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Analyzing At-Home Prosthesis Use in Unilateral Upper-Limb Amputees to Inform Treatment & Device Design

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***Abstract*— New upper limb prosthetic devices are continuously being developed by a variety of industrial, academic, and hobbyist groups. Yet, little research has evaluated the long term use of currently available prostheses in daily life activities, beyond laboratory or survey studies. We seek to objectively measure how experienced unilateral upper limb prosthesis-users employ their prosthetic devices and unaffected limb for manipulation during everyday activities. In particular, our goal is to create a method for evaluating all types of amputee manipulation, including non-prehensile actions beyond conventional grasp functions, as well as to examine the relative use of both limbs in unilateral and bilateral cases. This study employs a head-mounted video camera to record participant's hands and arms as they complete unstructured domestic tasks within their own homes. A new *'Unilateral Prosthesis-User Manipulation Taxonomy'* is presented based observations from 10 hours of recorded videos. The taxonomy addresses manipulation actions of the intact hand, prostheses, bilateral activities, and environmental feature-use (affordances). Our preliminary results involved tagging 23 minute segments of the full videos from 3 amputee participants using the taxonomy. This resulted in over 2,300 tag instances. Observations included that non-prehensile interactions outnumbered prehensile interactions in the affected limb for users with more distal amputation that allowed arm mobility.**

I. Introduction

Significant prior efforts have been made to better understand the function and use of unimpaired human hands [1], [2]. Initially motivated by biomechanical and rehabilitation fields, such research has more recently been applied to robotic gripper design (e.g. [3]). In particular, taxonomies of intact hand grasp types have been used to categorize hand interactions with the world [2]. An overview of such taxonomies may be found in [1] .

Despite the establishment of various methods for understanding healthy human hand function, relatively little literature is dedicated to examining object manipulation strategies when using hand substitutes, e.g. Upper Limb (UL) prosthetic Terminal Devices (TDs), particularly after long-term usage and in unstructured environments. This is surprising, given that UL prosthetics has been an active area of research and development in biomedical, therapeutic and engineering fields for many years. A result of such research has been a wide variety of prosthetic TDs (e.g. [4]–[6]). However, follow-ups of how such devices' are practically and specifically used has been limited outside of the laboratory. Further motivation for the need of such understanding comes from well-known high prevalence rates of (both body powered and myoelectric) device abandonment or limited use in amputee populations [7], [8]. Many standardized methods exist of evaluating capability of a user to perform functional ADL (Activity of Daily Living) tasks with a UL prosthetic device (e.g. [9], [10]). However, these tests are typically directed at highly specific tasks under instruction of an experimenter and may not cover the wide range of usage found in unstructured daily-life scenarios.

Figure 1: A video screenshot from the head-mounted camera (for participant P2).

A notable recent effort in classifying prostheses use has been the development of grasp-based and force-based taxonomies of 'split-hook' TDs, a simple but highly popular body-powered prosthetic [6]. Though the provided structure of these taxonomies delineates a comprehensive number of grasps, these are specific to a particular type of TD with unique mechanical features, and are not generalizable beyond this device type, e.g. into anthropomorphic TDs.

In this paper we report on the development of a general purpose taxonomy of prosthetic device use for unilateral amputees that can be applied to users of a variety of UL prosthetic systems, from wrist and hand substitutions of transradial (TR) amputees, to full arm systems of amputees with shoulder disarticulation. In addition to standard grasping considerations, we believe that this new taxonomy should encompass other UL manipulation actions performed by amputees. For example, we have observed that TDs are often used for non-prehensile pushing, support or stabilization of objects. Such interactions must be acknowledged when anticipating and optimizing new device designs, which frequently tend to focus primarily on grip functions (e.g. [5]). Indeed, given the difficulties with controlling complex prosthetic devices [11], [12] it may be that improving non-

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Figure 2: A head-mounted camera recorded participant's arms and hands during unstructured daily activities for up to 2 consecutive hours.

prehensile object interactions is an important and more easily achievable goal than extending grasp-type variety.

In summary, the overall goal of this work is to provide a comprehensive taxonomy of relevant manipulation strategies that can be referenced by persons such as engineers, prosthetists and occupational therapists, to facilitate better device design, assignment and training. This has been attempted in the development of the *Unilateral Prosthesis-User Manipulation Taxonomy,* whose formulation and initial application is described in the following section.

II. Methods

A. Equipment

In a similar approach to that used in [13]–[15], our data capture method involves an unobtrusive wide-angle, head-mounted video camera aimed downwards to capture the hands and arms of participants as they completed daily tasks within their own homes, independent of an experimenter. Unlike studies [13]–[15], which observed able-bodied professionals (housekeepers and machinists) during their working hours, our current work focuses on participant's completing mostly unstructured domestic tasks. The completion of tasks such as food preparation, cleaning and laundry are important for independent living, which is a goal of intervention for those with a limb deficiency. Indeed, standardized measures of manipulation capability simulate such tasks as part of their battery of tests [9], [10].

For the camera, we utilized a *GoPro Hero 3+ Silver* with a secure head strap, as used for extreme sports recording (Figure 1). The camera case and head-strap was modified to enable connection of an external USB power bank (for cell phone charging). This modification enabled 3hours of high-resolution widescreen video recording (at 2716×1524 pixels and 30fps) on a single 64Gb SD card as opposed to ~40minutes of recording with the built in battery. The power bank was selected for size, weight and power density (105×45×22mm, 134g, 6,400mAh) and fit within a participant's trouser pockets.

