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TITLE: **Studying Upper-Limb Amputee Prosthesis Use to Inform Device Design**

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

The proposed project investigates the nature of upper limb prosthesis use in everyday tasks through in-home and lab-based studies on upper-limb amputees and matched unimpaired subjects.
During the second year we recruited amputee participants and completed several at-home portions of the study. A study of the resulting videos led to a new prosthetics-use taxonomy that is generalizable to various levels of amputation and terminal devices. The taxonomy was applied to classification of the recorded videos via custom tagging software with midi controller interface. The software creates Matlab-readable log files. Motion capture development of a body compensation experiment and kinematics based metric were also made.
In the next year recruitment of amputee and able bodied participants will continue in an effort to complete more studies and generate data for analysis.

15. SUBJECT TERMS

Upper Limb Prosthetics, Amputee, Assistive Technology, Motion Capture

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1. INTRODUCTION

The proposed project centers on investigating the nature of upper limb prosthesis use in everyday tasks through both an in-home and lab-based study on upper-limb amputees and age and gender-matched normal subjects. For the in-home study we will use an unobtrusive head-mounted camera to record and then later observe prosthesis/hand use during domestic tasks. In the lab study we will use a motion capture studio and video cameras to record accurate and detailed upper body motion during a series of standardized tasks. These tasks are clinically validated measures of hand / arm function functional evaluation. By recording participant performance and examining prosthesis/hand use, we expect to identify shortcomings in current prosthetic terminal devices and implementations that will inform improvements to existing designs and inspire new classes of devices in the future.

2. KEYWORDS

Upper Limb Prosthetics, Amputee, Assistive Technology, Motion Capture

3. ACCOMPLISHMENTS

This reporting period covers the fourth year of the project. This portion of the project has focused on video data and motion study data acquisition and analysis in amputee and unimpaired subjects.

What were the major goals of the project?

The major goals of this project were observing the upper limb manipulation techniques used by numerous upper limb prosthesis wearers and 'healthy' individuals (i.e. those with intact upper limbs) when achieving a variety of tasks in unstructured (in their own home) and structured (in the lab) environments. Comparing data from these demographics over the different tasks and environment we aim to determine differences in manipulation techniques between prosthesis wearers and the healthy 'baseline'. In particular we wish to identify the shortcomings of particular prosthetic devices or setups while looking for methods employed by prosthesis users to overcome these limitations.

Originally the study proposed the use only of head-mounted cameras for observation. This was extended to include a motion capture system capable of accurately recording upper body motion to provide much richer movement data. The motion capture setup will be used only in the laboratory setup, due to the complexity of the measurement equipment and relatively limited capture volume.

What was accomplished under these goals?

In the **first year** we prepared measurement equipment and the necessary protocols to enter participants into our study. In particular the following achievements were made:

1. Experimental protocols were finalized
2. The protocol was approved by IRBs for all institutions and the DoD. Necessary human subjects training was also completed for relevant members of the study team.
3. The head-mounted camera setup has been established (a GoPro Hero 3+, modified to accept an external pocket sized battery – giving 6 hours of recording time instead of 30 minutes with the internal battery).
4. Software to aid analysis of the head-mounted camera data was prototyped

5. A Vicon optical motion capture system was selected (after reviewing several options), purchased and installed in the laboratory space of Yale University
6. Extensive familiarization with the Vicon system was completed. This began with on-site training from a Vicon representative but since then has led to the following:
    a. Optimized camera placement (13 cameras in a 5x5m space) for bi-manual upper body capture when standing or seated. This also involved installing mounting rails in the laboratory
    b. Optimized marker placement for robustness to marker occlusions (when motion capture markers are hidden from view in particular body poses). This includes flexible, wearable marker clusters and custom software methods to reconstruct occluded markers.
    c. Custom data processing scripts to extend the functionality of Vicon software to export skeletal angles. These scripts have been written to match the guidelines of the international society of biomechanics (ISB)
7. Collection and setup of materials for the laboratory space. This includes a variable height desk (to simulate a kitchen counter or work desk) and various household items.

The setup of equipment took longer than initially suggested in the original proposal. This was due to the inclusion of the motion capture system. This system required development of specific skills and significant trial and error regarding camera placement, focusing and marker sets.

In the **second year** of the project the following further development were made:

1. A pilot study was completed of the at-home study with a healthy non-amputee volunteer. This highlighted problems with reliability of the GoPro remote control and particular brands of memory card.
2. Amputee participant recruitment began, with various advertisements placed in specialist online forums and social media sites.
3. Three amputee participants were recruited within Connecticut and New York. Two were congenital transradial amputees (one male, one female, both body powered users) and one was a non-congenital shoulder disarticulation amputee (who uses a myoelectric prosthesis)
4. Custom video analysis software was completed, allowing quick and robust video tagging by use of a midi controller. Exported log files may be read by Matlab or Excel.
5. An initial ‘prosthesis use taxonomy’ was created, based on observation of the video, to allow structured recording and categorization of manipulation events observed in the recorded videos.
6. The recruited amputees all took part in the at-home study.
    a. Several hours of video data were generated for each participant
    b. A number of participant videos were de-identified via blurring of portions of the video
    c. Initial video tagging was completed by use of the custom software. A summer intern was hired and trained for this task. He will continue to work with us in his spare time for the remainder of the project.
    d. Initial trends were observed in video tagging log files, via Matlab analysis.
7. Further preparations were made for Motion Capture analysis, including a full pilot study with members of the lab
    a. An additional body compensation analysis was planned and piloted on members of the laboratory

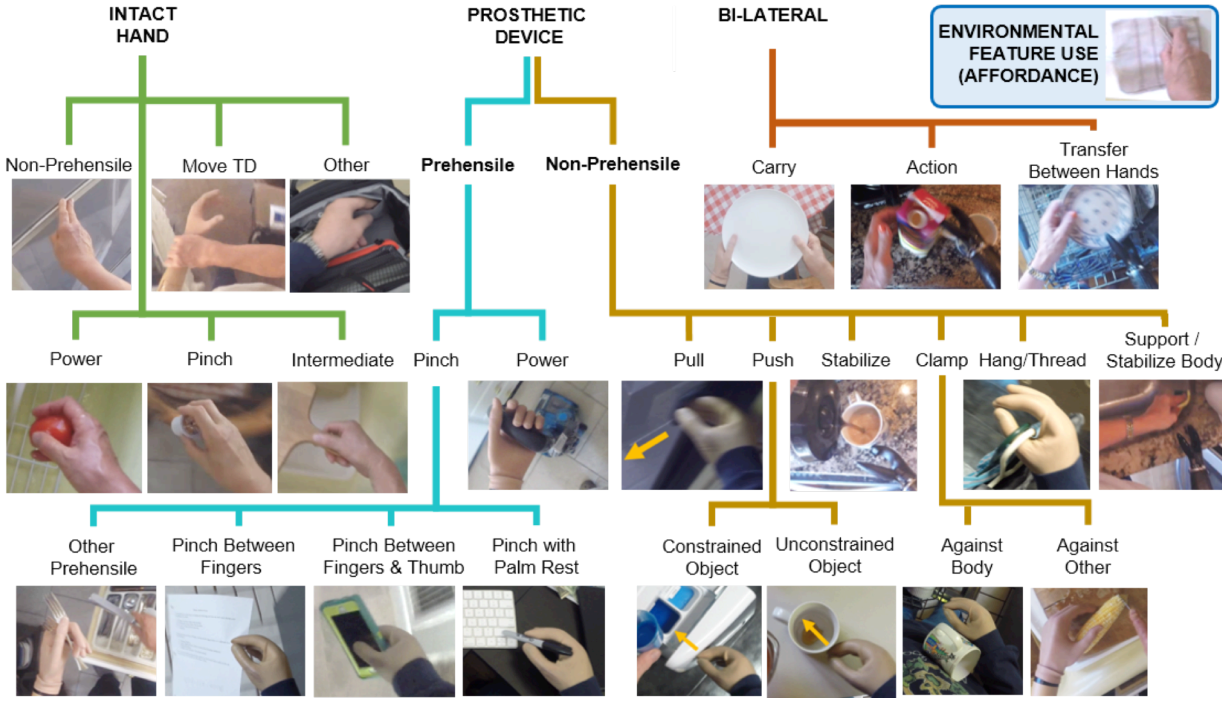


Figure 1: The fully developed prosthesis-use taxonomy

In the **third year** of the project the methods previously developed were refined, permitting analysis of the video data (which continues to be acquired) and leading to initial publication/dissemination. More specifically:

1. The prosthesis-use taxonomy was refined as finalized, as shown in Figure 1.
2. Improvements were made to the tagging and analysis software, removing bugs and increasing robustness.
3. 23-minutes of video data for the first three participants (whose data was collected in year 2) was processed using the video tagging software. This involved the identification of over 2,300 manipulation instances. Among other results, it was noted that the transradial participants using body-powered devices used more non-prehensile manipulations than prehensile grasping. Results of work completed in the fourth year with more video data and additional participants support this trend. The highlights from that extended work (that reiterate many of the results from this work in year 3) are included in the appendix.
4. The findings were accepted as a full paper with poster presentation at the IEEE International Conference on Rehabilitation Robotics (ICORR) in London, UK.
5. The findings were also accepted and presented as an abstract/podium presentation at the Myoelectric Control Symposium (MEC17), in Frederiction, New Brunswick, Canada.
6. Following limited amputee participant recruitment success over the first 2 years of the project, a paid Facebook advertisement and custom Facebook page were created to attempt recruitment by social media. This led to recruitment of one transradial amputee, who was visited in person by a member of the study team and completed the study.
7. After all options for local amputee participant recruitment (within ~150 miles of New Haven) had been exhausted, we modified our approach to enable amputees to take part in the study remotely, by receiving the camera kit and instructions via courier mail. This enabled us to recruit 5 more amputee individuals from across the US.

Figure 2: Video data has been collected from 7 participants to date, some of whom have used multiple terminal devices during the video recording (P7 did not record enough data with their multi-grasp hand to allow analysis).

8. Three of the ‘mail-out’ participants have completed or partially completed the GoPro study so far.
9. An undergraduate student was hired to perform video tagging on the project during the spring semester. Another was hired to perform video tagging full time over the summer and after her success at this has been kept on as a part-time video tagger during the school year. A grad student has also begun contributing to video tagging. This additional manpower has greatly increased data analysis output compared to when only a research scientist was completing the tagging (as was the case for the original 23 minutes of analysis).
10. Over 8 hours of data has now been analyzed for the seven amputee participants who have contributed data thus far. Some of these participants made use of more than one terminal device (Figure 2). This analysis involved the manual identification of over 15,000 manipulation tags.
11. A grad student in the Grab Lab has begun specifically investigating Within-Hand-Manipulation (WIHM) activities in the recorded videos, this is a largely unexplored aspect of human manipulation.
12. A different grad student in the Grab Lab has begun specifically investigating how participants are using the environment to aid grasping and manipulation. There is little existing literature on this area.
13. An advertisement recruiting able-bodied participants was posted on the local craigslist. Potential participants who passed screening had their details entered into a local database for gender / age / height matching to amputee participants. Matching participants will be enrolled once data collection has been completed for amputee participants.
14. Pilot studies have been completed with the motion capture system, using non-amputee participants.

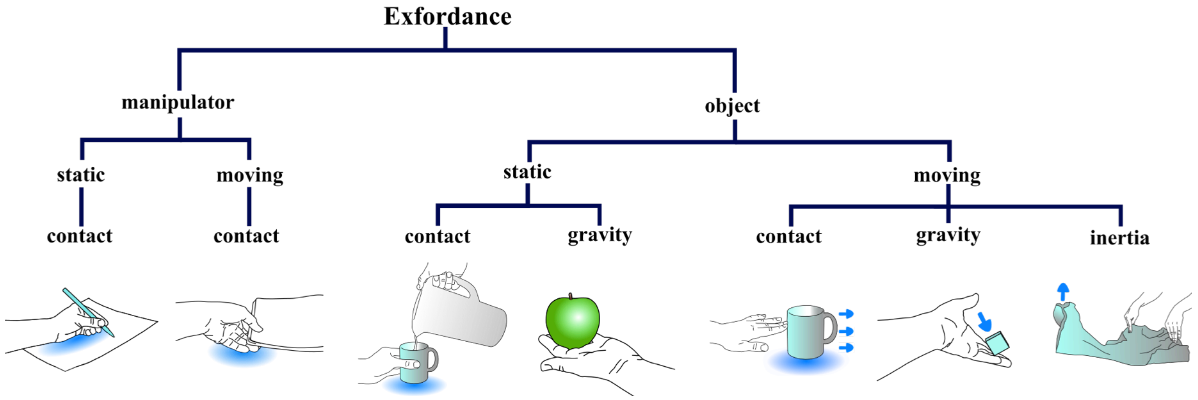
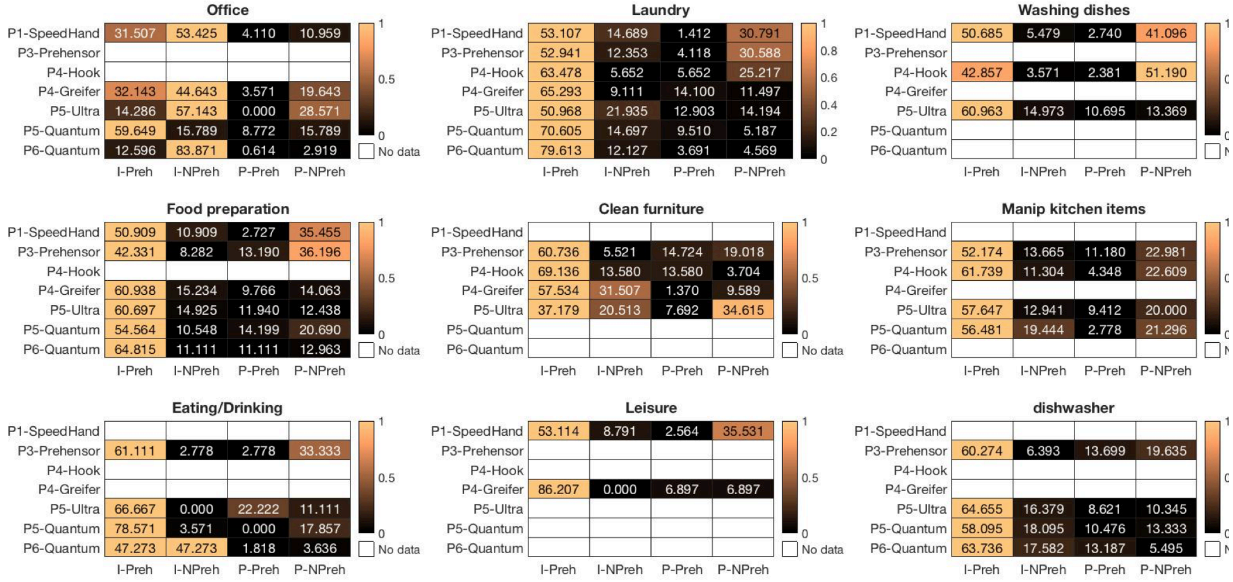


Figure 3: Exfordance Use Taxonomy



Office

	I-Preh	I-NPreh	P-Preh	P-NPreh
P1-SpeedHand	31.507	53.425	4.110	10.959
P3-Prehensor				
P4-Hook				
P4-Greifer	32.143	44.643	3.571	19.643
P5-Ultra	14.286	57.143	0.000	28.571
P5-Quantum	59.649	15.789	8.772	15.789
P6-Quantum	12.596	83.871	0.614	2.919

Laundry

	I-Preh	I-NPreh	P-Preh	P-NPreh
P1-SpeedHand	53.107	14.689	1.412	30.791
P3-Prehensor	52.941	12.353	4.118	30.588
P4-Hook	63.478	5.652	5.652	25.217
P4-Greifer	65.293	9.111	14.100	11.497
P5-Ultra	50.968	21.935	12.903	14.194
P5-Quantum	70.605	14.697	9.510	5.187
P6-Quantum	79.613	12.127	3.691	4.569

Washing dishes

	I-Preh	I-NPreh	P-Preh	P-NPreh
P1-SpeedHand	50.685	5.479	2.740	41.096
P3-Prehensor				
P4-Hook	42.857	3.571	2.381	51.190
P4-Greifer				
P5-Ultra	60.963	14.973	10.695	13.369
P5-Quantum				
P6-Quantum				

Food preparation

	I-Preh	I-NPreh	P-Preh	P-NPreh
P1-SpeedHand	50.909	10.909	2.727	35.455
P3-Prehensor	42.331	8.282	13.190	36.196
P4-Hook				
P4-Greifer	60.938	15.234	9.766	14.063
P5-Ultra	60.697	14.925	11.940	12.438
P5-Quantum	54.564	10.548	14.199	20.690
P6-Quantum	64.815	11.111	11.111	12.963

Clean furniture

	I-Preh	I-NPreh	P-Preh	P-NPreh
P1-SpeedHand				
P3-Prehensor	60.736	5.521	14.724	19.018
P4-Hook	69.136	13.580	13.580	3.704
P4-Greifer	57.534	31.507	1.370	9.589
P5-Ultra	37.179	20.513	7.692	34.615
P5-Quantum				
P6-Quantum				

Manip kitchen items

	I-Preh	I-NPreh	P-Preh	P-NPreh
P1-SpeedHand				
P3-Prehensor	52.174	13.665	11.180	22.981
P4-Hook	61.739	11.304	4.348	22.609
P4-Greifer				
P5-Ultra	57.647	12.941	9.412	20.000
P5-Quantum	56.481	19.444	2.778	21.296
P6-Quantum				

Eating/Drinking

	I-Preh	I-NPreh	P-Preh	P-NPreh
P1-SpeedHand				
P3-Prehensor	61.111	2.778	2.778	33.333
P4-Hook				
P4-Greifer				
P5-Ultra	66.667	0.000	22.222	11.111
P5-Quantum	78.571	3.571	0.000	17.857
P6-Quantum	47.273	47.273	1.818	3.636

Leisure

	I-Preh	I-NPreh	P-Preh	P-NPreh
P1-SpeedHand	53.114	8.791	2.564	35.531
P3-Prehensor				
P4-Hook				
P4-Greifer	86.207	0.000	6.897	6.897
P5-Ultra				
P5-Quantum				
P6-Quantum				

dishwasher

	I-Preh	I-NPreh	P-Preh	P-NPreh
P1-SpeedHand				
P3-Prehensor	60.274	6.393	13.699	19.635
P4-Hook				
P4-Greifer				
P5-Ultra	64.655	16.379	8.621	10.345
P5-Quantum	58.095	18.095	10.476	13.333
P6-Quantum	63.736	17.582	13.187	5.495

Figure 4. Proportion of hand use based on activity for a selection of activities analyzed.

