tended to use their intact hand more for grasping and their prosthetic more for non-prehensile manipulations (Table 2).
10. Though all TR participants were observed to use non-prehensile manipulations with their prosthetic more than prehensile manipulations, this difference was only significant for body-powered device users (FW-3 and FB-2).
11. Nearly all participants performed more prehensile manipulations with their intact hand than with their prosthetic (FW-4) and more non-prehensile manipulations with their prosthetic than their intact hand (FW-5).
12. The most common non-prehensile manipulations for the TR-BP group was stabilizing objects and clamping objects against a surface. This was the same for the PE group, but with lower quantities. For TR-Myo, supporting bodyweight was the most frequent action.

### *C. Multi-Grasp Prosthetic Hands*

13. Multi-grasp myoelectric hands do not appear to facilitate an increase in prosthesis use for TR amputees, compared to single DOF myoelectric devices (FB-4).
14. Multi-grasp hands also do not lead to increase prosthesis use in above-elbow amputees, compared to single DOF myoelectric split hook devices (FB-5).
15. Multi-DOF device users use the non-prehensile 'hang' manipulation less than participants with 1-DOF devices (Section 5.C.3). This may be due to perceived/actual fragility of multi-grasp devices.

### *D. Manipulation Duration*

16. Manipulations performed with a prosthetic device take longer than those performed with the intact hand (DW-1). This is significant for both prehensile (DW-4) and non-prehensile (DW-5) manipulations.
17. Power grasps last longer than pinch grasps for both the intact hand (DW-6) and prosthetic (DW-7).
18. Generally, manipulations used for transporting/carrying objects while walking lasted the longest. In prehensile grasps, this was the power grasp, in non-prehensile manipulations, this was 'hang/thread through' and 'clamp against body' (DW-10)
19. The spread of manipulation times is much wider with the prosthetic than the intact hand, within each participant (Fig. 9, Section 5.E.3).
20. TR amputees generally demonstrate shorter manipulation durations with their prosthetic than above-elbow amputees (DB-1).
21. Prehensile and non-prehensile manipulations had shorter durations for TR body powered device users than for TR myoelectric users (DB-2).
22. TR users of 1-DOF myoelectric devices exhibited shorter duration prehensile grasps than TR users of multi-DOF devices (DB-4). No difference of this sort was detected for above-elbow amputees (DB-5).
23. TR users of multi-DOF devices had insignificant duration differences for prehensile and non-prehensile manipulations, when compared to PE multi-DOF device uses (DB-7).

### *E. Discussion: Recommendations for Future Prosthetic Devices / Therapeutic Interventions*

Terminal device designers have typically focused on dexterity [54], often priding themselves on the variety of prehensile grasps that they can achieve (e.g. the iLimb Quantum product page states that 36 different grips are available [55]). However, this study found that non-prehensile manipulation dominates prosthetic device use in trans-radial amputees, regardless of type of terminal device used (Fig. 7 and Table 2).

Given our findings, we suggest that designers consider interaction surfaces of the hand/grip other than just the fingertips, and carefully consider the geometry and surface materials of these elements. The greater use of non-prehensile 'hang' manipulations by users of 1 DoF devices (Section V.C.3) supports the benefits of fewer points of articulation in some designs, which may also reduce points of weakness. Indeed, it may also be worthwhile to consider terminal devices in terms of their balance between prehensile and non-prehensile capability, with features at either end of the spectrum being beneficial in different ways.

The important role of non-prehensile manipulation in daily tasks also suggests that therapeutic training of new amputees or amputees with new terminal devices should include practice with non-prehensile tasks.

### *F. Future Work*

Additional and future work will build upon these initial findings. First, we will compare limb use between the persons with amputation detailed in this work and non-amputee control participants, who have also completed the at-home study scenario detailed in this work. The goal is to identify differences between intact/prosthetic and dominant/non-dominant limb-use across the two groups of participants, while also examining bi-lateral limb use patterns.

Second, we plan to make the video data used for this study publicly available, to allow future analysis by other research groups, the education of prosthetist / occupational therapists, or for other non-profit applications. This release will follow appropriate de-identification of the video data and publication of the unilateral amputee/non-amputee comparison study.