B. Experimental Method

The experimenter using an Android tablet to remotely view the output of the GoPro while positioning the camera on the participant's head. Once the camera was suitably aligned, participants were instructed in how to stop and start the video recording by using the intact hand to press a button on the top

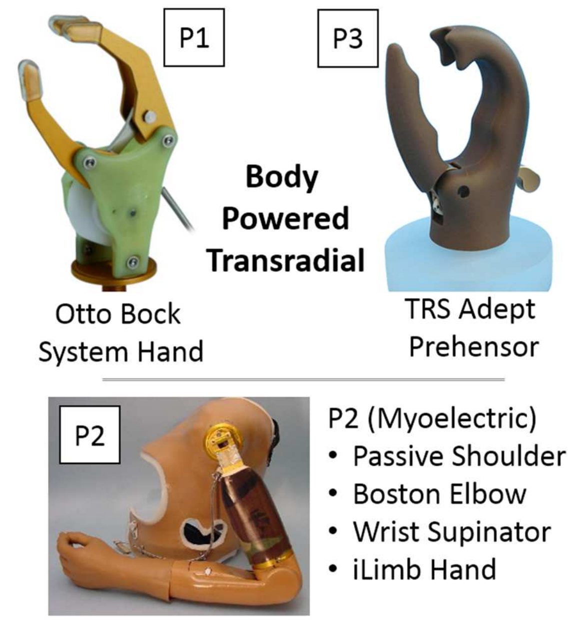

Figure 3: Participant prosthetic devices. All participants have used their device every day for over 6 months.

of the camera, should they require privacy. A GoPro wireless remote control was tested for this function but proved unreliable. Once setup was complete the experimenter started the recording then left the participants home.

Participants were requested not to leave their home during the study (for example, they could not go shopping), but were permitted to go to outside to their yards. They were requested not to spend more than 30 minutes of the day watching television, using a computer/tablet/smart phone or reading, as these activities involve limited manipulation. They were also requested to complete the following actions:

1. Make and drink a hot drink
2. Brush their teeth
3. Sweep / Vacuum the Floor.

Note however that all participant's completed these actions in different manners. E.g. task 1 varied between participants depending on whether they were drinking coffee or tea and which appliance they used (*'Keurig'*, microwave or drip coffee maker) to prepare the drink. This variation of course applied to all recorded activities, because possessions, room layouts personal preferences varied across individual and homes.

This study was ethically approved by the Yale University Human Subjects Committee HSC #1408014459.

B. Participants

To date, three unilateral amputees have participated in this study. Recruitment of suitable individuals has proven more difficult than first anticipated, though the study is ongoing and additional participants will be recruited in the future. Because a goal of our work is to investigate expert prosthesis use, our recruitment criteria specifies that all participants must have used their device every day for at least 6 months. Indeed, all of our participants have had their

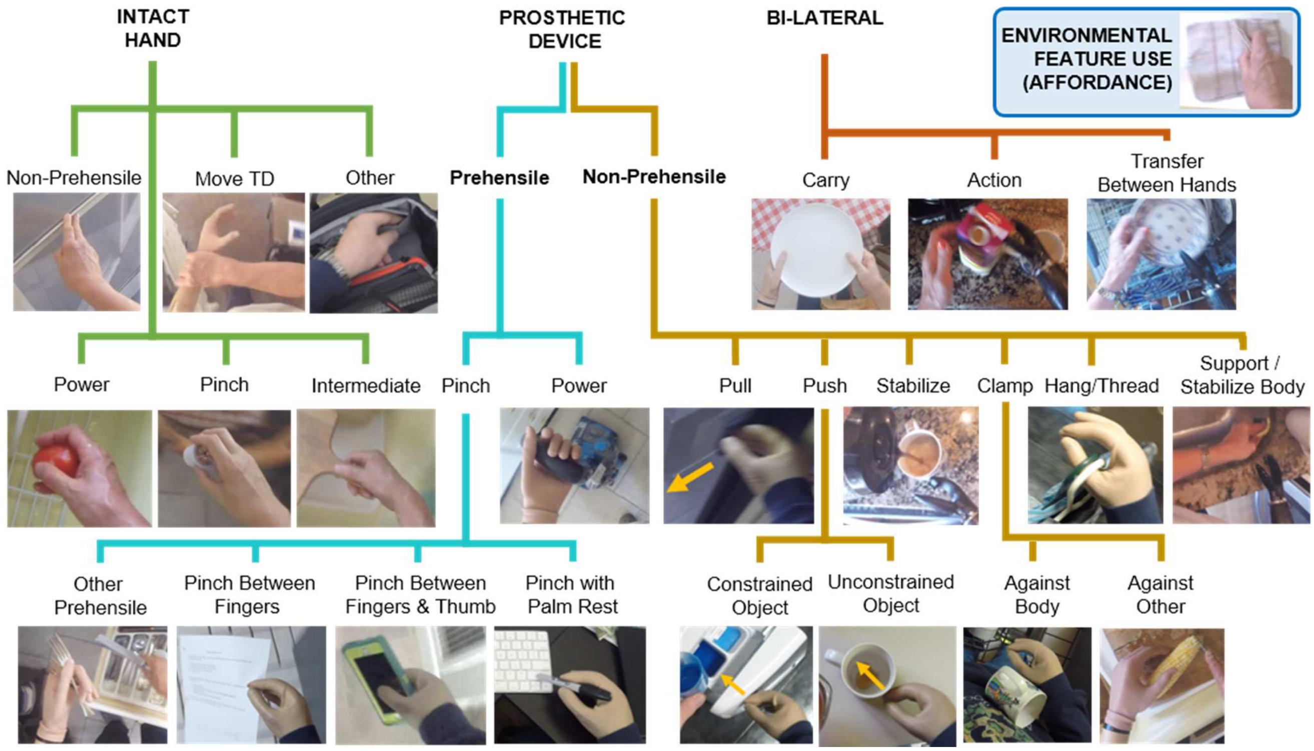

Figure 4: The Prosthesis-User Manipulation Taxonomy. The Top-level categories of manipulation actions are not mutually exclusive. E.g. a bi-lateral action will involve manipulation tags for both hands and may also use environmental features to assist with object stability (affordance use). Note that Environmental Feature Use may apply to any category.