15. Following positive reception of work presented at ICORR, Dr. Spiers was invited to provide a keynote presentation on this project at the next Trent International Prosthetics Symposium (TIPS 2019, UK)

In the **fourth year** more data for the at-home and in-lab portions was collected and analyzed from amputee and able-bodied participants. Use of the external resources for grasping and manipulation was defined, explored, and published. More specifically:

1. Completed recruitment, data collection, and video analysis for amputee participants. In total we have approximately 70 minutes of video data analyzed for each of 8 amputee participants. Some participants provided data for multiple devices leading to a total of 13 cases (Fig. 2).
2. The results of the at-home portion of the study with amputees have been analyzed with non-parametric statistical tools to show the differences in prosthesis use based on frequency and duration of various grasps. See figure 5 for an excerpt from that analysis and the appendix for further explanation.
3. The exfordance use taxonomy was defined, as shown in Figure 3. Exfordance is the use of external forces and surfaces or object inertia to aid in the stabilization or manipulation of the

manipulator or object.

4. Video data (35 minutes) from 5 of the amputees was tagged for exfordance use. Results were published in the proceedings of the BioRob 2018 conference, and a summary of these results is included in the appendix.
5. Recruited gender, age and height matched non-amputee participants for completion of home studies. We have collected all the at-home video data for non-amputee participants. At this time the video data from the non-amputees are still being analyzed. The results thus far are reported in the appendix.
6. Four able-bodied subjects completed the in-lab motion capture study. Results concerning the impact of wrist mobility on body compensation based on the grid reaching portion were published in the proceedings BioRob 2018, and a summary of the results is included in the appendix.
7. A visiting student in the Grab Lab investigated how grasping and manipulation varies by activity in the at-home video. See figure 4.
8. We have used statistics to compare portions of the data to the whole in order to prove that we have analyzed a sufficient amount of data. Ten minutes of data seems to provide similar results as 60 minutes of data (fig 6).
9. Completed the in-lab motion capture study for two amputee participants. Motions for standardized tests, ADLs, and reaching to points on a grid were captured. Figure 7 shows the grid reaching trajectories for one able bodied participant.
10. The table below provides the number of participants that completed each portion of the study

At-home Video Study		In-lab Motion Study	
Amputee	Unimpaired	Amputee	Unimpaired
• 8 subjects • (13 devices)	8 age, height, weight, gender matched subjects	2 transradial subjects	• 2 age, height, weight, gender matched subjects • 10 other subjects

What opportunities for training and professional development has the project provided?

The project provided the opportunity for familiarization with literature on prosthetics, motiom capture and functional outcome measures. Attendance at the MEC (Myoelectric Controls Symposium, New Brunswick Canada) and ICORR (IEEE International Conference on Rehabilitation Robotics) conferences have greatly contributed to familiarization with the field of upper limb prosthetics.

Technical training was completed by Dr Adam Spiers on the Vicon motion capture system. Training was also completed by Dr. Spiers on protocols and policies regarding human experiments. Dr. Spiers has subsequently trained two grad students in how to use the motion capture system and written a guide for use in the lab.

As a result of the at-home studies, Dr. Spiers and Jillian Cochran have become familiar with running studies in non-laboratory scenarios.

Two undergraduate students and two graduate students have been trained in video tagging and identifying manipulation activities.

How were the results disseminated to communities of interest?

Results have been presented to within our lab group.

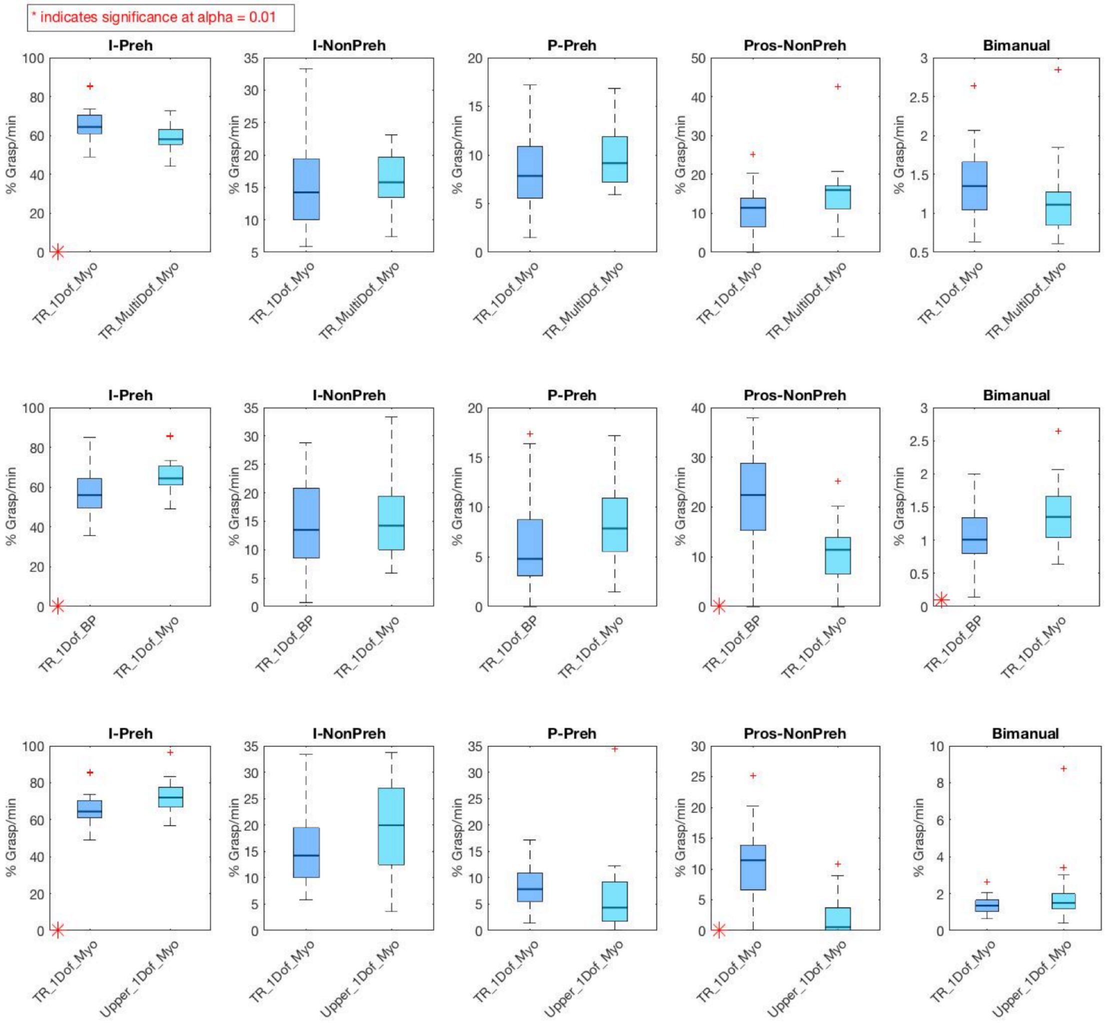


Figure 5. Boxplots display the median and spread of percent use per minute for various groups of participants across five categories. For the bimanual category the average number of bimanual tags per prosthetic tags are reported instead. Permutation testing is used to detect significant differences between two groups. Asterisks in the lower left hand corner denote significance at the 0.05 level with the Bonferroni correction.

A regular paper was accepted for ICORR 2017 (IEEE International Conference on Rehabilitation Robotics) and a poster presentation given at the event.

An given abstract was accepted for MEC 2017 (Myoelectrics Control Symposium) and a podium presentation at the event.

Two papers were published in the proceedings of BioRob 2018. One paper detailed the exfordance use in transradial amputees while the other explored the effects of wrist mobility on body compensation during reaching.

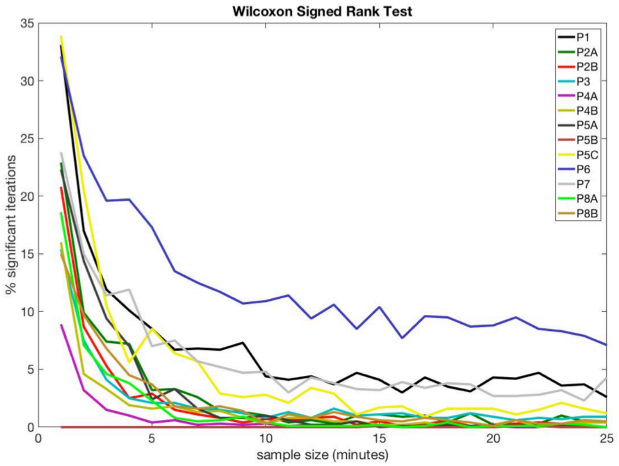


Figure 6: Results of cross validation with the Wilcoxon Signed Rank test to provide intuition for the amount of data needed to adequately represent hand use.

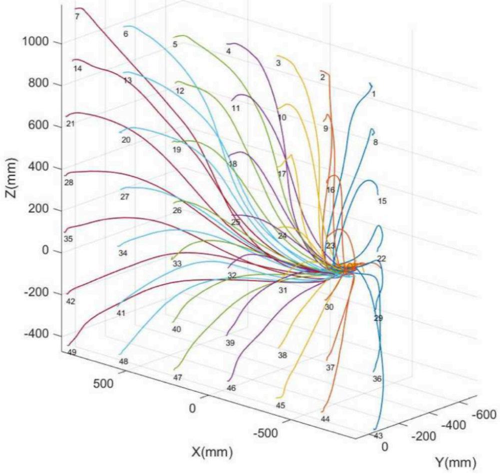


Figure 7: Segmented wrist center reaching trajectories for P2, showing 49 motions to each point on the grid.

4. IMPACT

What was the impact on the development of the principal discipline(s) of the project?

Describe how findings, results, techniques that were developed or extended, or other products from the project made an impact or are likely to make an impact on the base of knowledge, theory, and research in the principal disciplinary field(s) of the project. Summarize using language that an intelligent lay audience can understand (Scientific American style).

The manipulation taxonomy developed for this work fills a gap in prosthetics terminology that we assume will be used by other researchers in the future. Such manipulation taxonomies (e.g. the Feix taxonomy) are widely used in healthy human and robotic hand analysis, yet no such tool exists for prosthetics use. Though Belter et al created a ‘split hook’ taxonomy, this was not applicable to other terminal devices, such as multi-finger hands. We have designed the taxonomy to be generic and applicable to all upper limb prosthetic systems and levels of amputation.

The analysis on grasping and manipulation by amputees and non-impaired subjects alike provides more a more accurate depiction of how individuals use their hands on a day-to-day basis. This in turn can highlight hand important for every-day use, that can inform rehabilitation practices. This work can also provide insight for prosthesis design.

The definition and categorization of exfordance can aid the scientific community in better understanding how prosthesis users and un-impaired individuals use resources external to their hands to aid in grasping and manipulation. These strategies could be incorporated into training for new prosthesis users or even used for robotic manipulation.

We believe the body analysis in research, and possibly clinical setting. Despite body compensation being a known, unwanted factor of motion impairment, there is no universal method of quantifying the level of compensation for particular motions. This is addressed by our kinematics based algorithm, which may be easily added to a motion capture analysis. compensation measure under development for this project will also provide a tool that may be useful for motion.

What was the impact on other disciplines?

As described above, many of the results from this study have applications in the broader field of upper-limb rehabilitation, such as stroke rehabilitation. Furthermore, there are applications within robotics, especially the terminology and strategies related to "exfordance" use, which can inform non-prehensile manipulation strategies.

What was the impact on technology transfer?

We have identified some shortcomings in the design of existing prosthetic terminal devices that will inform device design/redesign. We expect these to eventually make it into commercial systems, but hardware changes are expensive and slow.

What was the impact on society beyond science and technology?

Nothing to report

5. CHANGES/PROBLEMS:

Changes in approach and reasons for change

Nothing to report

Actual or anticipated problems or delays and actions or plans to resolve them

Year 1 - Training, setup and familiarization of with the motion capture system added delays to the project compared to the original forecast. However we believe the quality and impact of the resulting data will be much higher as a result of this new measurement tool and the time taken to learn how to use it.

Year 2 – Difficulties in participant recruitment delayed the start of the at-home study and has slowed down project progress. Typical channels of subject recruitment (online advertisements) did not generate any participants. Instead personal connections through team members and/or their colleagues led to subject recruitment in all cases.

Year 3 – Amputee participant recruitment continued to be a source of problems in the first half of the year. This was alleviated by enabling the study equipment to be mailed out to participants across the US. Video tagging also took longer than anticipated (up to 2 hours of processing time for a minute of video), this was aided by assigning undergraduate and graduate students to video tagging roles.

Year 4 – Due to the nature of the data, we were unable to use out-of-the-box statistical tests for analysis. With the help of the Yale Statistics lab (StatLab), we were able to select the appropriate type of analysis.

Changes that had a significant impact on expenditures

We rebudgeted early on to purchase the motion capture system used in the in-lab studies.

Significant changes in use or care of human subjects, vertebrate animals, biohazards, and/or select agents

Nothing to report

6. PRODUCTS

Publications, conference papers, and presentations

Spiers, A. J., Resnik, L., & Dollar, A. M. (2017, July). Analyzing at-home prosthesis use in unilateral upper-limb amputees to inform treatment & device design. In IEEE 2017 *International Conference on Rehabilitation Robotics* (pp. 1273-1280).

Spiers, A. J., Resnik, L., & Dollar, A. M. (2017, August). Classifying and Quantifying Unilateral Prosthesis Use in Home Environments to Inform Device and Treatment Design. *Myoelectric Control Symposium, (MEC)*

Spiers, A. J., Gloumakov, Y., & Dollar, A. M. (2018, August). Examining the Impact of Wrist Mobility on Reaching Motion Compensation across a Discretely Sampled Workspace. In 2018 *Biomedical Robotics and Biomechatronics* (BioRob).

Cochran, J.C., Spiers, A. J., & Dollar, A. M. (2018, August). Analyzing Exfordance Use by Unilateral Upper-Limb Amputees. In 2018 *Biomedical Robotics and Biomechatronics* (BioRob).

Website(s) or other Internet site(s)

Recruitment Page

https://www.facebook.com/YaleGrabLab/

Technologies or techniques

Motion capture marker sets and processing techniques associated have been developed. These will accompany future publications as appendices.

The Midi controller based video tagging software developed for this project is robust and easily scalable. We are considering open-sourcing the code afterwards for use by other researchers.

The prosthetics use taxonomy is a manipulation classification technique that will be applicable to general analysis of upper limb prosthesis use.

The exfordance use taxonomy is a classification of use of resources external to the hand for grasping and manipulation technique that will be applicable to general analysis of upper limb prosthesis use.

The body compensation algorithm was explained in the BioRob paper and can be used for other related studies.

Inventions, patent applications, and/or licenses

Nothing to report

Other Products

Nothing to report

7. PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS

What individuals have worked on the project?

Name:	Aaron Dollar
Project Role:	PI
Researcher Identifier (e.g. ORCID ID):	Aaron.dollar@yale.edu
Nearest person month worked:	3
Contribution to Project:	**Expert on human hand functional use and robot / prosthetic hand development. Contributed to Protocol development, measurement equipment selection and setup.**
Funding Support:	This award.

Name:	Linda Resnik
Project Role:	Co-PI
Researcher Identifier (e.g. ORCID ID):	linda_resnik@brown.edu
Nearest person month worked:	4
Contribution to Project:	**Expert on upper limb prosthetics and measures of upper limb functionality and rehabilitation outcomes. Contributed to protocol development.**
Funding Support:	This award

Name:	Adam Spiers
Project Role:	Postdoctoral Associate
Researcher Identifier (e.g. ORCID ID):	adam.spiers@yale.edu
Nearest person month worked:	30
Contribution to Project:	**Postdoc researcher responsible for running at-home and in-lab studies. Contributed to protocol development, IRB submission (Yale only), equipment selection, setup, customization and familiarization.**
Funding Support:	This award.