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## VII. Appendix

### A. *Taxonomy Manipulation Tag Description*

This section details the various tags of the Taxonomy of Upper Limb Intact and Prosthetic limb use (TULIP), which is illustrated in Fig. 4. The Taxonomy consists of four major branches, as denoted by the following sub-headings.

#### *1) Intact Hand*

The Intact Hand portion of the taxonomy is based on the GRASP taxonomy [43], which classifies 33 detailed hand grasps into 3 major categories of Power, Pinch (Precision) and Intermediate (Lateral) grasps. Additional categories of use were developed for our taxonomy to address non-grasp manipulation (e.g. non-prehensile use).

1. Power Grasp – An object is held in a caging grasp or one that prevents mobility.
2. Pinch Grasp – An object is pinched between fingers, enabling re-orientation.
3. Intermediate – A lateral prehensile grasp that may use features such as the side of the fingers e.g. when performing a key grasp.
4. Non-Prehensile – This includes interactions that do not involve grasping an object. For example pushing a door or drawer.
5. Move TD – This occurs when the intact hand is used to reposition the terminal device.
6. Other Intact Hand – This includes any other intact hand use that does not fit into above categories. This includes complex simultaneous actions such as holding an object while pushing a light switch. Fig. 4 illustrates someone picking up small objects (sunflower seeds) from within a jar.

#### *2) Prosthetic Prehensile*

Where objects are grasped (secured) using the prosthetic device.

7. Power Grasp – The object is held in a caged grasp where the fingers and thumb enclose the object, preventing mobility.
8. Pinch Between Forefingers – A thin object (such as a credit card) is held between the forefingers with no thumb contact. This was only possible with anthropomorphic hands with close finger proximity e.g. an iLimb Ultra with cosmetic glove.
9. Pinch Between Finger and Thumb – A precision grasp where the object does not contact the palm.
10. Pinch with Palm Rest – Here an object is pinched but also stabilized by partially resting on the palm. A pen may be held in this arrangement to facilitate typing on a computer keyboard.
11. Other Prehensile – any other prehensile grasp that does not fit into the other categories

#### *3) Prosthetic Non-Prehensile*

Using the prosthetic device to manipulate objects without grasping.

12. Pull – e.g. Pulling a door handle or drawer without grasping it. Participants often made use of hook like features or finger arrangements to achieve this. Note that pulling was only observed for constrained (rather than unconstrained) objects.
13. Push a Constrained Object – This applies to drawers, doors, handles, tap levers etc.
14. Push an Unconstrained Object – Pushing a ‘free’ object such as a cup resting on a table.
15. Stabilize an Object – Using the TD to reduce mobility of an object without engaging in a grasp. This often applied to bi-manual tasks such as steadying a cup while pouring coffee into it.
16. Hang from / Thread through TD – Hanging a coat hanger, fabric item (shirt, tea towel), etc. from or over the TD. Threading is when a ‘loop’ is made with finger / thumb of the TD that a cable may be threaded through. Observed as being used for cord handling when vacuuming.
17. Clamp Against the Body – Clamping the object between the arm and parts of the body, (typically the torso or legs).
18. Clamp Against Environment – Typically clamping the object against a stable environmental feature to reduce object mobility e.g. clamping a food item against a chopping board to stabilize it when cutting.
19. Support / Stabilize Body – Using the TD to lean on a chair back, counter etc. Also applies to using a bannister.

#### *4) Bi-lateral*

Activities that require both the intact hand and terminal device. These tags were applied *in addition* to tagging the unilateral actions of both limbs.

20. Bi-lateral Carry – Carrying an object (e.g. dinner plate, broom) using both the intact hand and TD.
21. Bi-lateral Action – Manipulating a single object (e.g. a broom) with both hands, or two objects related to the same action (e.g. a milk carton and cup – Fig. 1).
22. Transfer Object Between Hands – Passing an object from one hand to the other. Generally the intact hand placed or removed objects from the TD, though this was not always the case. The tag was started and ended by the arm motion related to the transfer, as the transfer itself is often instantaneous.

### *B. Home Instructions to Participants*

#### *1) Consent Form Instructions*

The following is an excerpt from the consent form, which provided the study instructions to the participants. These were deliberately kept brief to encourage self-selection of tasks.