devices for several years. Many amputees have prostheses, but do not use them frequently [7], [8].

The three participants are described below. Details of their prosthetic devices are shown in Figure 3.

P1 – Male, Age 49, who is a congenital transradial amputee. Uses a Body Powered *Otto Bock System Hand* (three fingered) with cosmetic glove. The hand is powered via a shoulder harness.

P2 – Male, Age 69, with a shoulder disarticulation resulting from a traumatic injury over 20 years prior. Uses an arm-hand system compromising of a *Boston shoulder* (passive 2 DOF flexion and abduction with chest mounted locking switch), *Boston powered elbow*, *Otto Bock active wrist rotator* and *iLimb* multigrasp hand with cosmetic glove. The system has myoelectric electrodes on the front and back of the molded torso harness (Figure 3). Co-contraction allows switching between the powered DOF (elbow, wrist or hand), allowing independent proportional control. The participant also has a myoelectric split hook grasper (a *Motion Control ETD*) which he did not make use of during this study.

P3 – Female, Age 60, who is a congenital transradial amputee. Uses a body powered *TRS Adept Prehensor* (two fingered formed grasper) without a cosmetic glove. The Body powered cable is anchored to an adhesive patch on the participant's back.

III. Data Analysis

A. Taxonomy Creation

The three participants each contributed the following video lengths: P1 - 1h50m, P2 – 4hs, P3 – 4h. The videos covered a wide range of activities, including food preparation, cleaning, laundry, packing (luggage) and gardening. The videos were viewed by the research team, at increased speed for certain portions, with notes made on usage of the manipulation approaches by the unimpaired and impaired limb during a variety of tasks. In particular, categories were created and refined to define the observed manipulation activities. The final results led to the generation of the 'Unilateral Prosthesis User Manipulation Taxonomy', illustrated with examples in Figure 4, which addressed all types of hand and arm usage observed across both the intact and prosthetic limbs. The category of 'other' was included for unclear or difficult to define actions (typically a result of poor camera visibility due to occlusion, light or actions occurring outside the cameras field of view).

The taxonomy consists of 4 portions: Intact Hand Use, Unilateral Prosthesis Use, Bi-Lateral Interactions and Environmental Feature Use. These categories of activity are not mutually exclusive and often overlap. In some examples of Figure 5, bi-manual tasks are shown that simultaneously demonstrate prehensile intact hand use and non-prehensile prosthetic device use. Sometimes this is combined with environmental feature use e.g. bi-manual cutting of sweetcorn by non-prehensile pinning against a chopping board with a TD's thumb, while the intact hand grasps a knife (Figure 4). The categories of the taxonomy will now be explained below.

The <u>Intact Hand</u> portion of the taxonomy is based on the GRASP taxonomy [1], which classifies 33 detailed hand grasps into 3 major categories of Power, Intermediate (Lateral) and Precision grasps. Additional categories of use

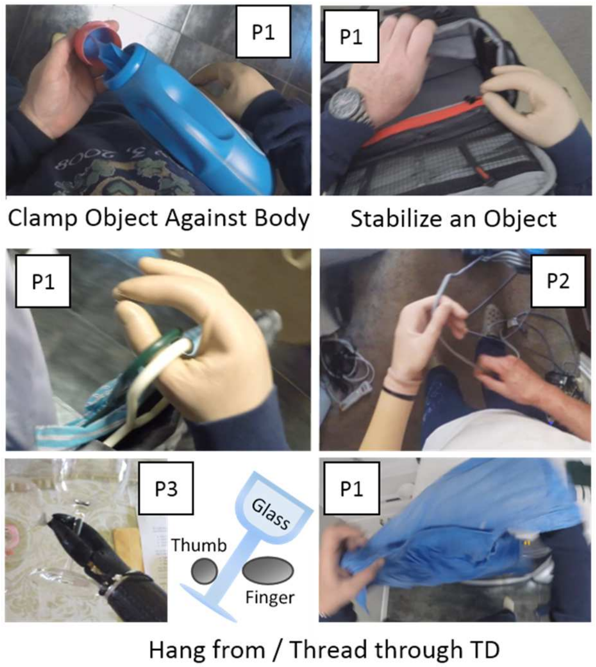

Figure 5: A sample of non-prehensile object interactions. In the top right image the flap of a bag is being held open. In the bottom left image the stem of a wine glass is much smaller than the closed grasp aperture, hence the glass 'hangs' from within the TD.

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 without using the handle.
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. Figure 4 illustrates someone picking up a small object while reaching into a bag's pocket with forefingers.

The Prosthetic Device portion is split into two sections.

Prehensile - Where objects are grasped (secured) using digits.