Name:	Kate Barnabe
Project Role:	Administrative Lead

Researcher Identifier (e.g. ORCID ID):	Kate.Barnabe@va.gov
Nearest person month worked:	4
Contribution to Project:	**Protocol development. IRB submissions (all institutions and DOD). Project administration.**
Funding Support:	This award

Has there been a change in the active other support of the PD/PI(s) or senior/key personnel since the last reporting period?
Nothing to report

What other organizations were involved as partners?
Nothing to report

8. SPECIAL REPORTING REQUIREMENTS

A Quad Chart accompanies this report

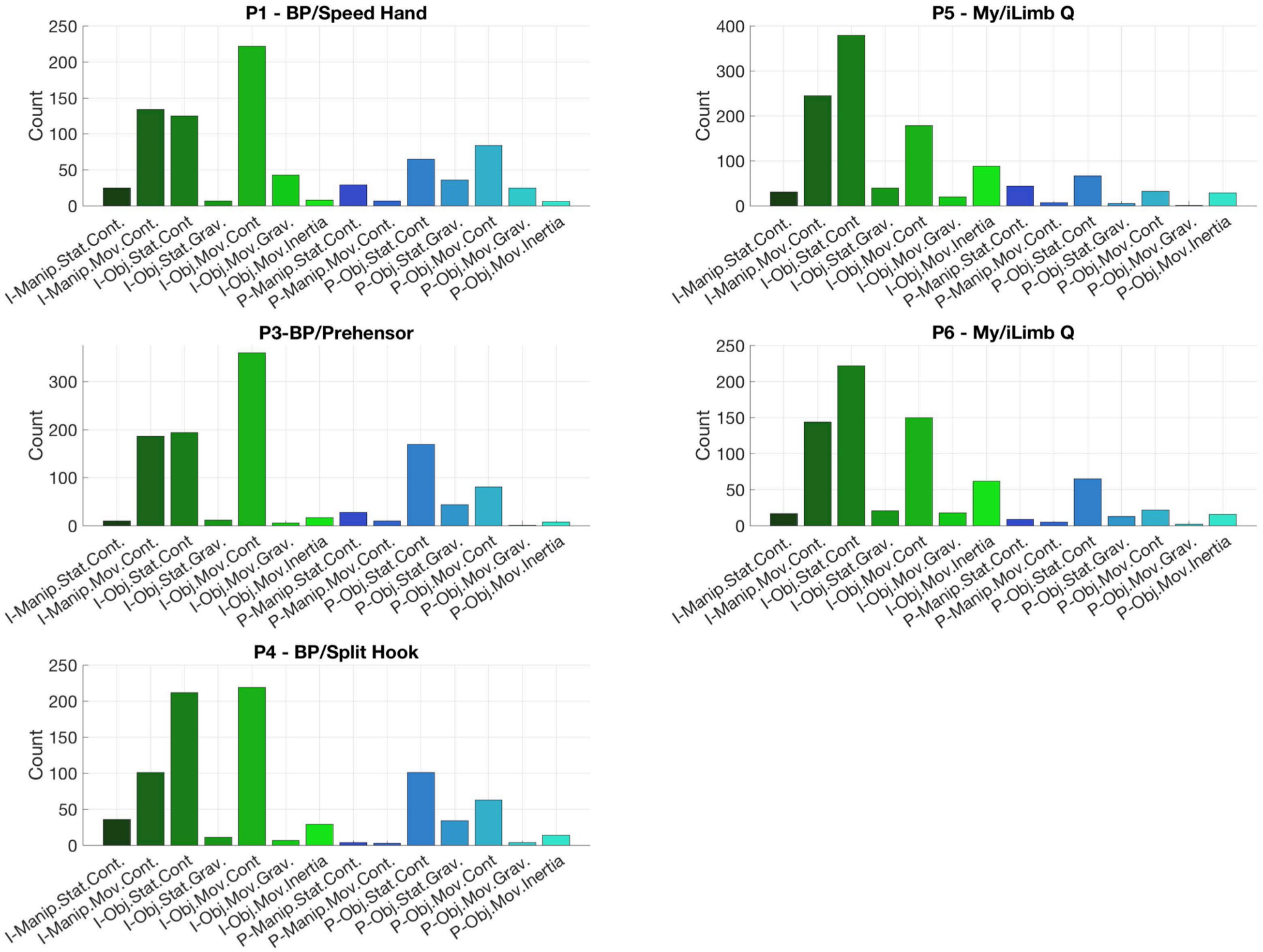
9. APPENDICIES

Appendix A. *Exfordance Use in Unilateral Upper-Limb Amputees*

Background
While studying grasping and manipulation in unilateral upper limb prosthesis users it became clear that the subjects often use the environment to aid grasping and manipulation and stabilize their bodies. Subjects use these strategies with both the prosthesis and sound limb. When it is difficult to pick up a credit card directly from a table, we may slide it to the edge. To walk up the stairs, we often use a handrail to aid stability. Indeed, environmental constraints are often used even when they are not necessary for task completion [1][2]. We define the usage of features external to the object being manipulated, including contacts with the environment or other objects and gravitational forces as "exfordance use" – harkening the concept of "affordances"[3], but focusing specifically on features that are generally external to the design of the object being grasped or manipulated. The definition of human exfordance use was developed empirically after viewing video footage of naturalistic and undirected motions from 5 amputees and noticing the frequent utilization of external features to aid in manipulation tasks.

Aside from providing more general insight into the nature of human manipulation function (which has use in rehabilitation, robotics, and animation, among other areas), studying exfordance use in amputees can give insight into the design and control of upper-limb prosthetics as well as other assistive technologies. This work aims to understand the use of exfordance strategies with the prosthesis (perhaps compensating for its relatively limited functionality) as well as the non-usage of exfordance (since certain strategies cannot be performed).

The video data from the at-home study is tagged according to the prosthesis use taxonomy [4] and the exfordance taxonomy in Fig. 3 [5]. Thirty-five minutes of data have been tagged for exfordance use for five transradial prosthesis users. Participant numbers in this section are in agreement with the study


P1 - BP/Speed Hand

P5 - My/iLimb Q

P3-BP/Prehensor

P6 - My/iLimb Q

P4 - BP/Split Hook

Figure 8. Frequency of exfordance tags for each category during 35 minutes of video for each participant. 'I' refers to intact hand and 'P' to prosthetic.

discussed above. Often more than an hour is needed to tag 1 minute of video; 35 minutes of data resulted in a considerable number of tags. Definitions of each exfordance strategy along with the example shown in taxonomy are included below.

Please note that the name of each exfordance use type was crafted to be succinct and to differentiate the seven types from one another. In some cases, longer, more descriptive names may have been more appropriate but were not used in favor of brevity. One example is Object.Moving.Inertia that is used to evoke the idea of using the dynamic motions of the arm and taking advantage of the object's inertia to change its configuration with respect to the hand. This idea is similar to the "active dynamic" strategy detailed in [6] but is primarily used to describe subjects moving their arms quickly to change the configuration of a deformable object (eg. moving one's arms quickly in attempt to untangle a knotted power cord). Note that this label is not incorrectly implying that the inertia of the object is the cause the change in motion of the object. The terminology is primarily a label for some of the phenomena seen in the video footage.

1. Manipulator.Static.Contact – the environment is used to *support* the *static* manipulator through contact between the environment and the manipulator. Example: the table supports and steadies the hand while writing
2. Manipulator.Moving.Contact – the environment is used to *guide, augment, or constrain* the *motion* of the manipulator through contact between the environment and the manipulator. Example: while picking up a flat object, the fingers are guided by the countertop

3. Object.Static.Contact – the environment is used to support the static object through contact between the environment

and the object. Example: the table supports a portion of the weight of the cup during a pouring task

4. Object.Static.Gravity – a gravitational force is used to aid in stabilizing the static object. Example: the subject takes advantage of gravity acting on the apple and is able to “hold” the static apple without a prehensile grasp
5. Object.Moving.Contact – the environment is used to *guide, augment*, or *constrain* the motion of the object through contact between the environment and the object. Example: the subject pushes a cup and the support surface constrains the motion of the cup to the plane
6. Object.Moving.Gravity – a gravitational force is used to augment the motion of the object. Example: an object rolls down the angled hand toward the fingertips
7. Object.Moving.Inertia – dynamic motions of the manipulator change the configuration of the object relative to the manipulator. Example: subjects were observed moving their arms quickly to unfold a piece of clothing

Results

The most frequently used exfordance categories for the intact and prosthetic hands were identified. The count data for each exfordance type and participant can be viewed in fig 8. I developed a measure of exfordance use that adjusts for differences in overall hand activity as measured by number of grasping and manipulation tags for each hand. I analyzed overall exfordance use across all categories along with use of individual categories for each hand. Given the few number of participants and limited amount of data analyzed, the results may not be representative of the entire amputee population. For similar reasons, statistical significance is not reported. However, the video and data do indicate:

1. Exfordance use commonly occurs during ADLs (over 4,700 instances for 35 minutes of data in 5 individuals).
2. After adjusting for hand activity, the prosthetic and intact hands use exfordances with approximately the same frequency. On average (excluding P6) the prosthetic contributes to 46% of the total exfordance use.
3. Object based exfordances are used 62% more than manipulator based exfordances.
4. The specific exfordance strategies vary substantially between limbs
5. The prosthetic hand relies on gravity to stabilize or grasp a static object 56% more than the intact hand.
6. The intact hand’s motion is constrained by the environment 74% more than the prosthetic hand.

These observations suggest the importance a robust hand design that accommodates hanging items from the prosthetic. The presence of a wrist and haptic feedback would likely enable the user to directly interface with the environment, which is typically performed by the intact hand. Compliant fingers could also facilitate the prosthesis in picking up small objects from the environment similar to the strategy proposed by Odhner et. al. for an underactuated robotic gripper [7]. Though the fingers should not be too compliant such that non-prehensile pushing and stabilization become difficult, which are also important for the prosthetic.

Appendix B. *Wrist Mobility and its Affect on Body Compensation during Reaching*

Background

Developments in the field of upper limb prosthetics often focus on creating more dexterous prosthetic terminal devices, to replace the absent hands of amputees and facilitate object holding and grasping. This is demonstrated by the wide range of anthropomorphic prosthetic hands generated by industry academia and hobbyists. In comparison, there has been fairly little attention given to the development of prosthetic wrists, despite the fact that this part of the body is also absent in many amputees. It is common for above-wrist amputees to be fitted with prosthetic devices that either have no wrist, or only a passive pronation/supination mechanism that must be rotated by the other limb or some environmental feature. This effectively fixes the alignment of their prosthetic device with regard to their forearm. Such an absence of wrist mobility limits the orientation capability of the hand relative to the body. In order to achieve the same target hand orientations necessary for grasping a variety of objects, it is necessary to modify the motion trajectories of other joints. This leads to compensatory movements, which can place additional stress on the body and lead to overuse complications for the remaining joints. An example compensatory motion for a trans-radial amputee involves elevating the elbow while drinking, to facilitate the tipping of mug or bottle to the mouth, an action that is usually carried out by the wrist. This action increases shoulder motion to compensate for the lack of wrist mobility.

In this work we introduce a method of studying compensatory motions across a user's workspace with a semi-abstract reaching task. We use an equally spaced 7x7 grid of vertically orientated cylindrical targets to simulate the grasping of common objects (e.g. cups, cans, etc.) at various heights and lateral displacements from a participant's body. A Vicon motion capture system enables recording of body motion for the reaching actions necessary to grasp each target, thereby allowing characterization of the workspace with respect to a variety of metrics. Reaching to objects at various locations in a workspace is a common manipulation scenario that may be found in many kitchen, wardrobe or supermarket settings. These environments are associated with eating, dressing and shopping, which are beneficial for personal independence. In this study, participants reach to all points on the grid unimpaired and whilst wearing a custom device to brace wrist motion.

Methods

To impair wrist motion on the participant's dominant arm, a padded orthopedic wrist brace featuring an aluminum internal structure (DonJoy ComfortFORM Wrist Support Brace – DJO Global, Vista CA, USA) was combined with a padded elbow brace with elbow articulation (Orthomen ROM Elbow Brace) by means of a bolt. An additional wooden insert was added to this setup to prevent wrist extension (Fig 4). In all, this combination of orthotic devices effectively limited wrist pronation/supination, radial/ulnar deviation and wrist flexion/extension.

Participants stood on marks made on the floor at a distance of 0.6m from the grid. They were requested to reach to each target on the grid, forming a power grasp and squeezing the target. Following each target they were asked to return to a relaxed position with arms by their sides. Targets were completed one row at a time, in a right to left order, starting with the top right target. Participants were requested to only step away from the start position on the floor if necessary to reach a target and to return to the start position after each grasp. If participants failed to return to the start position for a target then the reaching motion was repeated for that target.

Summary of Results

In addition to the standard measure of joint ROM, we have also measured Euclidean path length of four body segments in Cartesian space. The results visually indicated how regions of the workspace influence individual joint ROM, joint-level trajectories or Cartesian path changes when the user is moving naturally, or when wrist motion is impaired in 2DOFs. Though clear ROM and Euclidean patterns are present for un/impaired reaching motions (showing gradual metric change throughout the workspace), the difference metrics provides less clear spatial patterns, with limited observable similarity between participants.

Statistical approaches were implemented to quantify, unimpaired/impaired variable differences and correlation between participants. **Significant ROM changes between the unimpaired and impaired cases were identified for all joints except the trunk. Significant Cartesian trajectory length changes occurred for the elbow and wrist**, which matched general observations of wrist-less prosthetic user behavior. Measures of similarity across participants showed consistent ROM for the trunk and shoulder in impaired and unimpaired cases though this was less so for the compensatory (dROM) cases. In terms of Cartesian length, participants seemed to show similar braced motion strategies but were uncorrelated otherwise. The general trend of correlation in un/impaired cases but not in compensation (difference) is interesting and unexpected. It seems that though participants have comparable reaching strategies, the differences between these strategies is subject to some noise.

These initial findings indicate the value of spatial workspace sampling, as metrics change considerably depending on workspace location. The typical approach of measuring body compensation for a task at single location may lead an investigator or therapist to overlook varied data in neighboring locations. Secondly the impact of increasing wrist mobility (via interventions such as rehabilitation, surgery or prosthetic devices) on reducing gross changes in joint ROM and trajectory length have been shown. The results may also be used in guiding therapists in understanding which areas of the workspace has the most motion demands on different aspects of the body.

Appendix C. *Grasping and Manipulation in Upper-limb Amputees*

Please note that these results with the extended data set (all 8 subjects with a total of 13 devices) have not yet been published.

Related Work

Generally prostheses are evaluated in three ways: self-reported measures, standardized tests, and with less structured such as a video study. All three provide valuable information that should be used in concert to develop a clear idea of prosthesis use, satisfaction, functionality, and shortcomings. Kay et al. administered a survey in 1958 asking participants to rate the usefulness, frequency of use, and ease of use of their device during activities of daily living (ADLs) [8]. Subjects were also asked to explain why they did not use their prosthesis for certain activities. Some of the responses included that it was "easier to perform without the prosthesis" and the "terminal device is inadequate." TAPES, a standardized questionnaire, asks amputees to rate how they feel using their prosthesis in a social context and their satisfaction associated with characteristics such as color, shape, and weight of the device [9]. While self-reported measures provide the unique perspective of the end user that should be considered when designing a prosthesis, they do not provide detailed information about the functionality of the device.

Standardized tests such as SHAP provide a measure of prosthetic device function. Participants completing a SHAP test perform simulated ADLs and tasks with abstract objects for time [10]. The score, called index of function (IoF), is based on the completion times. While this is an objective measure with high repeatability, it is debatable that time should be the only factor considered when evaluating a prosthetic. AMULA, a measure of activity performance in prosthesis users, is similar in that the participant performs a number of ADLs [11]. Yet, a clinician scores the performance based on five criteria: extent and speed of completion, movement quality, skillfulness in grasping voluntarily, and independence. Despite having a more subjective scoring system, AMULA has high inter-rater agreement and test-retest reliability [11].

Ostlie et al. administered a questionnaire, interview, and clinical test to prosthesis users to better understand the relation between skill and actual use in everyday life [12]. The level of satisfaction with a terminal device, amputation level, and skill shown in the clinical test did not relate to the reported use of the device. Participants reported using the device for approximately half of ADLs. This result warrants further investigation of how amputees are using their devices in ADLs especially given that reported and actual prosthesis use may differ.

Less structured studies of prosthesis use seem to be rare in the literature. One notable study from 1983 reports the prosthesis use of 42 unilateral upper-limb amputees performing 26 tasks in their own home [13]. Only a subset of the participants performed all 26 tasks. The authors took note of grasps and a variety of non-prehensile manipulations including supporting, pushing, and fixation of an object between prosthesis and body or prosthesis and environment. The authors report that subjects with myoelectric devices grasp more frequently than those with body-powered hooks, whom grasp more frequently than those with body-powered hands. Subjects with transradial amputations use their prosthesis more frequently than those with above elbow amputations. Their study also indicates that subjects typically clamped objects instead of grasping with the prosthesis. When the subjects use their prosthesis to actively grasp an object, it was typically an indirect grasp, meaning the object was passed to the prosthesis from the intact hand.

In a paper from 1998, Fraser et al. examines amputees' use of cosmetic and functional prosthetic devices (n = 66) [14]. All participants performed the same three activities in their own homes, and video was

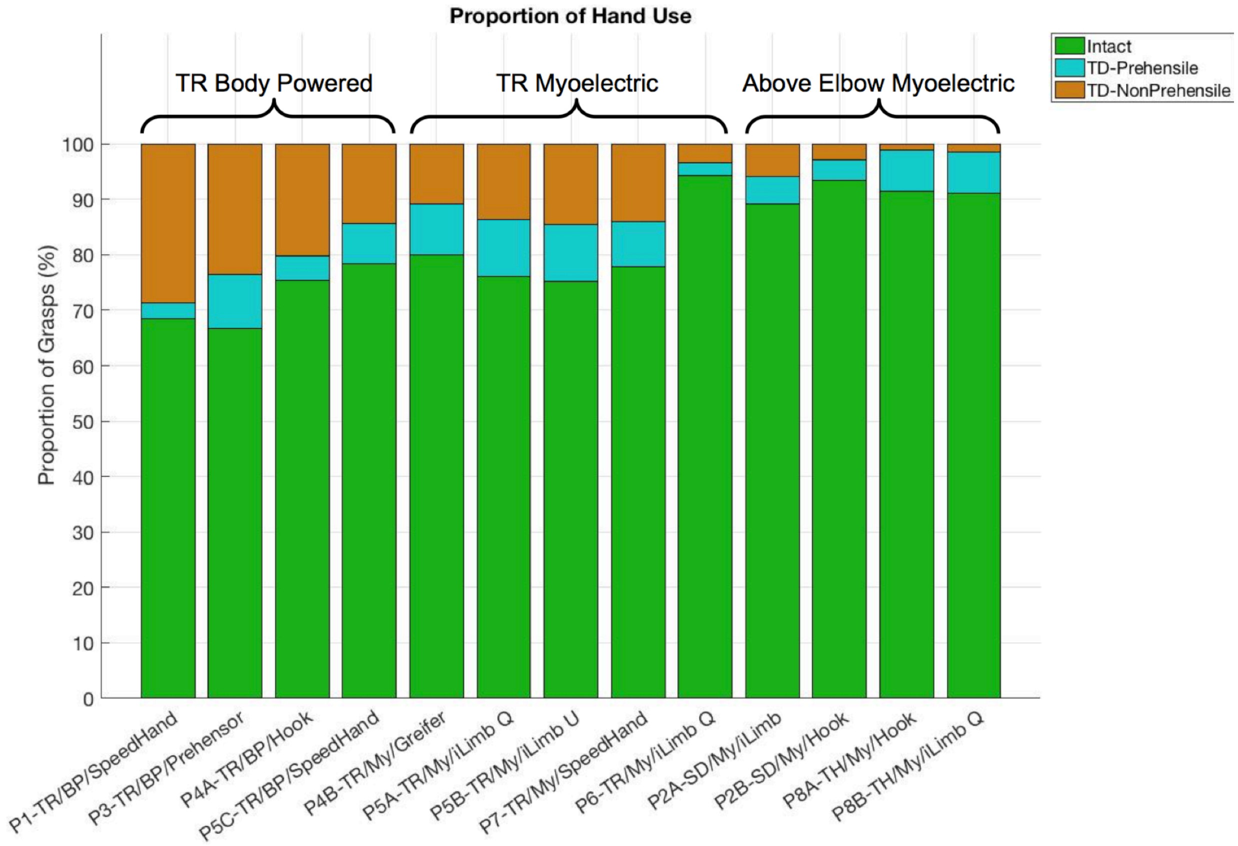


Fig. 9. The bar plot presents the proportion of total hand use for each case. The bars are grouped based on amputation level and powering of the device to highlight trends.

recorded for post-study processing. The authors quantified prehensile and non-prehensile use of the prosthesis. In agreement with [13] and the preliminary results of this study [4], the authors found that an important role of the prosthesis is supporting, pushing, pulling, clamping and stabilizing one's body. They argue non-prehensile manipulations may be of more use to the amputee than having the ability to grasp small objects, which is often included in new users' training regimens [15]. While amputees are proficient in grasping a range of objects in the clinical setting, Fraser et al. suggest that tasks requiring active grasping are typically performed by the intact hand in everyday life [14]. This finding is essential for improving rehabilitation practices and prosthesis design.