*Participation in this study will involve wearing a camera attached to a head mount. […] You will be asked to wear the camera in your home and record your daily activities over the course of 8 hours. The 8 hours can be recorded over the course of 1-2 days and must include several activities of daily living. These activities are common household tasks such as preparing and eating food and cleaning your home. A list of qualifying activities will be given to you by the study team.*

*You will be taught how to stop the camera recording at times that you need privacy (for example when using the restroom or bathing). At the end of each day that you record your activities, you will be asked to complete a survey about your experience. When we review your video files, we will make sure to delete and/or hide any sensitive information that may be recorded. We ask that you please try to avoid filming other people in your home during this time.*

#### *2) Home Instructions*

The following instructions were provided to each participant at the start of the study. This consists of the list of qualifying activities mentioned in the consent form. Again, this was kept brief to encourage self-selection of tasks.

*We would like you to make sure you complete the following activities at least once during your time filming at your home:*

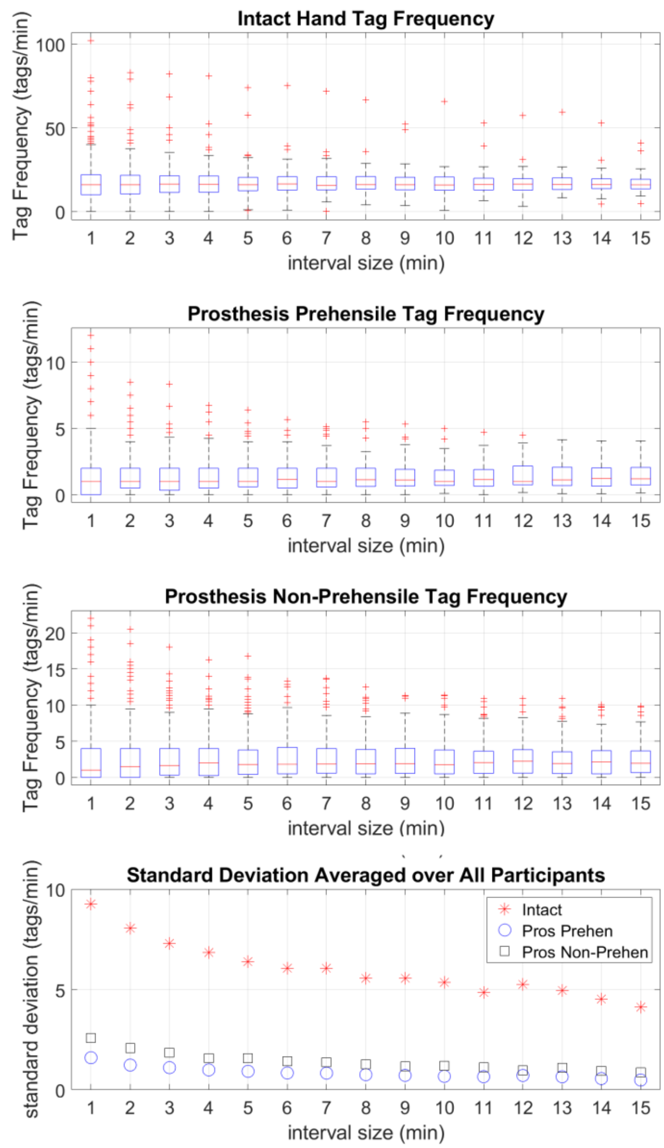
- *Make a cup of tea / coffee / other hot drink*
- *Drink the cup of tea / coffee / other hot drink*
- *Vacuum / sweep the floor in one room*
- *Brush teeth*

*We ask that during the course of filming, you keep the following activities to a minimum (less than 30 minutes):*

- *Watching Television*
- *Using a computer, tablet, e-reader or mobile phone (including smartphone)*
- *Playing video games*
- *Reading a book / magazine / other printed material*

*Note: The study staff may amend this list as needed on a case-by-case basis in order to meet the needs of the study and accommodate each study participant's needs.*

### *C. Interval Size Effect*




Appendix C. The boxplots of tag frequency for all participants show a decrease in the number of outliers when larger interval sizes are used. The scatter plot shows how the standard deviation averaged over all participants' changes based on interval size.