7. Power Grasp – The object is held in a caged grasp where fingers enclose the object
8. Pinch Between Forefingers – A thin object is held between the forefingers with no thumb contact. This only applied to the anthropomorphic hands of P1 and P2.
9. Pinch Between Finger and Thumb – A precision grasp that does not contact the palm.
10. Pinch with Palm Contact – This occurs when holding a pen.
11. Other Prehensile – any other grasp

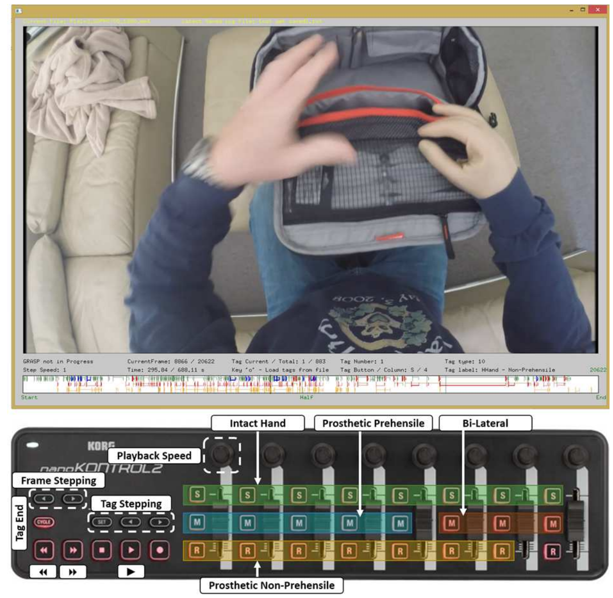

Figure 6: A screenshot from the custom video player software (top). Logged tags are shown in the playback progress bar. A hardware midi interface (below) is used to precisely control video playback and tagging.

Non-Prehensile – Using the prosthetic device to push, clamp or otherwise act on objects without grasping. Several examples are given in Figure 5.

12. Pull an object – e.g. Pulling a door handle or drawer. Note that pulling was only observed for constrained (rather than unconstrained) objects.
13. Push an unconstrained object – Pushing a 'free' object such as a cup resting on a table
14. Push a constrained object – This applies to drawers, doors, handles, tap levers etc.
15. Stabilize an object – Using the TD to reduce mobility of an object without engaging in a grasp. Often applies in bi-manual tasks such as keeping a steadying a cup into which coffee is being poured, or holding a bag open (Figure 5).
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 used for cord handling when vacuuming (Figure 5).
17. Clamp against the body – Typically clamping the object between the TD and torso or legs. Forms a grasp without using the TD.
18. Clamp against environment – Typically against an immobile 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 – Leaning on a counter, chair back or using a bannister with the prosthesis.

Bi-lateral – Activities that require both the intact hand and terminal device. These tags are applied in addition to tags for the actions of both hands.

20. Bi-lateral Carry – Carrying an object (e.g. dinner plate, broom) using both the intact hand and TD.

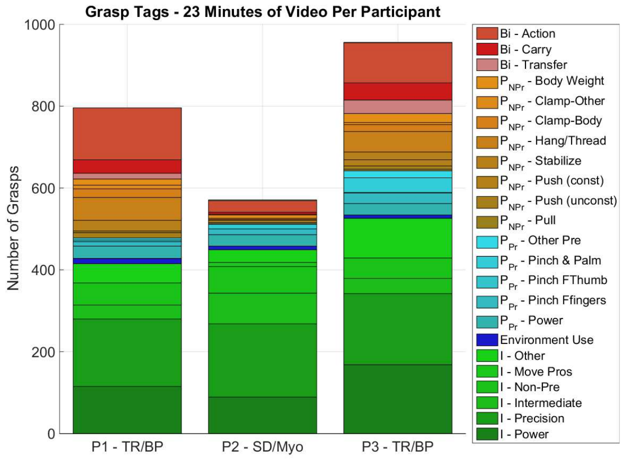

Figure 7: Tag frequency across participants. I refers to the intact hand. P_{Pre} and P_{NPr} refer to prehensile and non-prehensile prostheses use. Bi is Bilateral.

21. Bi-lateral Action – Manipulating a single object (e.g. a broom) or two objects related to the same action (e.g. coffee pot and cup, as in Figure 4's *Stabilize* example) with the intact hand and TD simultaneously.
22. Transfer object between hands – Generally the intact hand places or removes an object from the TD, though this is not always the case. The tag is started and ended by the arm motion related to the transfer, as the transfer itself is often instantaneous.

Environmental Feature Use – Environmental features may be used to assist with object stability or mobility. E.g. folding a hand towel by first placing it on a surface, as opposed to folding it 'in-the-air' using both hands. Such environmental feature use is also known as 'Affordance Use' and has been exploited in robotic manipulation [16]. Environment feature use also includes using object inertia or gravity to aid manipulation. E.g. P2 arranged loops in a power cord by 'flicking' parts of the cord into the air and onto itself.

23. Environmental Feature Use across either or both hands.

B. Video Tagging Software

The construction of the taxonomy allowed the manipulations observed from the videos to be objectively categorized in terms of frequency and timing. As it was clear that manipulation activities were extremely dense in portions of the videos, custom video 'tagging' software was created to simplify this task (Figure 6).

The video tagging software was created in C++ using the *openFrameworks (OF)* library. The software uses a *Korg NanoKontrol 2* Midi controller to playback videos in forward and reverse directions, with enhanced control over playback speed and the option for frame-by-frame stepping. The NanoKontrol 2 also has 24 buttons that are pressed to indicate the start of taxonomy tags at given points in the video. A general 'Tag End' button is used to indicate when an action terminates. Though the taxonomy is made up of 23 tags at the moment, we are aware that other tags may require addition if new scenarios are encountered with future study participants. In this case we are able to select different functions of each button by turning the knobs also located on the controller.