New technologies have been developed and released commercially since 1998, such as the iLimb hand, which debuted in 2007. This study presents updated information regarding prosthesis use and compares use across a range of devices – from a body powered split hook to the iLimb Quantum. Perhaps the development of new multi-grasp devices will reduce the frequency of non-prehensile use. Furthermore, the proposed study removes the researcher from the data collection process by using head-mounted cameras in hopes of capturing more natural movement, similar to [16]. In contrast to the two studies on amputees discussed previously, this study includes a greater variety of tasks, and the participants select the order and length of ADLs to perform during the data collection process. Subjects are not given specific instructions on how to make coffee for example, but are simply asked to make a hot drink at some point during video collection. The previous studies only quantified use of the prosthesis without regard to the intact hand. We will explore differences between intact and prosthetic hand grasping and manipulation.

Method

Eight unilateral upper limb amputees with six or more months of experience with a prosthesis were recruited and asked to provide 4 hours of video from a head-mounted GoPro Hero 3+. The subjects' devices and amputation levels are displayed in the appendix. Video data from unimpaired control subjects matching the amputee subjects' height, weight, age, and gender were also collected. Subjects were asked to complete ADLs in their own homes from a list that includes cooking, cleaning, laundry, and vacuuming among others. We requested participants avoid activities such as reading, watching tv, or using a smart phone for more than thirty minutes as these activities usually involve limited hand use.

Seventy minutes of video were selected from the data provided by each subject. Video segments were chosen to limit downtime and include a wide range of activities. As detailed in [3], researchers 'tagged' the type and beginning and end of each grasp and manipulation in the videos according to a prosthesis use taxonomy [3] using a custom video processing software. The resulting data were processed in Matlab. Preliminary results of this study with 23 minutes of data for 3 subjects are presented in [3]. Additional participants and video footage provide more support to the preliminary findings and new insights into prosthesis use.

Statistical Tools

The tagging process provides the type and start/end times of each grasping and manipulation instance. If we consider the total number of grasps completed in 70 minutes for each grasp type, there is only one data point per participant per grasp. Detecting significant differences in frequency of grasps between the intact hand and prosthesis or between two different grasp types requires that each subject have multiple data points to describe grasp frequency. Therefore, each participant's video data is divided into smaller time intervals. As the time interval size increases, there are fewer data points, which must be taken into consideration when running a statistical test. The data is divided into intervals sequentially and the last portion of data is truncated if the total number of minutes of the video data is not a multiple of the interval size. The truncation of the data can cause the mean to shift when changing the interval size.

The data from larger sampling intervals generally have a smaller range of grasp frequencies within a grasp type. This is favorable for statistical testing in that it is easier to differentiate between two groups when both groups have smaller variances. Yet, larger intervals also have fewer data points. Five-minute intervals were selected to balance the number of data points and spread of the data. Unlike the frequency data, the duration of each grasp constitutes a data point; averaging the data over intervals is not required for statistical analysis of grasp durations.

To detect significant differences in the frequency and duration of various grasps and manipulations, we use a combination of parametric and non-parametric hypothesis tests. If the Kolmogorov-Smirnov test determines that the residuals of the data are not normal, a non-parametric version of the t test is used, otherwise, the t test is employed.

When comparing frequency of use of one grasp versus another for a participant, we use a paired t test (1) where X_1 is the data points from variable 1, and N is the number of data points.

$$t_p = \frac{\frac{1}{N}\sum_{k=1}^{N}(X_{1,k}-X_{2,k})}{\frac{std(X_1-X_2)}{\sqrt{N-1}}} \qquad (1)$$

Each data point collected for one grasp for a participant occurred over the same five-minute interval as the second type of grasp for that participant. Given the two types of grasps happened over the same time period by the same individual, we no longer assume that the two samples are independent from one another. In the case for which the residuals are not normal, the Wilcoxon Signed Rank test is used. Welch's t test (2) is used when comparing comparing groups of participants against one

$$t_W = \frac{\overline{X_1} - \overline{X}_2}{\sqrt{\frac{s_1^2}{N_1}+\frac{s_2^2}{N_2}}} \qquad (2)$$

another. Welch's t statistic is used to provide a measure for the difference in means between the two samples. Unlike Student's t statistic, Welch's t statistic does not pool the variance of the two samples. The mean of sample 1, its variance, and sample size are $\overline{X_1}$, s_1^2, and N_1. Again, if the residuals of the data are not normal, a Mann Whitney U test (the non-parametric alternative to a two sample t test) is used. 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 the alternate set of tests.

Results

Fig. provides an overview of the results by showing the proportion of use of three types of grasps as compared to total use of both hands for each participant. The total number of grasps varied across participants, and using proportions makes comparing the grasp breakdown across participants more clear. The bars were ordered based on amputation level and powering of the device to emphasize the similarity within these groups. A few trends are immediately apparent such as frequent use of the intact hand as compared to the prosthesis, and subjects with transradial amputation use non-prehensile manipulations more frequently than prehensile grasps. The following statistical analyses explore differences in grasping and manipulation. The first analysis compares grasping within each subject. The second compares groups of participants based on amputation level, powering of the device, and device type.

Within Participant Analysis: Frequency

This section details the comparison of one grasp (such as intact power) or a group of grasps (such as intact prehensile) to another grasp or group of grasps for each participant individually. When reporting metrics to represent the value and size of the frequency data, average medians and the size of the interquartile ranges (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. As expected all participants use the intact hand more frequently than the prosthesis. On average participants perform 16.4 grasps/minute (IQR = 8.5) with the intact hand and 4.1 (IQR = 2.2) with the prosthesis. This could result from a number of factors including but not limited to prosthetic weight, strength, speed, control complexity, and lack of haptic feedback and proprioception. Participants have learned to accomplish many tasks solely using the intact hand. Additionally, subjects rarely dropped items with the prosthesis, indicating that they are familiar with its limitations. This, too, could have influenced the frequency of use.

TABLE 1. THE TABLE DISPLAYS THE MEDIAN FREQUENCY (TAGS/MIN) ACROSS FIVE CATEGORIES FOR GROUPS OF LIKE PARTICIPANTS.

	Intact Prehensile	Intact Non-prehensile	Prosthetic Prehensile	Prosthetic Non-prehensile	Bimanual
TR 1Dof BP	13.4	3.0	1.0	5.6	7.0
TR 1Dof Myo	12.4	2.7	1.5	1.9	5.8
TR Multi Dof	11.4	4.0	1.6	2.2	3.8
TR Myo	11.8	3.5	1.6	2	4.8
Upper 1 Dof	9.4	2.1	0.6	0.1	1.4
Upper Multi Dof	14.5	2.7	1.2	0.4	3.0

Given that the intact hand is used more frequently than the prosthesis, the following analyses compare percent use for which the denominator is frequency of all grasps for the hand in question. For example, we compare the number of power grasp with the prosthesis over total number of prosthesis tags to the number of power grasps with the intact hand over total number of intact hand tags. For 8 of 9 transradial participants (excluding P6), prehensile grasps with the intact hand make up 79% (IQR = 12%) of all grasps by the intact hand and the prehensile with the prosthesis, 30% (IQR = 21%).

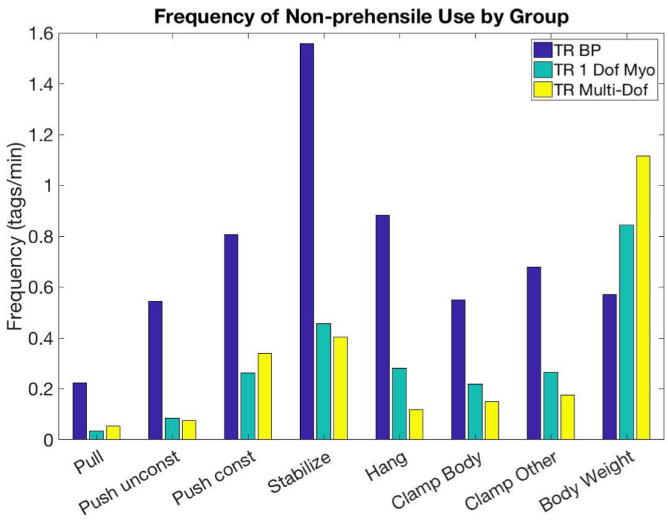


Fig. 10. Frequency of non-prehensile manipulations for three groups of participants. Transradial participants with body-powered devices use all types of non-prehensile manipulations (excluding supporting one's body weight) more frequently than other transradial participants with myoelectric devices.

Relatedly, all transradial participants' (including P6) use of non-prehensile manipulations out of total hand use with the prosthesis (71%, IQR = 23%) is significantly more than the use with the intact hand (22%, IQR = 15%). This is likely a direct result of the general lack of dexterity and tactile feedback, small grasp aperture, and slow grasping rates of the prosthesis compared to the healthy hand. There is more uncertainty associated using a prehensile grasp with the prosthesis than the intact hand. Given the shortcomings of the prosthesis, the object can be easily dropped or knocked over when trying to grasp it. The participant may instead opt for a non-prehensile push or clamp that does not rely on the prosthetic device's ability to grasp.

All transradial participants tended to use non-prehensile manipulations more frequently than prehensile grasps though only seven of nine (excludes P4B, P5A) had significant differences ($p < 0.05$). P8 exhibited the opposite trend, using prehensile grasps more frequently than non-prehensile manipulations. These results confirm the trend originally suggested in [4] that transradial participants are using non-prehensile manipulations more than prehensile grasps with the prosthesis. Transradial participants have greater arm mobility that allows them to push and pull objects more easily.

Between Participants Analysis: Frequency

To discern differences in frequency of use between groups of similar participants, we compare them across 5 categories: intact prehensile, intact non-prehensile, prosthetic prehensile, prosthetic non-prehensile and bimanual frequency of use. Subjects were grouped based on amputation level (transradial and above elbow), DoFs (1 DoF and multi-DoF), and powering of the device (body-powered and myoelectric). Median frequency values are included in table 1.

It is important to consider that participants with multiple devices were often in both groups used in the comparison when interpreting the following results. For instance, when comparing 1 DoF and multi-DoF device use in subjects with above elbow amputations, P2 and P8 are in both 1 DoF and multi-DoF groups. This violates the assumption that the two groups were sampled independently from one another. Given the small number of participants, this is unavoidable.

Subjects with transradial amputations use non-prehensile manipulations with the prosthesis (3.8 tags/min, IQR = 4.0) significantly more frequently than subjects with above the elbow amputation (0.25, tags/min IQR = 0.65). Again, this could relate to level of arm mobility. When comparing P8 (transhumeral) to P2 (shoulder disarticulate), P2 uses non-prehensile manipulations more frequently than P8 across all types of non-prehensile manipulations. This is surprising in that the transhumeral amputee still has use of the glenohumeral joint permitting greater arm mobility than the participant with a shoulder disarticulation. Participant 6's grasp breakdown (as shown in fig. 9) resembles the participants with above elbow amputations rather than other transradial participants with myoelectric devices. P6 is a congenital amputee who began using a prosthesis a few years ago and is adept at using the intact hand exclusively for many tasks. If we remove P6 from the transradial group, then transradial participants (1.3 tags/min, IQR = 1.2) use prehensile grasps more frequently with the prosthesis than above elbow participants (0.9

tags/min, IQR = 1.05). This remains true no matter the number of DoFs of the device. In agreement with [13], overall, transradial participants use their devices more frequently than above elbow participants.

Comparing transradial subjects based on device actuation method reveals that those with body-powered devices (5.6 tags/min, IQR = 6.0) use non-prehensile manipulations with the prosthesis significantly more frequently than those with myoelectric devices (2.0 tags/min, IQR = 2). It is reasonable to assume the inclusion of three multi-grasp devices in the myoelectric device category may skew these results. However, if we compare the body-powered participants all of whom have 1-DoF devices to those with 1 DoF myoelectric devices, the difference in frequency of non-prehensile manipulations is still significant. Figure 10 shows the frequency of use for each type of non-prehensile manipulation for the transradial subjects. The only category the participants with myoelectric devices use more frequently than those with body-powered devices is supporting one's body weight. In subjects using myoelectric devices those with multi-Dof devices used hang approximately half as frequently as the 1 DoF myoelectric users. Perhaps the users of multi-Dof devices avoided hanging objects from their prostheses due to the cost and related fear of damaging the device.

Lastly, we compare participants with 1 DoF devices to those with multi-Dof devices. In transradial participants there are no significant differences for prehensile and non-prehensile use with the prosthesis between users of 1 Dof devices and those with multi-Dof devices. For participants with above-elbow amputations, the statistical test was not able to detect a difference between the 1 DoF and multi-DoF users in prosthesis prehensile or non-prehensile use. This, however, is likely due lack of power to detect such a small effect size.

Given the results of this study and the video content itself, I would like to propose a few mechanical design considerations for future prosthetic devices. Most of these suggestions pertain to increasing the ease of non-prehensile manipulations with the prosthesis, which is frequently used by the transradial subjects in this study. The addition of a high friction, compliant surface to the volar side of the socket may aid prosthesis users in stably clamping objects against their bodies. The compliant surface can conform to objects and could potentially be detachable for cleaning or replacement. As seen in figure 10 transradial participants pushed objects more frequently than pulling them.

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 pulling. Transradial subjects, especially those using body-powered devices, frequently use their prosthesis to stabilize objects (fig. 10). Sometimes participants placed 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. Having a flat surface on which to rest objects may aid prosthesis users in supporting objects. Terminal devices should also be designed such that prosthesis users can push objects with two points of contact rather than one as this leads to "stable pushing" [17]. While humans are adept at using visual information to guide movement of the prosthesis, perhaps designing the device to allow stable pushing could decrease the user's dependence on visual feedback. Further exploration of these suggested modifications for non-prehensile use likely would not contribute greatly to the scientific community.

Within Participant Analysis: Duration

During the video analysis process, the type and duration of each grasp and manipulation are recorded. In contrast to the sampling method used to analyze frequency of use, analyzing duration does not require dividing the video into five minute intervals to create multiple data points. Instead, the duration of each grasp or manipulation is a data point. Some grasps were used sparingly within the 70 minutes of data analyzed leading to small sample sizes. Only grasps or manipulation that occurred five or more times were included in this analysis. Normality of the residuals is determined with the Kolmogorov-Smirnov test. Given the lack of normality, the Mann Whitney U test is used to detect significant differences in duration of various grasps.

Overall the prosthesis is used for grasps that are significantly longer than those performed with the intact hand. This is the case for both prehensile grasps and non-prehensile manipulations. 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 the terminal device is a common complaint among users of myoelectric prostheses [18]. 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 by the prosthesis are 7.3 s longer than those with the intact hand. Participants will often grasp 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 10.6 s and 5.6 s longer with the prosthesis than the intact hand, respectively.

Non-prehensile manipulations are on average 5.3 s longer with the prosthesis than the intact hand. 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 [19]. 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 and complete the manipulation especially if the subject is relying on visual feedback [19]. Hang/thread through, which is sometimes used to transport objects with the prosthesis (eg. hanging a grocery bag or hanger on the device), could also contribute to longer manipulation times since it is used almost exclusively by the prosthesis.

Across all participants prehensile grasps with the intact hand are significantly longer in duration than non-prehensile manipulations with an average difference of 1.9 s. This difference is expected in that push and pull are usually performed quickly while other prehensile grasps such as a pinch grasp on a pen may require a longer duration. For most participants the intact hand performed power grasps significantly longer than pinch grasps (with P6 being the exception to the trend). Power grasps such as the medium wrap mentioned in a related study are well suited for long grasping times and are often used when transporting objects, which could contribute to this difference in duration [16].

Similar to the intact hand most participants used longer prehensile grasps than non-prehensile manipulations, yet the results were less homogenous. Three participants showed the opposite trend, such that non-prehensile manipulations were used for longer durations than prehensile grasps. For the intact hand, all participants had differences in duration between prehensile grasps and non-prehensile manipulations between 1 and 3 s. In contrast the difference in average duration for the prosthesis ranged anywhere from -6 to 17 s (where the negative sign denotes that prehensile duration is shorter than non-prehensile). The spread of the duration of the grasps is much wider for the prosthesis than the intact hand within each participant.