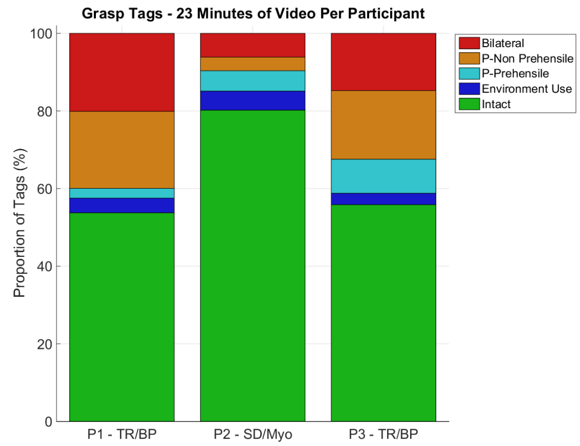

Figure 8: Overall tag distribution by group per participant, as a proportion of 100% of their recorded tags. P2 uses their intact hand more than other users.

The recorded tag start and end markers are visually indicated to the user via the progress bar of the software GUI (Figure 6). As tags are recorded, a .csv log file is created of the tag type and start / end frame numbers. This can be loaded back into the software for further editing, or read into MATLAB for analysis.

C. Video Analysis

While recording, the GoPro camera automatically splits lengthy video recordings into smaller segments. These segments are each 11minutes 38seconds in length. As a preliminary data set for analysis with the taxonomy we selected two segment from each of the three participants' videos. These segments were selected to involve the densest manipulation actions per participant and resulted in a total of 2,320 tags over the 23minute 16seconds period. Each segment took between 2-5 days to process by an experimenter using the custom software. Due to the unstructured nature of the experiment, the activities within each segment were of course different, limiting options for direct comparison between participants. Participants did not however 'rest' during any of the selected segments, while in other segments they briefly watched television or read magazines. The selected videos included activities of vacuuming, sweeping, unloading a dishwasher, preparing a salad (washing and cutting vegetables), packing a bag, wiping surfaces, making coffee and doing laundry.

IV. Results

The output files of the video tagging software were analyzed in MATLAB with results shown in Figures 7-10. Colors have been kept consistent for ease of cross-referencing.

A. Tag Category Analysis

Figure 7 shows the cumulative tags for the three participants while Figure 8 shows the same data grouped into major categories and scaled as a proportion of 100% of tags (per participant). This data is also presented numerically in Table 1. It is clear that the intact hand dominates (over 50%) in manipulation activities for all individuals.

TABLE 1: BREAKDOWN OF ALL TAGS BY MANIPULATION CATEGORY ACROSS PARTICIPANTS

	P1		P2		P3	
	Count	% of Total	Count	% of Total	Count	% of Total
Healthy Hand	428	53.8%	458	80.2%	534	55.9%
Prosthetic Prehensile	20	2.5%	30	5.3%	84	8.8%
Prosthetic Non-Prehensile	158	19.8%	20	3.5%	169	17.7%
Bi-manual	160	20.1%	35	6.1%	141	14.7%
Affordance	30	3.8%	28	4.9%	28	2.9%
Total	796	100%	571	100%	956	100%

P1 and P3 (who both have body-powered prostheses and are transradial amputees) have similar breakdown in their manipulation technique categories. Both have intact hand use in the 53-66% range, TD prehensile grasps of less than 9% and non-prehensile actions between 17-20%. P2, who is has a much more proximal amputation performs less manipulation overall (less than half the tags of P3) and has greater reliance on his intact hand. In general P2's prosthesis is much slower to position and use, as only one active degree of freedom may be controlled at a time and the shoulder has no active control. This is likely to be the reason for P2's lower use of non-prehensile actions, which generally involve arm dexterity to position, push, pull and clamp (etc.) with a prostheses. The other participants use their shoulder and elbow for such actions, while P2 is limited to an active elbow and needs to use his torso for arm positioning above elbow flexion. P2 also makes use of environmental affordances more often than the other participants. Indeed, the reduced capability of the impaired limb to perform non-prehensile stability tasks led to many instances where the environment fulfilled such a requirement.

It is interesting to note that P2's prehensile actions with his prosthesis are more frequent than those of P1. Indeed, though P2 has reduced and slower arm mobility, he does use a sophisticated multi-grasp TD (an iLimb) with five powered fingers and adaptive grasps. This permits a wider range of objects that can be held, irregular object stability and a larger grasp aperture than can be achieved with P1's body powered TD (an Otto Bock System Hand with Glove). P3's device is the most limited in terms of grasps (due to only having a single finger and thumb), but can achieve the widest aperture and has various notches on the fingers to aid precision (Figure 3) grasping. It was noted that P3 was the quickest at performing dexterous bi-manual tasks (such as unscrewing a bottle) with their TD.

If we consider the amount of prosthesis use from Table 1 that is bi-lateral (calculated as bilateral / (prehensile + non-prehensile)), we obtain the following proportions P1 = 90%, P2 = 70%, P3 = 56%. P1, uses their prosthesis almost entirely for bi-lateral tasks while P2 and P3 perform many more unilateral tasks.

B. Specific Tag Analysis

A lateral breakdown of specific manipulation tags (from

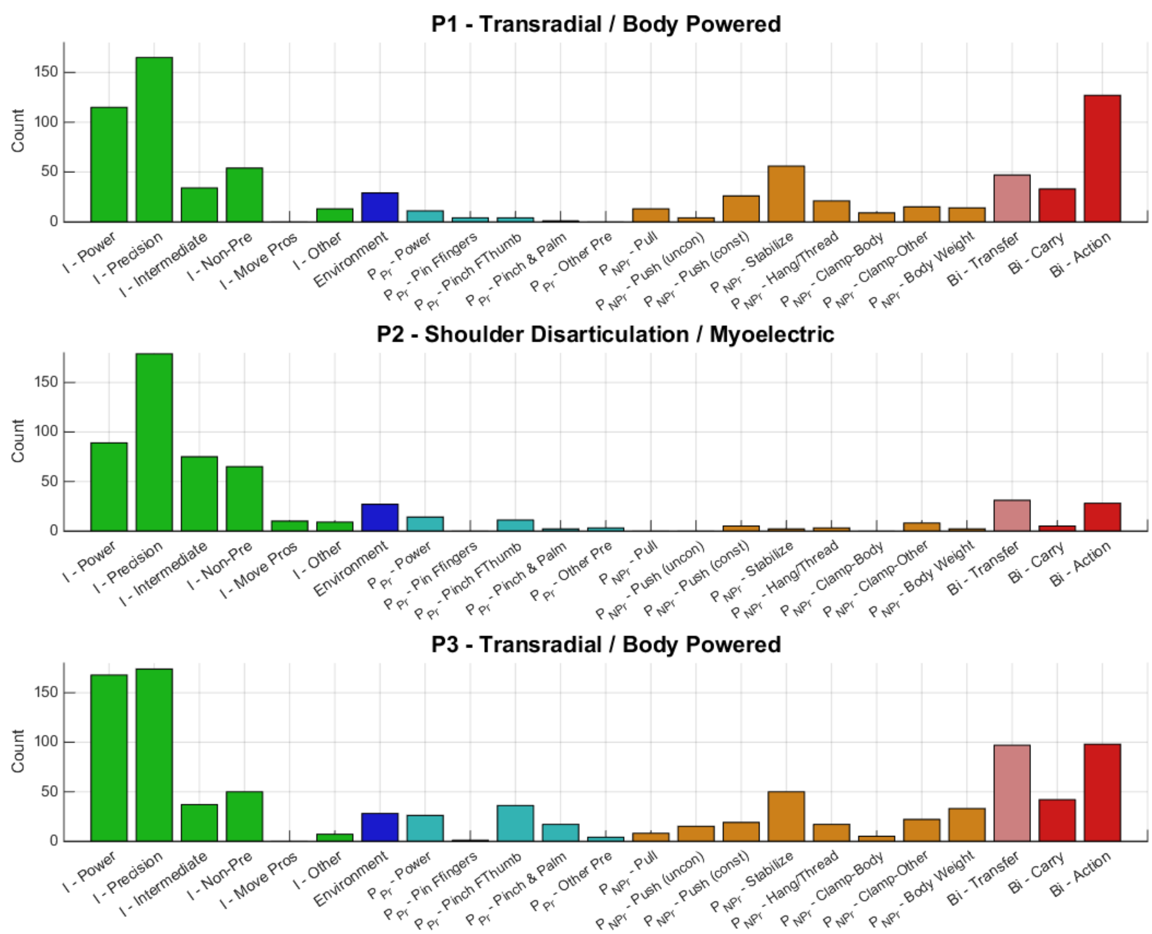

Figure 9: Frequency of different manipulation tags across the participants during the analyzed videos.