Power grasps are often more stable for the prosthesis than pinch grasps so it is reasonable that power grasps are used for longer periods of time than pinch grasps for all participants except P2A and P8A. 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. Supporting one's body weight also tended to last longer than the other non-transport non-prehensile manipulations.

Between Participant Analysis: Duration

Similar to the previous analysis between participants, we compare duration of grasps 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 DoFs. The subjects (both transradial and above elbow amputee subjects) used significantly longer prehensile grasps and non-prehensile manipulation with the intact hand when using 1 DOF devices than when using multi-DOF devices. Yet, users of 1 DoF and multi-DoF devices did not have significant differences in the duration of grasps or manipulations with their prosthetic devices.

In the transradial 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. On average there is a difference of 1.7 s. Similar to the results based on frequency, this difference between body powered and myoelectric devices is not solely dependent on 1DOF vs. multi-DOF devices. Even among transradial subjects with 1DOF devices, those with body-powered devices use shorter non-prehensile manipulations than those with externally powered devices. Participants with transradial amputations use bimanual carry, action, and transfer on average two seconds shorter than those with more proximal amputations. This is the case for both 1 DOF and multi DOF device users. Lastly, those with transradial amputations use shorter prehensile grasps with the prosthesis than those with above elbow amputations.

Design Considerations

Given the importance of non-prehensile manipulations, with the prosthesis, we would like to suggest a few recommendations for design of new prosthetic devices. These suggestions are especially relevant for users with transradial amputations given that those subjects in this study used significantly more non-prehensile manipulations than the other subjects with above elbow amputations. The suggestions are relevant for both body powered and myoelectric devices. Subjects with body-powered devices used non-prehensile manipulations with the prosthesis with high frequency so these design suggestions may make it easier to use the device in ways they were already using it. For those with myoelectric devices, the design changes may enable the user to employ non-prehensile manipulation strategies that they were less comfortable performing previously. The device should allow for large lateral loading on the fingers so that users can hang objects from the fingers without damaging the device. The end of the digits should be thin enough to insert into handles to permit pulling. Part of the device should have a flat surface to allow for a platform grasp. Subjects in this study often support an object from below with the prosthesis while grasping it with the intact hand. A large flat surface may make it easier for the user to support an object. Lastly, given the high frequency of clamping an object to one's body, we would like to suggest the addition of a high friction, compliant section of the socket that would make clamping objects to the body more stable.

Appendix D. *Grasping in Amputees as Compared to Unimpaired Controls*

Please note that these results have not yet been published.

Background

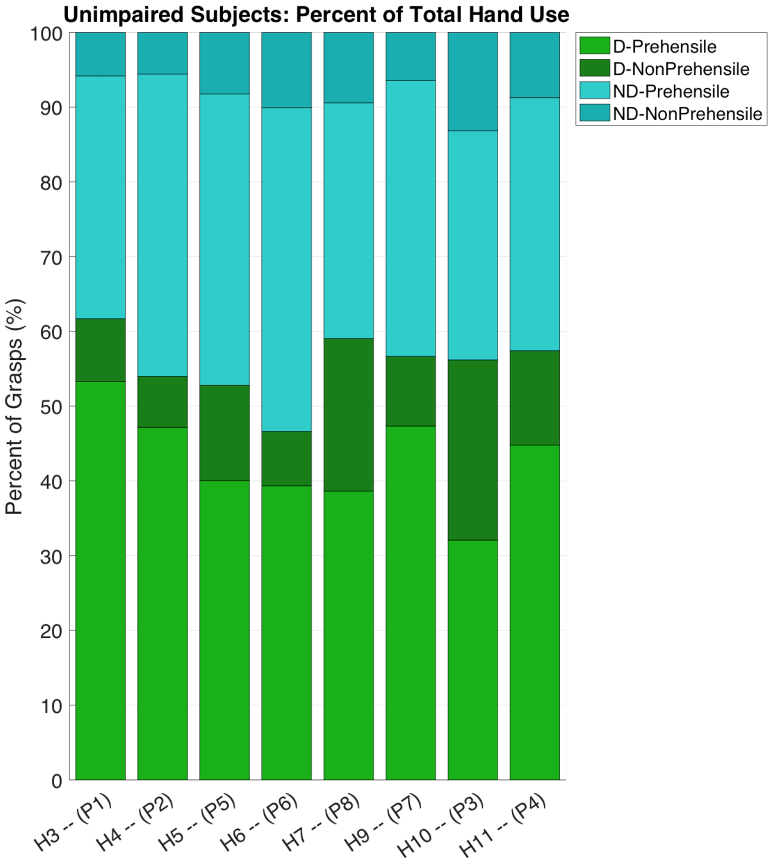


Fig. 11. The bar graph shows the percent breakdown of prehensile and non-prehensile use for each hand out of the total number of tags by both hands. D stands for dominant and ND for non-dominant.

While there have been studies of grasp use in healthy individuals [20][16], for a direct comparison against our amputee subjects, it is important to collect data in the same way, using the same taxonomy and from similar unimpaired participants. As mentioned previously, all amputee subjects use their intact hand significantly more frequently than the prosthesis. Yet, if the intact hand is considered their dominant hand, it is expected that they would use it more frequently. Comparing the hand use in amputees to the unimpaired subjects will demonstrate to what extent dependence on the intact hand differs from controls' dependence on the dominant hand. This analysis will also consider specific grasp use, which may show that amputees use certain grasps with the intact hand to compensate for shortcomings of the prosthesis.

Methods

Eight able-bodied subjects matching the age, height, weight and gender of the amputee subjects were identified and recruited. These subjects completed the at-home video study using the same set of instructions so that the resulting film and data can act as a control to the amputee grasping and manipulation data. The videos are tagged using the same video processing software, and the tags are analyzed with the same statistical tools. Both the dominant and non-dominant hands of these participants are tagged according to the same set of tags used for the intact hand of the amputee participants (ie. power, pinch, intermediate, non-prehensile, other). Instances of bimanual use are also tagged and analyzed.

Results

Figure 11 displays the percent of total hand use for each of the 8 unimpaired participants. In contrast to the amputee subjects, the controls have grasp and manipulation percentages that are very similar to one another. The controls also use each of their hands approximately equally (~50% of total use for each hand) whereas the amputees used their intact hand significantly more frequently than their prosthesis. Another difference between the amputee and control subjects is that the controls use a larger percentage of prehensile grasps than non-prehensile manipulations with their non-dominant hand. Additionally, the unimpaired participants are using more prehensile grasps with the non-dominant hand than the amputees are using with their terminal device. Yet, the data from some of amputee subjects had the reverse trend: the subjects used more non-prehensile manipulations than prehensile grasps with their non-dominant hand (ie. their prosthesis) as discussed previously.

We compared the frequency of power, pinch, and non-prehensile tags between the controls' dominant hands and the amputees' intact hands. Likewise, we compare frequency of tags between the controls' non-dominant hand and the amputees' terminal device.

1. Across all types of grasping and manipulation, the amputees use their intact hand significantly more frequently than the controls use their dominant hand.
2. The amputees use their terminal device significantly less frequently than the controls use their non-dominant hand. This is expected, as the prosthesis is not able to function at the same level as the non-dominant hand of the control.
3. Controls use more bimanual action and carry than the amputee subjects.

Because amputees and controls are using their hands with different frequencies, we must consider percent of hand use in order to more accurately compare use of specific grasps. Therefore, the results below refer to percent use by the intact hand or prosthesis. For example, we will compare the percent of all dominant hand tags that are power by the control to the percent of all intact hand tags that are power by the amputee.

1. The amputee participants use a significantly ($p < 0.05$) larger percentage of non-prehensile manipulations out of total intact hand use than the control participants. Perhaps the amputee participants adopt some of the same non-prehensile strategies that they commonly use with their prosthesis with their intact hand.
2. The controls use a larger percentage of power and pinch out of total non-dominant hand use than the amputees. Conversely, the controls use a smaller percentage of non-prehensile manipulations out of total non-dominant hand use than the amputees, which reflect the results discussed previously.

The results above discuss general trends observed when grouping all the amputees and comparing them against all of the controls. However, it is important to consider the different level of amputations, types of terminal devices, and powering of the devices as well. We will consider both frequency of non-prehensile manipulations and percentage non-prehensile manipulations of total prosthesis use as compared to that by the controls' non-dominant hand.

1. Grouping all participants together reveals no significant differences in frequency of use of non-prehensile manipulations between the amputees and controls. Yet, if we look at the amputees based on their amputation level and powering of the device we see the following:
    1. Amputee participants with transradial amputations using body-powered devices use significantly more non-prehensile manipulations than their matched controls.
    2. Yet, there were no significant differences between the transradial participants with myoelectric devices and their controls.
    3. The amputees with above elbow amputations use significantly fewer non-prehensile manipulations than their controls with their non-dominant hands. This is likely related to the limited arm mobility that may make use of some non-prehensile strategies challenging.
2. Given that the prosthesis is used much less frequently than the controls use their dominant hands, we must also consider percent non-prehensile tags out of total prosthesis use as compared to percent non-prehensile tags of total non-dominant use. Grouping all participants together shows that amputees use a significantly larger percent of non-prehensile manipulations out of all prosthesis tags than the controls.
    1. This same trend is true when we consider transradial amputee participants with body-powered devices against their controls and also the transradial participants with myoelectric devices as compared to their controls.
    2. Yet, for the amputees with above elbow amputations, there are no significant differences in percent use of non-prehensile manipulations out of total prosthesis use when compared to their controls.

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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 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.

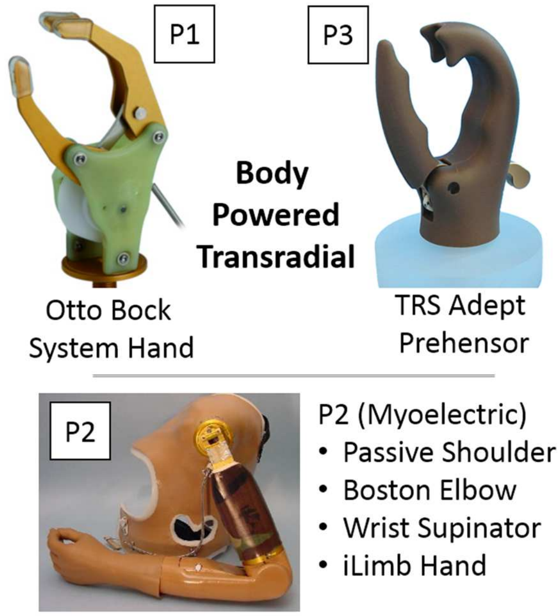

Figure 3: Participant prosthetic devices. All participants have used their device every day for over 6 months.

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

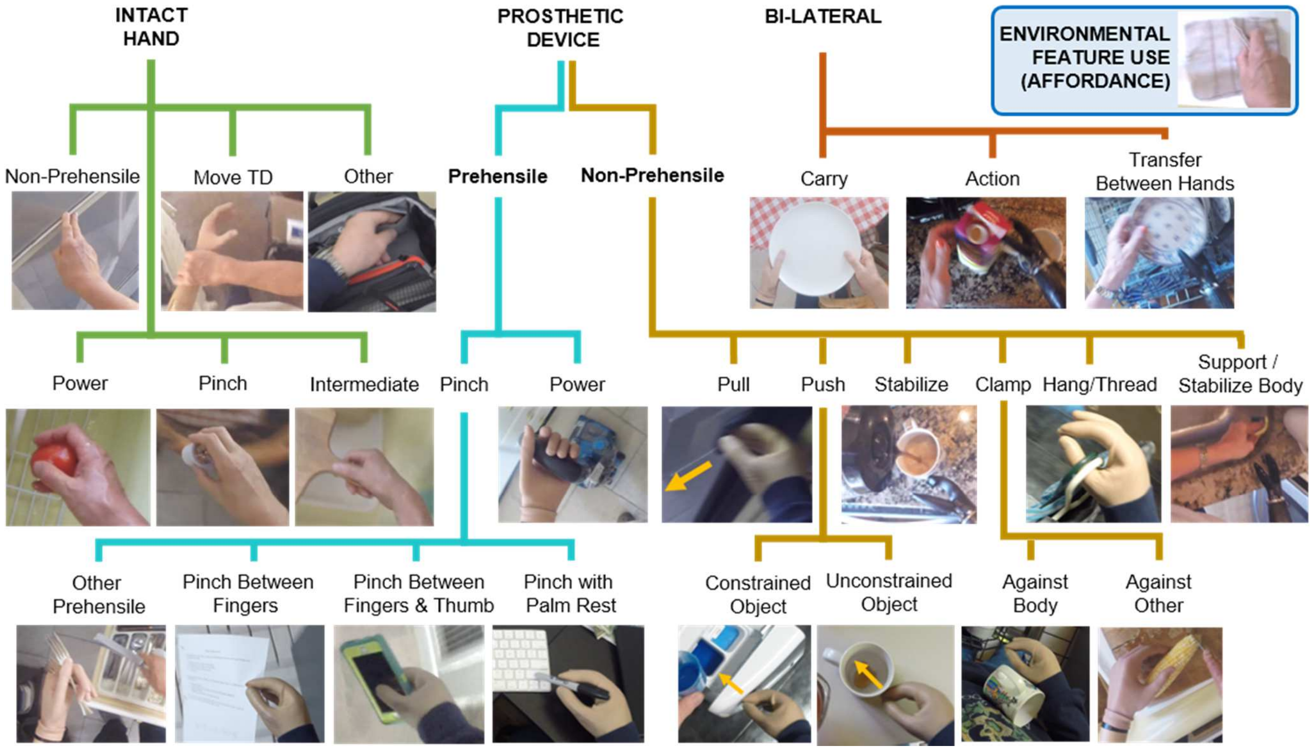

Figure 4: The Prosthesis-User Manipulation Taxonomy. The Top-level categories of manipulation actions are not mutually exclusive. E.g. a bi-lateral action will involve manipulation tags for both hands and may also use environmental features to assist with object stability (affordance use). Note that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

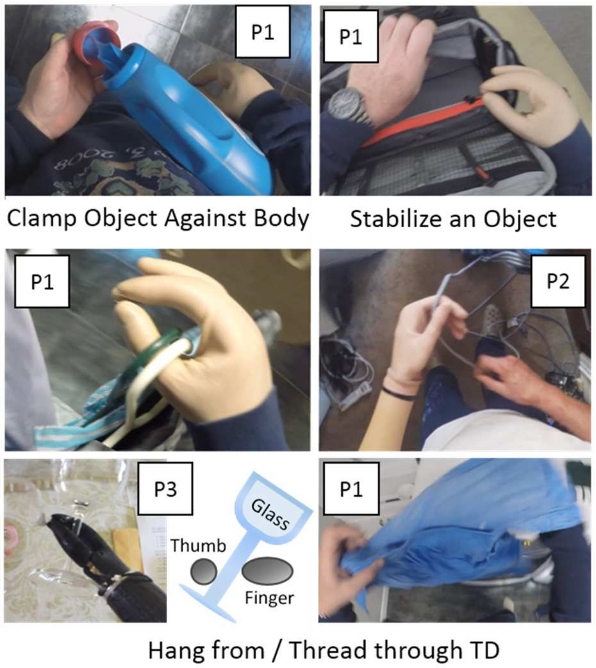

Figure 5: A sample of non-prehensile object interactions. In the top right image the flap of a bag is being held open. In the bottom left image the stem of a wine glass is much smaller than the closed grasp aperture, hence the glass 'hangs' from within the TD.

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

```
GRASP not in Progress      CurrentFrame: 8866 / 20622   Tag Current / Total: 1 / 883    Tag Number: 1                 Tag type: 10
Step Speed: 1              Time: 295.84 / 688.11 s      Key 'o' - Load tags from file   Tag Button / Column: S / 4    Tag label: HHand - Non-Prehensile   20622
Start                                           Half                                           End
```

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.

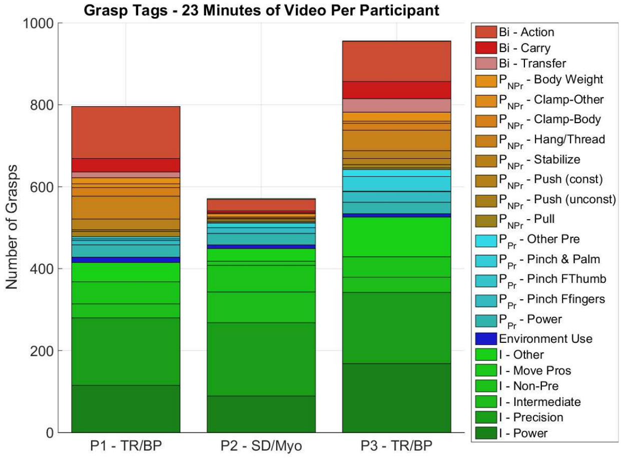

Figure 7: Tag frequency across participants. I refers to the intact hand. P_{Pre} and P_{NPr} refer to prehensile and non-prehensile prostheses use. Bi is Bilateral.

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.

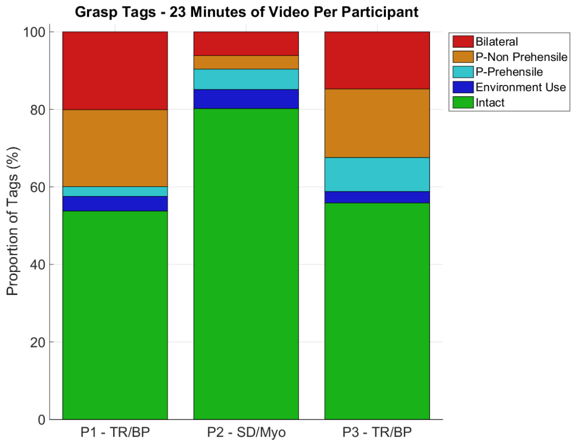

Figure 8: Overall tag distribution by group per participant, as a proportion of 100% of their recorded tags. P2 uses their intact hand more than other users.