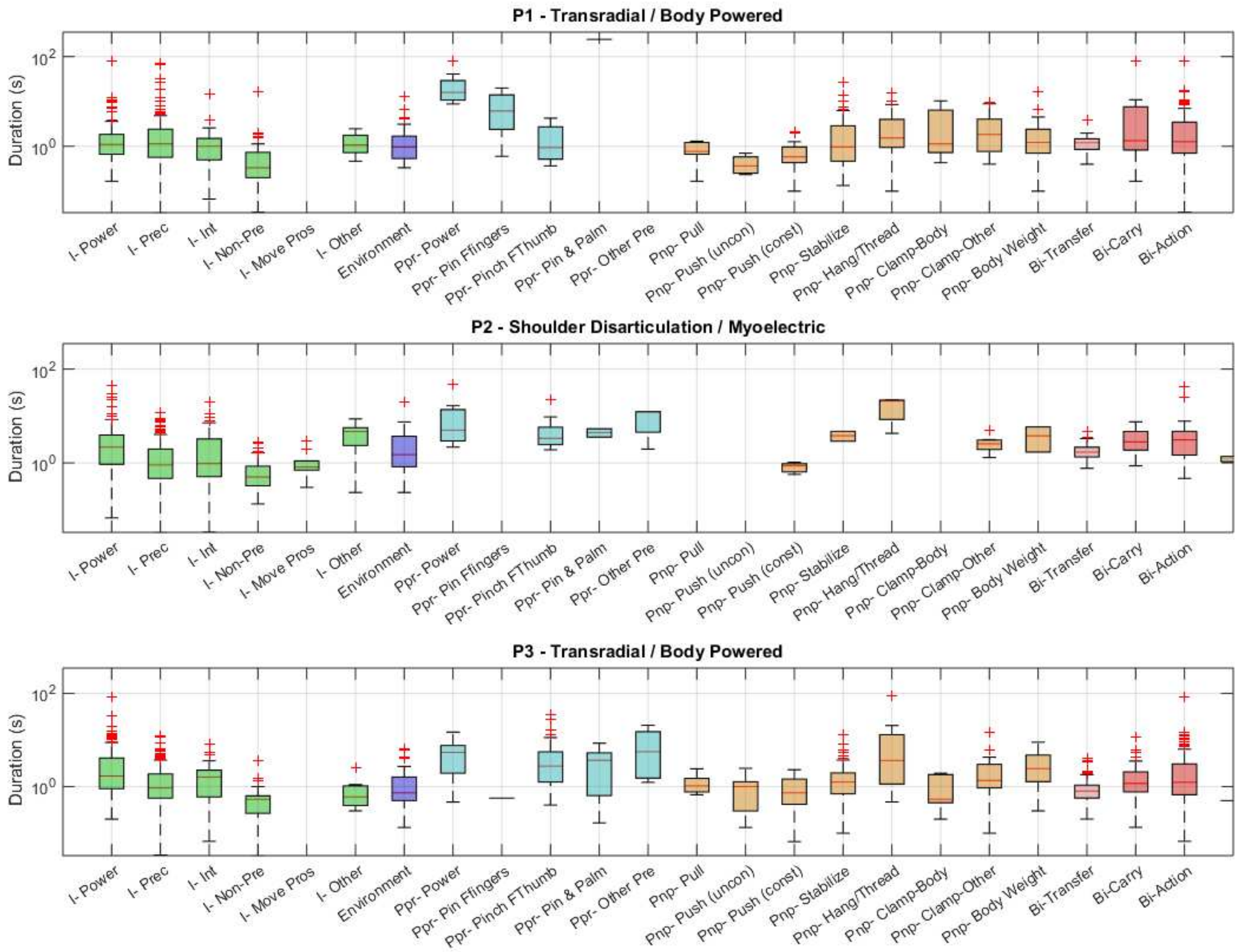

Figure 10: Tag length distribution. Note the time scale is logarithmic.

Figure 7) is presented in Figure 9. Here we see that the intact hand is primarily used for Power and Precision grasps across participants, with limited Intermediate and non-Prehensile use. Indeed, this expected breakdown resembles the major design motivations of many TDs [5]. Despite this intuitive goal of hand design, it is clear that TD use is distributed much more widely across a variety of use categories. It appears that P3 performs the most diverse prehensile motions despite having only a 2 fingered TD. This may be due to both the wide aperture and notched design of her TD in combination to her body powered system, which allows quick motions and haptic feedback. P1 is the only participant who makes use of the passive grip between fingers, which he used for carrying paper and envelopes.

It has already been mentioned that non-prehensile actions outnumber prehensile grasps for the body powered TR participants. In Figure 9 we can see that the most frequent non-prehensile function is to stabilize an object (typically as part of a bi-lateral action), with pushing, handing and clamping objects also occurring often (as unilateral tasks).

Within the Bi-manual group, transferring an object between hands occurs more often than carrying an object with both hands simultaneously. Bi-lateral actions are activities where both hands perform a functional task simultaneously. These are tagged at the same time as individual action tags for both the intact hand and TD.

C. Tag Timing Analysis

Boxplots showing the timing distribution of all recorded tags are presented in Figure 10. Note that the intact hand use is quite consistent across all participants, with a similar range of timings across all tags.

A notable observation is that prehensile grasps with the prosthetic hand tend to last longer than other manipulation actions. The videos illustrated that TDs would often be used to carry (transport) objects in a fixed grasp for extended periods of time (e.g. when moving across or between rooms). In both P1 and P3, the TDs are active opening, meaning effort must be expended to open the hand, while a spring holds it closed. For P2, the iLimb requires no effort to hold a position, but additional effort to open or close. The low-energy states of all hands therefore lend themselves well to holding static poses, such as when carrying an object. As power grasps are more stable then precision grasps it seems sensible that these should be used for longer transport task. An exception is P1’s singular lengthy holding of a pen in their TD for several minutes.

In the non-prehensile grasps, the ‘Hang Grasp’ (in which objects are hung from or over the TD) are also used for transport (Figure 6 shows coat hangers hung from a TD's Thumb), leading to lengthy tag times. Shorter hang grasps occurred when participants folded fabrics over their TDs (e.g. when doing laundry or folding a tea-towel). In comparison, the actions of pushing and pulling objects are relatively short. Clamping actions had a wide range of times for P1 and P2 and often formed part of bilateral tasks (see Figure 6).

Bi-manual transfer tasks were recorded as relatively short, despite being recorded as the start and end of the arm motions responsible for the transfer of the objects.

CONCLUSION

This paper presents the preliminary findings of our work in trying to understand natural prosthetic device use by unilateral amputees in daily life. Though past work has studied prosthesis use, to our knowledge this is the first attempt at establishing a generally applicable (across different prostheses) method of manipulation categorization and quantification outside of a laboratory or clinical setting.

Our work has so far collected almost 10 hours of head-mounted video from three expert unilateral prosthesis-users. Studies of these videos generated a taxonomy of manipulation tags for both intact and impaired limbs. This taxonomy was then applied to the analysis of video samples (11m40s each) to identify manipulation strategies across different participants.