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

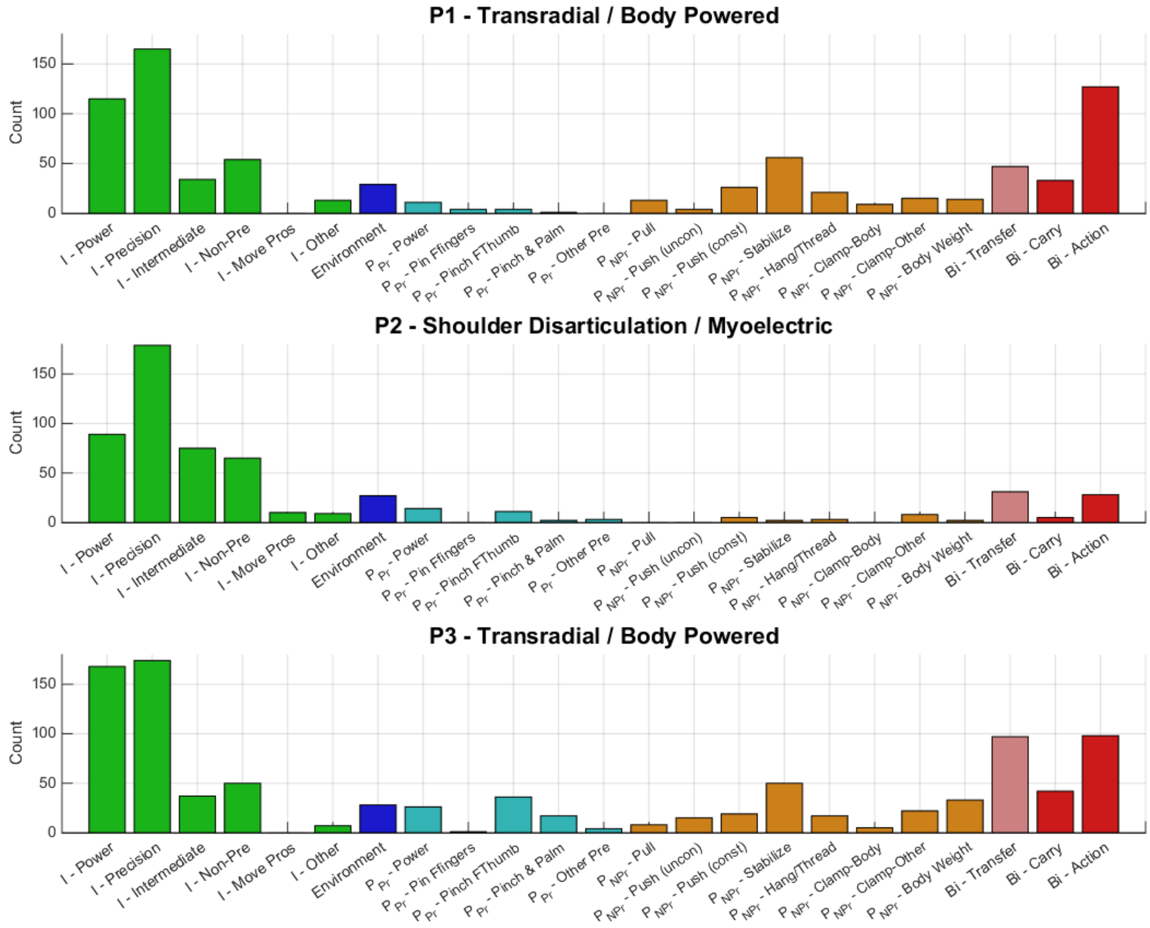

Figure 9: Frequency of different manipulation tags across the participants during the analyzed videos.

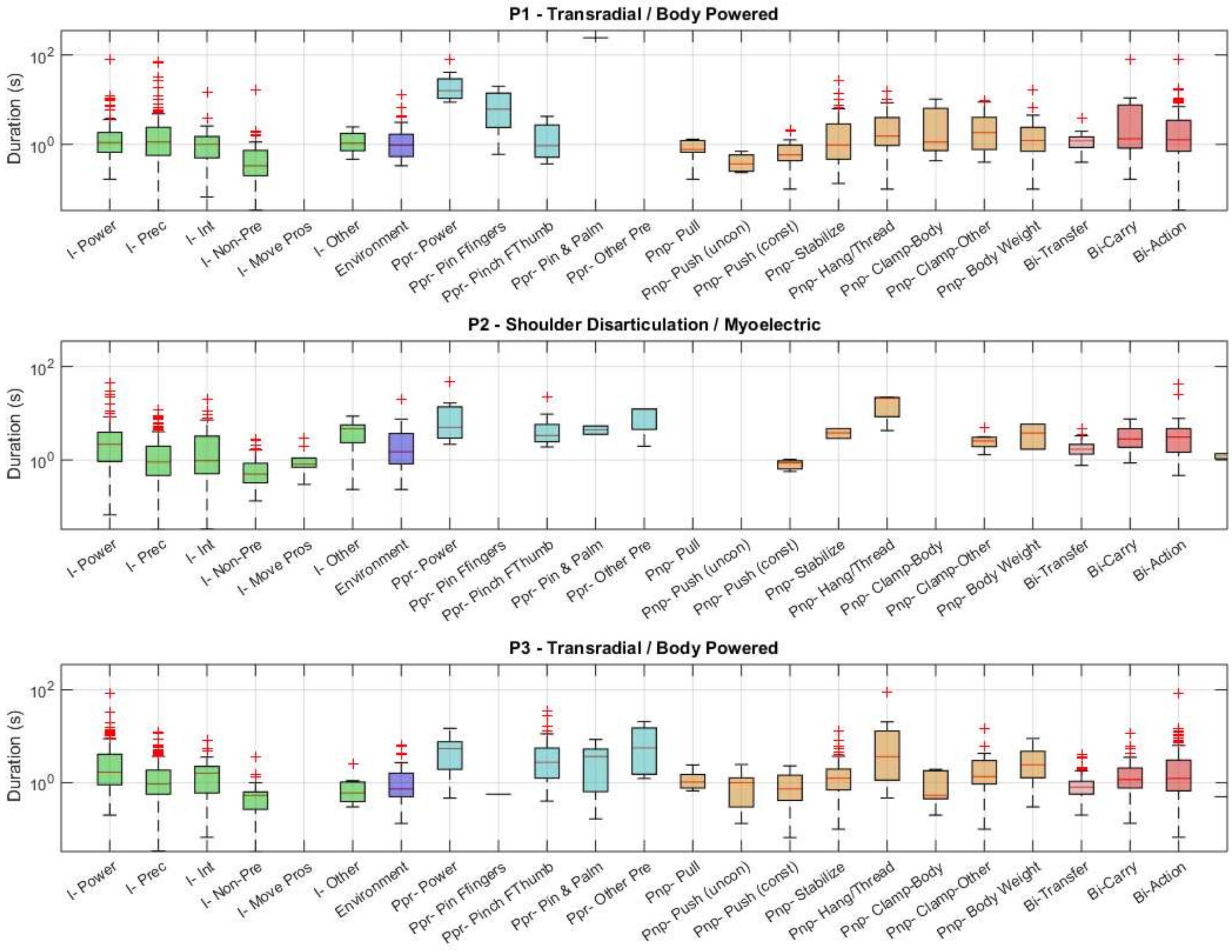

Figure 10: Tag length distribution. Note the time scale is logarithmic.

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.

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Analyzing Exfordance Use by Unilateral Upper-Limb Amputees*

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Abstract— **Humans often use features of their environment for assistance in picking up and manipulating objects or in stabilizing their own bodies. This 'exfordance' use occurs when external contact or gravitational or inertial forces are utilized to aid in task completion or stabilization. This paper presents a categorization of exfordance use and applies the new framework to quantifying how experienced unilateral upper-limb amputees use of exfordances during everyday activities, both in their affected and unaffected limbs. Head-mounted cameras were used to record video footage of participants in their homes while they completed self-selected activities of daily living. A total of 35 minutes of dense manipulation footage has been analyzed for each of 5 trans-radial amputees with different prosthetic devices, resulting in over 4,700 instances of observed exfordance use. The results indicate that participants used exfordance-based vs. non exfordance-based manipulation strategies approximately the same amount with both their intact and prosthetic hands, after adjusting for overall hand use. Furthermore, the specific exfordance use strategies vary substantially between limbs, with participants using environmental surfaces such as tables to guide the motion of their unaffected hand more frequently than with their prosthetic hand, possibly due to increased control and passive conformation ability. Also, participants used gravity-based exfordances (e.g. hanging a towel over the hand) much more frequently with their prosthetic, likely due to its reduced grasping capabilities.**

I. INTRODUCTION

Humans frequently use features of their environment to aid manipulation and stabilize their bodies: When it is difficult to pick up a credit card directly from a table, we may slide it to the edge. To walk up the stairs, we often use a handrail to aid stability. Indeed, environmental constraints are often used even when they are not necessary for task completion [1][2]. We define the usage of features external to the object being manipulated, including contacts with the environment or other objects and gravitational or inertial forces as "exfordance use" – harkening the concept of "affordances" [3], but focusing specifically on features that are generally external to the design of the object being grasped or manipulated.

Figure 1. A screenshot of the head-mounted video camera footage of P3.

Aside from providing more general insight into the nature of human manipulation function (which has use in rehabilitation, robotics, and animation, among other areas), studying exfordance use in amputees allows us to address our hypothesis that amputees utilize exfordances in a significantly different way than non-amputees, both in the usage of the prosthetic (e.g. making up for its relatively limited functionality) as well as in the non-usage of it (e.g. since certain strategies cannot be performed). Understanding this can give insight into the design and control of upper-limb prosthetics as well as other assistive technologies.

This paper presents a categorization of human exfordance use, which is useful for both amputees and non-impaired individuals alike. It then applies that categorization to video data collected from an experiment in which the upper-limb usage of uni-lateral upper-limb amputees is filmed via a head-mounted camera pointed in front of the wearer (e.g. fig. 1)[4]. That video data is analyzed to better understand how unilateral upper-limb prosthetic-users take advantage of the external resources during common activities of daily living (ADL).

A. Related Work

We don't take the proposal of new terminology lightly, but while there are some terms used in the literature that are related to the concepts that we are trying to capture, nothing has been proposed that fits properly. In a study examining the configuration of a one degree of freedom compliant hand as determined by the object, control inputs, and the surrounding environment, Bonilla et al. utilizes the term 'enabling constraints', which are "the set of all possible physical interactions between the hand, the object and the environment" to achieve the desired grasps [5]. Another effort created a grasp planner that exploits 'environmental constraints', which are defined as "a feature of the environment that enables replacing aspects of control and/or

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perception with interaction between hand and environment" [6]. Both of these concepts are similar to what is being proposed here, but the first is too broad and the second, too narrow. Enabling constraints includes the forces between the hand and object, which cannot by itself constitute exfordance use. Strategies that exploit 'environmental constraints' are limited to the environment whereas exfordance use also considers object inertia.

Lastly, the concept of 'extrinsic dexterity' has been described as a robotic hand's additional in-hand manipulation capabilities conferred by use of external forces including gravity, contact between the object and a surface and the motion of the robot arm [7]. However, the term does not describe the external forces/contacts themselves nor does it consider how external forces can aid non-prehensile manipulations. Furthermore, these concepts do not include interaction between the manipulator and environment when there is no object to be manipulated.

Instead, we build off of the concept of 'affordances' first introduced in the psychology literature used to describe perception of action possibilities [3]. Stairs afford climbing; a chair affords sitting, lifting or pushing. The idea of affordances has proven promising in terms of planning for humanoid robots [8]. Exfordance is related to the idea of affordance in that it refers to how the environment enables humans to perform certain actions. Exfordance, however, refers to external resources that specifically aid the hand in grasping, manipulating, and completing tasks. The two ideas are distinct, thereby requiring a new term.

In the human manipulation research literature, several studies have explored motions that can be considered exfordance use in non-impaired humans in structured environments. Chang et al. conducted a study on pre-grasp manipulations and found that humans choose to rotate an object prior to grasping it even when that manipulation is not necessary [2]. The authors suggest that rotating the object helps the human to avoid an extended elbow, tilted torso or atypical grasp. Other commonly used pre-grasp manipulations that require the use of the environment and are enumerated in [9].

Two notable studies measured the level of interaction between the hand and a support surface while picking up small cylindrical objects such as screwdrivers and pens [1][10]. When participants were asked to avoid contacting the support surface, they were able to complete the task with little effect on their success rate. Nevertheless, when no constraint was present, participants took advantage of the support surface. The authors discovered interaction with the environment increases with larger uncertainty of the location of the object, simulated by blurring the subjects' vision [10]. Wang and MacKenzie found that the presence of a support surface increases manipulation speed when sliding an object from a start position to a goal position in the same plane [11]. The authors attribute this to the support surface's effect of constraining manipulator's motion to two dimensions, thereby reducing uncertainty in the object's position.

In robotic manipulation, traditional approaches generally sought to avoid any interaction with the environment as it was seen as an obstacle and could result in large unintended forces. In recent years however, roboticists, inspired by the notion that environmental contact reduces the uncertainty associated with grasping and manipulation have created control strategies that take advantage of environmental constraints. These strategies can utilize forces from the environment applied to the hand or to the object. The methods of [1][10][12] suggest strategies for grasping small objects from a surface. This strategy, termed surface-constrained grasping [10] involves bringing compliant fingers into contact with the surface, closing the hand and letting the surface constrain the fingers to a plane as the fingers begin to grasp the object. Yet another paper presents strategies for grapping in clutter that involves sweeping and push-grasping both of which rely on the environment [13]. Taking advantage of the environment resulted in shorter task completion times and a strategy that is more robust to uncertainty associated with object position [13]. In addition, the studies described at the beginning of this section [5]–[7] all describe work relevant to that proposed in this paper.

II. METHODS

A. Experimental Method

The human subject studies cited in Section I.A took place in structured environments and were limited in scope as they only considered a few ways in which humans use the environment. Though the provided insights are valuable, it is unlikely that these studies capture the full range of manipulation activities and environmental use found in everyday life. In contrast, other approaches for gathering data in unstructured environments, primarily using head-mounted cameras without experimenters present, may provide a more accurate representation of human hand use during day-to-day activities [4],[14], [15]. This method does however come at the cost of less controlled experimental procedures, leading to data analysis challenges.

A brief overview of the experimental method is presented in this section, though a more detailed description may be found in [4]. Video footage is collected using head mounted GoPro cameras, aimed downwards, so that the hands of the participant are in view. Subjects are asked to perform a variety of ADL's from a provided list. This includes such activities as 'preparing a meal', 'sweeping the floor' and 'folding laundry'. Participants are also requested to limit the time spent in sedentary activities such as watching television or using the computer. The subjects are in their own homes without the presence of an experimenter. Eight hours of video are collected per participant and then analyzed using custom video tagging software.

The video tagging software uses a midi interface (Korg NanoKontrol 2) as a hardware controller. This allows the researcher to adjust playback speed, step through the video frame-by-frame, and record the beginning and end of each exfordance use (referred to as a 'tag') using dedicated buttons. A tag is associated with either the intact, prosthetic, or both in the case of a bimanual action. The exfordance type, start and end times are recorded and later processed using MATLAB. Two researchers tagged the videos for exfordance use. Inter-rater agreement is assessed by visually comparing the frequency of tags from the two taggers on the same video.

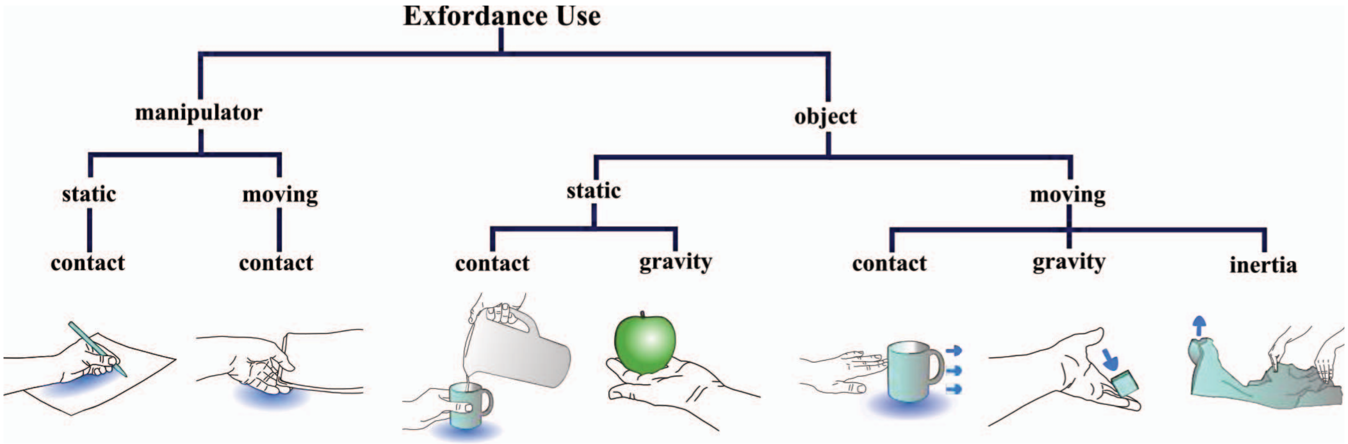

Figure 2. Exfordance use taxonomy. The blue shaded areas highlight contact with the environment, and the blue arrows indicate motion.

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

B. *Participants*

The study recruited unilateral upper-limb amputees that have had their prosthetic device for at least six months and use the device everyday. Participant details are in table 1.

TABLE I. PARTICIPANT INFORMATION

	Age	Gender	Prosthetic	Power	Glove
P1	49	M	Otto Bock System Hand	BP	Yes
P3	60	F	TRS Adept Prehensor	BP	No
P4	40	M	Split Hook	BP	No
P5	51	M	iLimb Quantum	Myo	Yes
P6	22	F	iLimb Quantum	Myo	No

While the full study includes subjects with varying levels of amputation, this paper only analyzed video data for trans-radial amputees. The participants are named P1-P6 to correlate with [4]. This paper does not include analysis of P2, given that participant has a shoulder disarticulation.

III. DATA ANALYSIS

A. *Exfordance Terminology*

As mentioned above, we define the usage of features external to the object being manipulated, including contact with the environment or other objects or gravitational or inertial forces as “exfordance use.” Humans use exfordances when the object’s inertia or any external forces from the environment help stabilize the object or affect its motion. Humans also use exfordances when contacting the environment with the manipulator aids in stabilizing oneself or affects the motion of the manipulator for the execution of a manipulation task. The definition of human exfordance use was developed empirically after viewing video footage of naturalistic and undirected motions from 5 amputees and noticing the frequent utilization of external features to aid in manipulation tasks.

In this paper the term manipulator refers to both the hand and arm, as the arm is commonly used in stabilizing one’s body and to carry objects by hanging them over the arm. The environment includes external force fields, namely gravity and the set of surfaces that is neither the manipulator nor the object itself. Other objects that are surrounding the object being grasped or manipulated can also be considered the environment. For instance, when a subject is reaching inside a backpack to grasp a notebook, the backpack becomes the environment and the notebook is the object. Yet, when the subject is grasping the backpack, it is considered the object.

Such considerations have led us to formulate the hierarchical taxonomy in fig. 2. Initially exfordance is divided into two main groupings based on whether the exfordance directly involves the *manipulator* or the *object* itself. Exfordance strategies are categorized in the same way for the intact hand and prosthetic hand cases. Creating the taxonomy resulted in 7 distinct types of exfordance uses shown at the end point of each branch in fig. 2. Each type is named based on the branch from which the end point originated.

The *Manipulator* section of the taxonomy is further subdivided into two categories, based on whether the object is static or moving. These types of exfordance use are due to the manipulator’s contact with the environment as opposed to gravity or inertia. This is reinforced by “Contact” at the end of the category name.

1. Manipulator.Static.Contact – the environment is used to *support* the *static* manipulator through contact between the environment and the manipulator
2. Manipulator.Moving.Contact – the environment is used to *guide, augment, or constrain* the *motion* of the manipulator through contact between the environment and the manipulator

Manipulator.Static.Contact is commonly used by humans to steady themselves when they perform actions that alter the location of center of mass from its typical location. For example, leaning over a counter or crouching down on the ground. This exfordance usage occurs during the ‘support/stabilize body’ non-prehensile manipulation tag defined in the Unilateral Prosthetic-User Manipulation Taxonomy (UPM) [4]. This strategy is also used during tasks like writing. In such an activity, part of the hand rests on a surface to steady the hand position while the fingers move the writing implement. In robotics, this strategy can be used to stabilize the body of a humanoid [8] or to grasp small objects. To grasp a small object the palm is positioned against a surface while the fingers push the object toward the palm[10].

Manipulator.Moving.Contact has previously been suggested as a promising strategy for grasping objects with compliant hands under the name 'force compliant grasping' [1] or 'surface constrained grasping' [10]. This strategy has also been used in grasping small objects with underactuated fingers [12]. Our study participants commonly use this strategy with their intact hand when picking up an object from a surface. The surface guides the fingers as it approaches the object. This strategy is used in surface-constrained and wall-constrained grasping presented in [6]. Wiping a table such that the surface constrains the motion of the hand is yet another example of this strategy. Even though environmental contact is required in this case (since the subject would not be able to complete the task of wiping the counter without physically contacting the counter) it is still considered use of an exfordance

The *Object* section of the categorization also has two main categories based on whether the object is static or moving at the time the exfordance is used. These categories are further subdivided based on the source of the force: contact with a surface or gravity. Object inertia is also considered since it is a feature separate from the manipulator that affects the motion of the object. The robotics literature has not included the static portion of the categorization since the community has traditionally focused on manipulating an object or in grasping an object without help from the environment.

3. Object.Static.Contact – the environment is used to support the static object through contact between the environment and the object
4. Object.Static.Gravity – a gravitational force is used to aid in stabilizing the static object
5. Object.Moving.Contact – the environment is used to *guide, augment*, or *constrain* the motion of the object through contact between the environment and the object
6. Object.Moving.Gravity – a gravitational force is used to augment the motion of the object
7. Object.Moving.Inertia – the inertia of the object is used to affect the motion of the object

A human may employ the **Object.Static.Contact** strategy by using the environment to support some of the object's weight to reduce fatigue on the limb or in securing the object during a non-prehensile manipulation. The UPM defines 'stabilize an object', 'clamp against the body', and 'clamp against the environment' all of which use this exfordance [4]. In the case of a deformable object, the support surface can stabilize the rest of the object while the human is manipulating a portion of it. A common situation in which human subjects use this strategy is in folding laundry. A subject lays the item of clothing flat on a surface and picks up different sections to fold it over on itself. In terms of the enabling constraints found in [5], this strategy and Object.Moving.Contact are results of the reaction forces between the object and the environment.

The **Object.Static.Gravity** category is often used when hanging an object from or over the manipulator, defined as the 'hang from/thread through' in the UPM [4]. Gravity also helps stabilize the object during non-prehensile platform grasps, which involves an object resting on a flat, open hand.

The **Object.Moving.Contact** category has been alluded to in several papers [2][5]–[7][10][11][13]. One way to exploit environmental constraints is surface-constrained sliding during which the manipulator cages the object and moves it across a surface, such that the motion of the object is constrained by the support surface [6]. Similar to surface constrained sliding is sweeping which typically involves pushing or pulling an object across the surface using a non-prehensile manipulation [13]. In terms of extrinsic dexterity, Object.Moving.Contact falls under quasi-static manipulations of an object with external contact [7]. In quasi-static manipulation with external contacts, the object orientation or position in the hand is modified via external contacts. The authors subdivide that category into specific strategies including but not limited to 'push-in-fingers', 'push-in-enveloping,' and 'roll-on-ground' [7].

Object.Moving.Contact can also be extended to manipulation of objects that are semi-permanently attached to the environment such as doors or multi-part objects that can be disassembled such as a water bottle and its cap. The hinges of a door constrain the motion of the door while opening or closing it, while the external threads on the bottle affect the motion of the cap when screwing it on. In terms of the UPM taxonomy, 'pull an object' and 'push a constrained object' would be considered Object.Moving.Contact. strategies [4].

When gravity augments the motion of an object, it is considered **Object.Moving.Gravity**. Dafle et al. defined this as a passive dynamic strategy that includes such actions as 'roll-to-fingertip', 'roll-to-ground,' and 'roll-to-palm' [7]. Yet, that taxonomy only considers rigid objects; we must also consider deformable objects. The deformable object such as a shirt will assume a new configuration due to gravity as it is being unfolded.

Lastly, **Object.Moving.Inertia** occurs when the object's inertia and the motion of the participant's arms affect the motion of the object. In terms of extrinsic dexterity, this strategy is considered an active dynamic action [7], which is used to reconfigure the object in the hand. Humans occasionally use this strategy with a rigid object to adjust their grasp, but according to our recorded video footage, the strategy is primarily used with deformable objects. For instance, subjects were observed moving their arms quickly to unfold a piece of clothing.

B. Video Analysis

The GoPro camera used to collect the video data automatically segments each video recording into 11m38s or 11m49s files. In this paper, the results from 3 segments were analyzed, leading to approximately 35 minutes of video for each participant. While it does not seem lengthy, this 35 minutes of video captures an average of approximately 1050 manipulation instances and 940 exfordance uses for each participant.

On average, a researcher takes 30 minutes to apply the exfordance framework to each minute of recorded video. The video segments selected had previously been tagged using the UPM taxonomy, as an extension of the preliminary results presented in [4]. While this paper does not discuss the implications of those tags, it does use them to adjust the

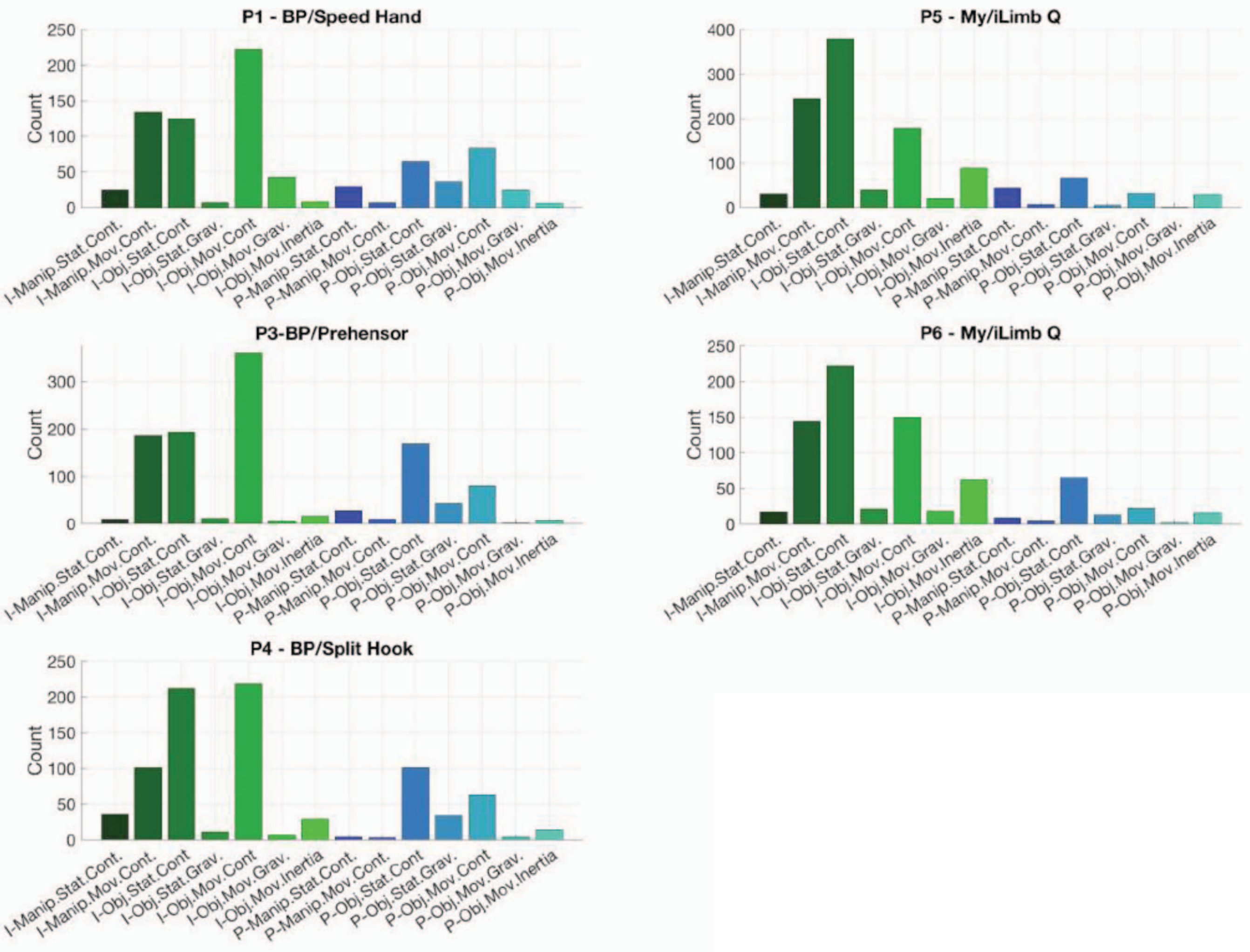

Figure 3. Frequency of exfordance tags for each category during 35 minutes of video for each participant. 'I' refers to intact hand and 'P' to prosthetic.

exfordance use tags based on hand use. [4] presents some data on "environmental feature use" tags, which are similar to exfordance use. However, these tags were collected under a less detailed definition, and so many exfordance uses were not considered. Therefore, the percentages reported in [4] do not match the information presented in Section IV.

The videos contain a range of different activities from leaf blowing and gardening to washing dishes, food preparation and cleaning a kitchen. The selected segments contain almost constant activity with little downtime. Yet, due to the unsupervised and at-home nature of the data recording, the participant's videos do not contain the exact same activities. In addition, participants naturally spent different amounts of times on similar activities. As such, directly comparing between the participants does present challenges.

IV. RESULTS

The log files produced by the custom video tagging software are analyzed using MATLAB. The next subsections will discuss the frequency of exfordance use, the top exfordance use categories, and the difference in exfordance use by the prosthetic and intact hand.

A. Exfordance Tag Analysis

Fig. 3 displays the total number of exfordance use tags for each category based on 35 minutes of analyzed video for each participant. On average the intact hand contributes to 75% of all exfordance use tags.

1) Top Exfordance Use by Intact Hand

The top three exfordance use categories for the intact hand for all participants are Manipulator.Moving.Contact, Object.Static.Contact, and Object.Moving.Contact. Yet, the order of these top three differs among the participants. For the body-powered participants (P1, P3, P4) Object.Moving.Contact is used most frequently while that is the second and third most common category for the myoelectric users, P5 and P6, respectively.

Object.Static.Contact is the most commonly used type of exfordance use for the intact hand of P5 and P6 and is the second most commonly used strategy for P4. These three users each had one video segment that almost exclusively contained manipulation of clothing. Manipulating part of an article of clothing while the remainder is resting on the surface, is considered Object.Static.Contact.

The third most commonly used exfordance for the intact hand is Manipulator.Moving.Contact. This tag was often associated with picking up objects. With smaller objects, participants would surround the object with their fingers and

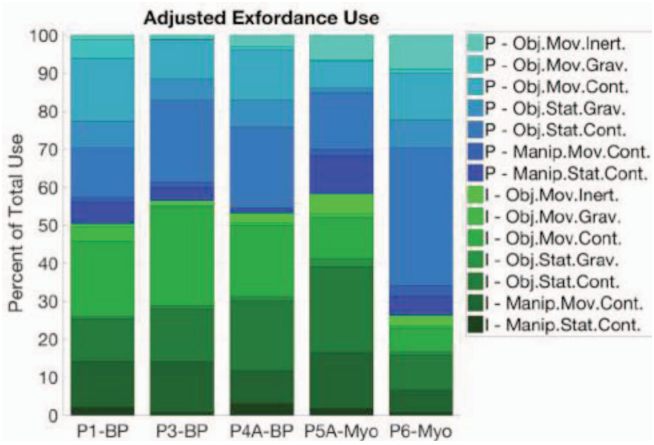

Figure 4. Exfordance use as calculated by (1) for each participant. 'I' refers to intact, 'P' to prosthetic.

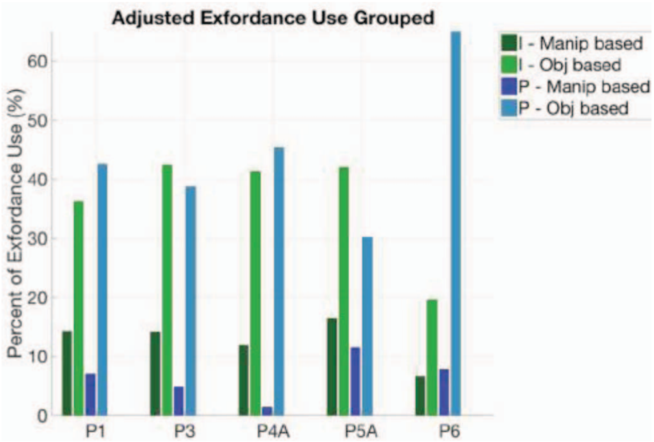

Figure 5. Exfordance use as calculated by (1) grouped based on whether the exfordance involves the manipulator or object.

then move their fingers in toward the object while the surface constrained their motion. With larger objects the amputees would often slide their intact hand on a surface while wedging their fingers underneath the object to lift up part of the object before grasping it.

2) *Top Exfordance Use by Prosthetic Hand*

The primary exfordance use strategies amputees employ with their prosthetic hand are Object.Static.Contact, Object.Static.Gravity, and Object.Moving.Contact. Two of these categories involve a static object, whereas for the intact case, the hand or object are typically moving. The prosthetic is generally used to stabilize a static object (Object.Static.Contact) while the intact hand does fine manipulation of objects that may require articulated finger or wrist motion. One example of this is when participants cut vegetables or fruit. They often clamp the object to the support surface with their prosthetic hand and cut the object with a knife held by the intact hand.

B. *Adjusted Exfordance Use Analysis*

This section analyzes exfordance use after adjusting for overall activity level of each hand. Without adjustment a participant may have many more instances by the intact hand than the prosthetic hand solely because they use the intact hand more often as seen in fig. 3. We assume the number of manipulation tags from the study in [4] provides an adequate measure for overall hand use. Table 2 shows the total number of manipulation tags.

TABLE II. HAND ACTIVITY FOR 35 MINUTES OF VIDEO

Total Number of Manipulation Tags

	P1	P3	P4	P5	P6
Intact	694	765	646	735	1201
Prosthetic	285	368	257	177	87

The following proportion (1) is used to compare the prosthetic hand's use of each exfordance type to total

$$P_{P,j} = \frac{E_{P,j} M_I}{\sum_k E_{P,k} M_I + \sum_k E_{I,k} M_P} \qquad (1)$$

exfordance use of both hands. There is a similar expression for the intact hand. M_P and M_I are the total number of prosthetic and intact hand manipulation tags from [4] $E_{P,j}$ and $E_{I,j}$ are the number of prosthetic and intact exfordance use tags for each category j. $P_{P,j}$ is the prosthetic exfordance use for category j as a proportion of total exfordance use by both hands. Fig. 4-5 present the data using this formulation. Note that the exfordance use tags for the prosthetic hand are multiplied by the manipulation tags of the intact. Alternatively, the exfordance use tags for the intact hand are multiplied by the manipulation tags for the prosthetic. This adjusts the exfordance use tags for both hands such that they are on the same scale.

For most participants, the total exfordance use with the prosthetic hand is roughly equal to that of the intact hand after adjusting for activity of both hands. This is seen in fig. 4 as the sum of each category of the intact exfordance use, $P_{I,j}$ (green) is approximately equal to the sum of each category of prosthetic exfordance use $P_{P,j}$ (blue) for most participants. This is surprising given the hands' difference in capabilities. However, the composition of these tags varies from participant to participant and between the intact and prosthetic hands.

Participant 6 stands out from the other participants in that she had less intact exfordance use and many more prosthetic exfordance use than the other participants. This is the result of many factors including number of manipulation tags (table II), activities in each video, experience, age, and prosthetic hand type.