Our work is on-going and at present our specific tagging analysis is limited to short videos from three individuals, so should not be considered as representative of larger populations or all actions. However, some notable findings follow: 1) Use of the intact hand dominates across all participants. 2) 'Typical' prehensile grasps with a TD are often used for carrying objects for longer times than the intact hand. 3) Non-prehensile manipulation actions are used more often than prehensile actions for body-powered device users with arm mobility. Such actions include pushing objects with the outside of fingers, hanging objects from the hand, threading cables through a closed grasp aperture and clamping objects using the forearm. 4) The prostheses were frequently used for bi-manual tasks beyond carrying, where they took a secondary role to the intact hand. Such actions include stabilizing objects that the intact hand is manipulation. 5) A multi-grasp TD facilitated improved prehensile grasping for a participant with low arm mobility.

These findings are intended to help inform the design of new devices and therapeutic interventions / training. Though future data capture and analysis is planned, which will lead to further information, initial recommendations are that more emphasis be placed on the non-prehensile design and training with prosthetic devices. For example, designers may wish to add compliant finger-pad-like surfaces and tactile features to the outside of TD fingers, to facilitate object pushing and clamping. Furthermore, strengthening lateral stress capability, or adding compliant mechanisms in TD fingers could enable further non-prehensile hanging, clamping and pushing without fear of damaging the TD. We recommend also that emphasis is placed on strategies of non-prehensile manipulation strategies by therapists who aim to increase functionality for amputees. Indeed, such manipulation could be a highly beneficial 'low-hanging fruit' with regard to improving amputee function without complex, costly or technical interventions.

ACKNOWLEDGEMENTS

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REFERENCES

[1] T. Feix, J. Romero, H. B. Schmiedmayer, A. M. Dollar, and D. Kragic, "The GRASP taxonomy of human grasp types," *IEEE Transactions on Human-Machine Systems*, vol. 46, no. 1, pp. 66–77, 2016.

[2] I. M. Bullock, S. Member, J. Z. Zheng, S. D. La Rosa, C. Guertler, and A. M. Dollar, "Grasp frequency and usage in daily household and Machine Shop Tasks," *IEEE Transactions on Haptics*, vol. 6, no. 3, pp. 296–308, 2013.

[3] I. M. Bullock and A. M. Dollar, "A two-fingered underactuated anthropomorphic manipulator based on human precision manipulation motions," *Proceedings - IEEE International Conference on Robotics and Automation*, 2016

[4] J. Zuniga, D. Katsavelis, J. Peck, J. Stollberg, M. Petrykowski, A. Carson, and C. Fernandez, "Cyborg beast: a low-cost 3d-printed prosthetic hand for children with upper-limb differences.," *BMC Research Notes*, vol. 8, no. 1, p. 10, 2015.

[5] J. T. Belter and A. M. Dollar, "Performance Characteristics of Anthropomorphic Prosthetic Hands," *IEEE International Conference on Rehabilitation Robotics (ICORR), 2011.*

[6] J. T. Belter, B. C. Reynolds, A. M. Dollar, and I. S. Member, "Grasp and Force Based Taxonomy of Split-Hook Prosthetic Terminal Devices," pp. 6613–6618, 2014.

[7] E. a Biddiss and T. T. Chau, "Upper limb prosthesis use and abandonment: a survey of the last 25 years.," *Prosthetics and Orthotics International*, vol. 31, no. 3, pp. 236–57, Sep. 2007.

[8] L. V McFarland, S. L. Hubbard Winkler, A. W. Heinemann, M. Jones, and A. Esquenazi, "Unilateral upper-limb loss: satisfaction and prosthetic-device use in veterans and servicemembers from Vietnam and OIF/OEF conflicts.," *Journal of rehabilitation research and development*, vol. 47, no. 4, pp. 299–316, 2010.

[9] L. Resnik, L. Adams, M. Borgia, J. Delikat, R. Disla, C. Ebner, and L. S. Walters, "Development and evaluation of the activities measure for upper limb amputees.," *Archives of physical medicine and rehabilitation*, vol. 94, no. 3, p. 488–494.e4, Mar. 2013.

[10] C. M. Light, P. H. Chappell, and P. J. Kyberd, "Establishing a standardized clinical assessment tool of pathologic and prosthetic hand function: Normative data, reliability, and validity," *Archives of Physical Medicine and Rehabilitation*, 2002.

[11] A. Fougner and O. Stavdahl, "Control of upper limb prostheses: terminology and proportional myoelectric control—a review," *Neural Systems and Rehabiliation Engineering*, 2012.

[12] F. Tenore, A. Ramos, and A. Fahmy, "Towards the control of individual fingers of a prosthetic hand using surface EMG signals," *Engineering in Medicine and Biology Society,* 2007.

[13] I. M. Bullock, S. Member, T. Feix, and A. M. Dollar, "Finding small , versatile sets of human grasps to span common objects," *Proceedings IEEE International Conference on Robotics and Automation,* pp. 1068-1075, 2013.

[14] T. Feix, I. M. Bullock, and A. M. Dollar, "Analysis of human grasping behavior: Object characteristics and grasp type," *IEEE Transactions on Haptics*, vol. 7, no. 3, pp. 311–323, 2014.

[15] T. Feix, I. M. Bullock, and A. M. Dollar, "Analysis of human grasping behavior: Correlating tasks, objects and grasps," *IEEE Transactions on Haptics*, vol. 7, no. 4, pp. 430–441, 2014.

[16] N. C. Dafle, A. Rodriguez, R. Paolini, B. Tang, S. S. Srinivasa, M. Erdmann, M. T. Mason, I. Lundberg, H. Staab, and T. Fuhlbrigge, "Extrinsic dexterity: In-hand manipulation with external forces," *Proceedings - IEEE International Conference on Robotics and Automation*, pp. 1578–1585, 2014.