1) *Adjusted Exfordance Use Grouped*

Fig. 5 groups $P_{I,j}$ and $P_{P,j}$ based on whether the exfordance involved the manipulator or object. On average participants use object based exfordances 81% and manipulator based 19% of total exfordance use. Additionally, all participants except P6 use fewer manipulator based exfordance strategies with the prosthetic hand (6%) than the intact hand (14%). Prosthetic hands have limited compliance and haptic feedback when compared to the intact hand. Therefore, it is reasonable that the intact hand would receive a greater benefit from directly contacting the environment than the prosthetic hand.

Several participants rely on object based exfordance strategies with their prosthetic hand (light blue) more than their intact hand (light green) as seen in fig. 5. This trend is likely due to the shortcomings of the prosthetic in that they

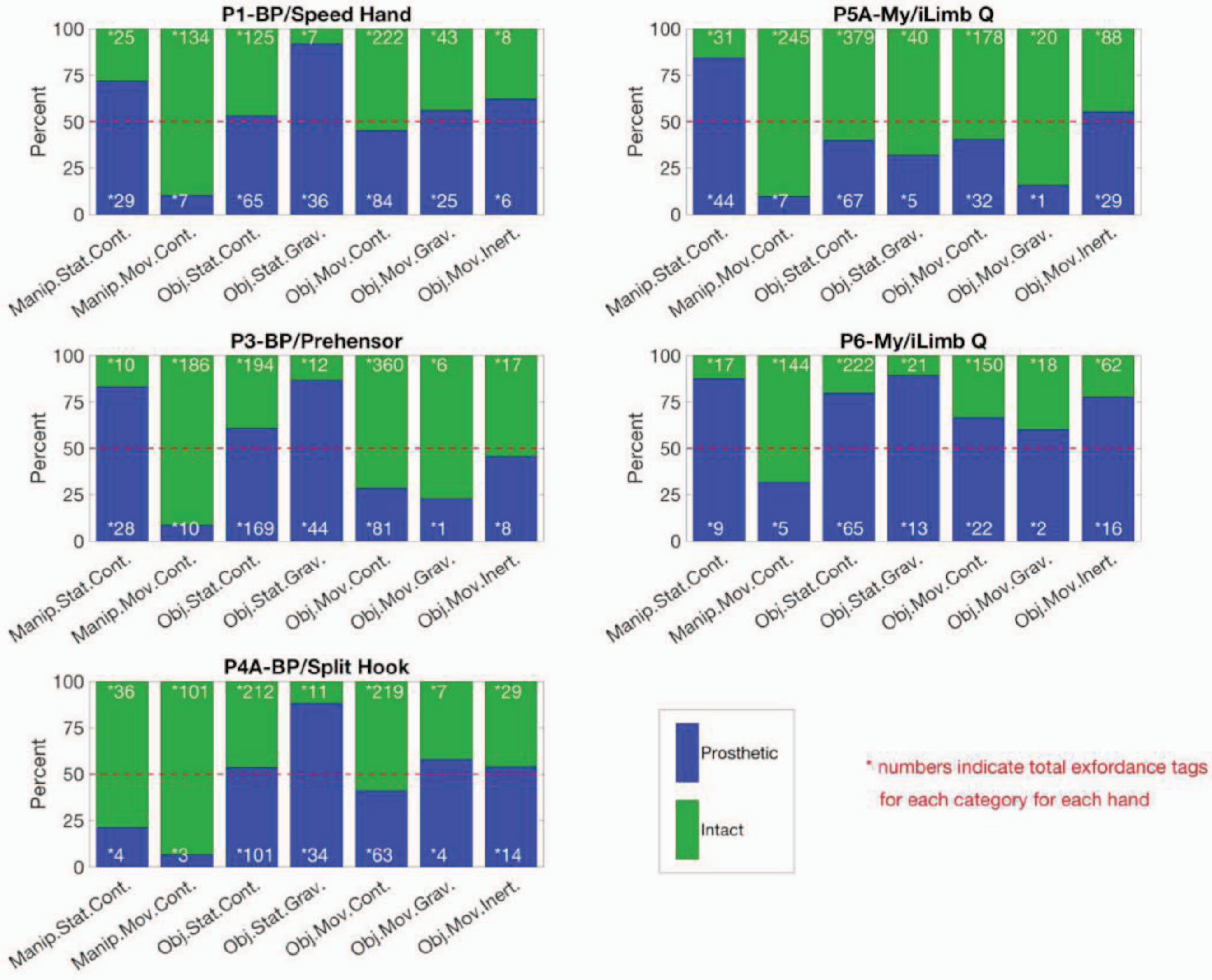

Figure 6. Proportion of exfordance use per category per hand after adjusting for hand activity according to (2).

must rely on gravity or a support plane to stabilize a grasp more so than the intact hand does.

2) *Prosthetic versus Intact Exfordance Use*

Fig. 6 compares prosthetic and intact hand exfordance use for each category. The data is shown as a proportion of total exfordance use by both hands for the particular category as shown in (2), where $C_{P,j}$ is prosthetic exfordance

$$C_{P,j} = \frac{E_{P,j}M_I}{E_{P,j}M_I + E_{I,j}M_P} \tag{2}$$

use for category j as a proportion of exfordance use of category j by both hands. If the division between prosthetic $C_{P,j}$ and intact hand $C_{I,j}$ exfordance use is around 50%, then both hands use that exfordance equally. Note that the numbers in fig. 6 are the raw exfordance use tag counts $E_{P,j}$ and $E_{I,j}$ not the proportion values $C_{P,j}$ and $C_{I,j}$. The number of exfordance tags should be taken into account when interpreting the proportions shown.

a) Manipulator Based Exfordance Use

After adjusting for hand activity using (2) and averaging across participants, the prosthetic hand contributes to 70% of the total use of the Manipulator.Static.Contact strategy by both hands. As mentioned previously, participants often use this strategy to steady themselves with the prosthetic hand while using the intact hand. P4's videos contained more writing, which likely increased the intact hand's use of this strategy.

The intact hand employs Manipulator.Moving.Contact more than the prosthetic hand for all participants (average of 87% of total use). The intact hand rather than the prosthetic hand almost always picks up objects when contact with the environment is required, such as when picking up a sheet of paper or finding an object inside a bag. Based on the video footage, it seems as if the amputees frequently pick up objects with the intact hand and pass them to their prosthetic hand. This suggests that the prosthetic terminal device is less able to interface with environmental constraints present during initial object acquisition likely due to a combination of a lack of a wrist, device adaptability, and haptic feedback.

b) Object Based Exfordance Uses

The Object.Static.Gravity strategy is used by the prosthetic 56% more than the intact. This strategy allows the prosthetic hand to interact with an object without relying on its ability to perform a prehensile grasp. The participants frequently hang items from the prosthetic hand or over it instead of grasping them [4], which contributes to the prosthetic hand's use of this strategy. This exfordance use also allows the prosthetic hand to hold an object without requiring any actuation of the hand.

The intact and prosthetic hands use Object.Moving.Contact approximately the same amount. Yet, the actions associated with this strategy differ between the two hands. When the prosthetic hand interacts with moving objects the objects are generally permanently constrained by the environment such as drawers or doors. Such highly constrained objects may simply be pushed, and they will move on the desired path. In contrast, the intact hand uses this exfordance for constrained objects in addition to objects with fewer constraints. Objects with fewer constraints such as mug resting on a table require more controlled wrist and hand motions to produce the desired motion, which is easier to achieve with the intact hand.

V. CONCLUSION

To the authors' knowledge, this paper presents the first study of amputees' use of external resources that aid in grasping and manipulation tasks. The preliminary results from 35 minutes of video of 5 participants indicate a number of interesting trends that may have implications for prosthetic and robotic hand design and control. Furthermore, identification of important exfordance use categories could influence therapeutic assistance of new prosthetic users in increasing their manipulation capabilities by taking advantage of environmental constraints. Given the few number of participants and limited amount of data analyzed, the results may not be representative of the entire amputee population. For similar reasons, statistical significance is not reported. However, the video and data do indicate:

1. Exfordance use commonly occurs during ADLs (over 4,700 instances for 35 minutes of data).
2. After adjusting for hand activity, the prosthetic and intact hands use exfordances approximately the same frequency. On average (excluding P6) the prosthetic contributes to 46% of the total exfordance use.
3. Object based exfordances are used 62% more than manipulator based exfordances.
4. The prosthetic hand and intact hand make use of different exfordances.
    a. The prosthetic hand relies on gravity to stabilize or grasp a static object 56% more than the intact hand.
    b. The intact hand's motion is constrained by the environment 74% more than the prosthetic hand.

These observations suggest a robust hand design accommodates hanging items from the prosthetic. The presence of a wrist, compliant fingers, and/or haptic feedback would likely better enable the user to directly interface with the environment to pick up objects, which is typically performed by the intact hand. Though the fingers should not be too compliant such that non-prehensile pushing and stabilization become difficult, which are also important for the prosthetic.

The study will move forward by analyzing additional videos from each of these participants and take a closer look at bimanual exfordance use. Additionally, we will explore the duration of each exfordance type and exfordance use in non-impaired individuals.

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Examining the Impact of Wrist Mobility on Reaching Motion Compensation across a Discretely Sampled Workspace

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***Abstract*— This paper presents an effort to characterize the impact of wrist mobility on reaching motion compensation over an evenly sampled planar workspace. When the degrees of freedom of the arm are limited due to injury or amputation, the behavior of other joints is modified to achieve the same motion goals. Though several past studies have measured motion compensation for simulated activities of daily living, the results tend to be specific to one spatial configuration of user and objects. Conversely, this paper aims to understand how motions and compensation vary when the same task (reaching-and-grasping) is conducted at a variety of locations across in the workspace. This high-resolution sampling enables spatial patterns of unimpaired and impaired movement to be identified. To achieve this, joint angles and Cartesian trajectories of the upper body were recorded as able-bodied participants reached and grasped 49 (7×7) equally spaced vertical cylindrical targets on a 1.9×1.9m grid, using their dominant hand. This was first completed naturally and then while wearing a custom orthopedic arm brace, which limits all 3DOF (degrees of freedom) of wrist motion. Each reaching motion was segmented and independently analyzed using metrics for range of motion, and Cartesian path length of body segments. A spatial 'heat-map' display approach visually indicates how regions of the workspace affect the behavior of different body joints and segments. Further statistical analysis quantifies these visual trends. The results indicate wrist mobility has significant impact on shoulder and elbow ROM in addition to the length of Cartesian motion trajectories for the wrist and elbow.**

I. Introduction

Developments in the field of upper limb prosthetics often focus on creating more dexterous prosthetic terminal devices, to replace the absent hands of amputees and facilitate object holding and grasping. This is demonstrated by the wide range of anthropomorphic prosthetic hands generated by industry (e.g. [1]), academia and hobbyists (e.g. [2]). In comparison, there has been fairly little attention given to the development of prosthetic wrists [3], despite the fact that this part of the body is also absent in many amputees. It is common for above-wrist amputees to be fitted with prosthetic devices that either have no wrist, or only a passive pronation/supination mechanism that must be rotated by the other limb or some environmental feature. This effectively fixes the alignment of their prosthetic device with regard to their forearm.

Such an absence of wrist mobility limits the orientation capability of the hand relative to the body. In order to achieve the same target hand orientations necessary for grasping a variety of objects, it is necessary to modify the motion trajectories of other joints. This leads to compensatory movements, which can place additional stress on the body and lead to overuse complications for the remaining joints [4], [5]. An example compensatory motion for a trans-radial amputee involves elevating the elbow while drinking, to facilitate the tipping of mug or bottle to the mouth, an action that is usually carried out by the wrist. This action increases shoulder motion to compensate for the lack of wrist mobility.

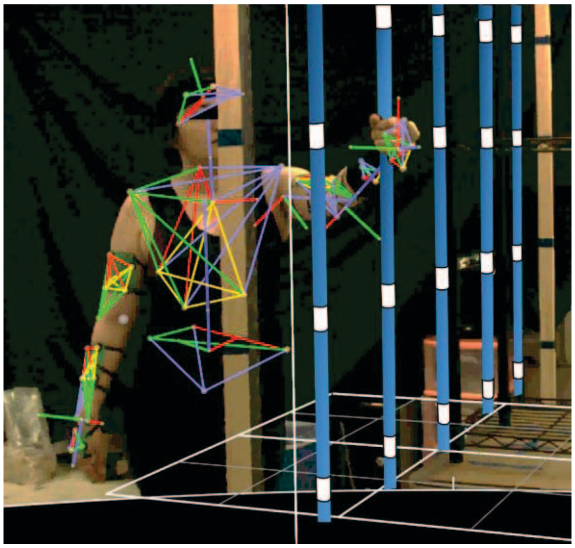

Figure 1. A participant reaching to one of the 49 targets on the grid. Their motion capture 'skeleton' has been overlaid, illustrating co-ordinate frames of their trunk and dominant (left) arm. Five of the seven vertical poles have been coloured blue to improve visibility in this image (their actual color is black, to reduce reflectivity).

The importance of the wrist for appropriately positioning the hand has been highlighted in work such as [4]. Here the authors argue that coupling a simple gripper with a dexterous wrist could be more effective for aiding manipulation than the current practice of fitting dexterous multi-grasp prosthetic hand to sockets without wrists. It should be noted however that prosthetic wrist technology is still limited in terms of capability, and that issues of controlling multi-DOF wrists have yet to be adequately addressed [3].

Compensatory motions have been previously studied by various groups for various medical conditions [4]–[7]. These studies all involved ADL (activities of daily living) tasks such as preparing food, lifting an object or completing tasks from a standardized hand function outcome measure (e.g. the SHAP

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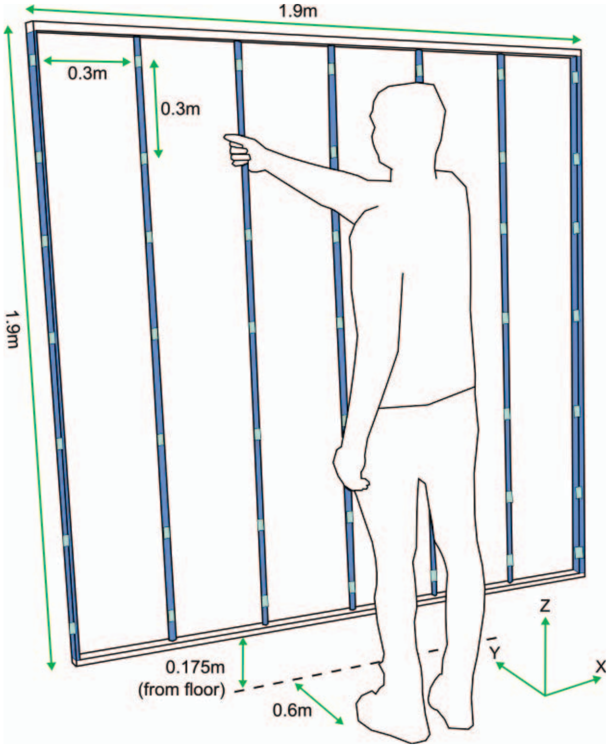


Figure 2. The grid is suspended from a modular shelving unit. The vertical poles and wooden outer supports of the grid feature reaching targets (indicated with tape). Targets have 0.3m seperation in vertical and horizontal directions. The global co-ordinate axis are shown.

test). In this work, we wish to build upon these studies by proposing the characterization of motion compensation over a user's workspace via discrete sampling. Similar approaches have been applied to modelling parameters across the workspace of simple robot manipulators [8]. Our goal in this work is to understand and quantify how different regions of a user's workspace impact compensatory motions in different joints of the body.

In this paper we introduce a method of studying compensatory motions across a user's workspace with a semi-abstract reaching task. We use an equally spaced 7x7 grid of vertically orientated cylindrical targets to simulate the grasping of common objects (e.g. cups, cans, etc.) at various heights and lateral displacements from a participant's body (Fig 1 and Fig 2). A Vicon motion capture system enables recording of body motion for the reaching actions necessary to grasp each target, thereby allowing characterization of the workspace with respect to a variety of metrics. Reaching to objects at various locations in a workspace is a common manipulation scenario that may be found in many kitchen, wardrobe or supermarket settings (Fig 3). These environments are associated with eating, dressing and shopping, which are beneficial for personal independence. In this study, participants reach to all points on the grid unimpaired and whilst wearing a custom device to brace wrist motion.

Figure 3. Supermarket shelving is a common environment that requires reaching to multiple target locations in an individual's workspace (image from Alamy.com)

Reaching motions and joint trajectories are known to be similar within and across unrestrained healthy participants [9], [10], though error bounds are visible in joint-angle measurements (e.g. [7]). To allow better interpretation of this similarity, we present a 'heat-map' based representation of various metrics. We also provide a statistical method to allow between subjects comparison of the resulting data, highlighting which joints have similar patterns of compensation across participants.

II. RELATED WORK

Various groups have highlighted and made efforts to quantify compensatory motion in persons with impaired wrist mobility (e.g. [4]–[7], [11]–[14]). A common protocol in these studies involves participants performing simulated ADLs, while under observation from a motion capture system. Often, the Range Of Motion (ROM) of a joint is calculated for different study conditions [4]–[7], [11], though other metrics, such as mean angle [14], have been applied.

The SHAP (Southampton Hand Assessment Protocol) [15] test has featured in a variety of motion studies, due to its standardized simulated ADLs, which explore different grasps and manipulation capabilities. In [7] the page-turning task of the SHAP test was used to compare the joint motions of unimpaired participants with those who had previously experienced a wrist injury. Joint ROM comparisons illustrated that impaired participant joint motion was often outside of the typical range of uninjured participants.

In [5] able bodied and amputee prosthesis-users performed a number of ADL tasks while their trunk and head motions were measured, with increased ROM identified in the prosthesis users. A similar study measured trunk, shoulder and elbow ROM during selected SHAP test tasks [11].

To enable the study of body compensation within-subjects, wrist splints (which limit flexion/extension, radial/ulnar deviation and partially limit pronation/supination) were used to constrain participant wrist mobility in [4], [13], [14]. In [4], participants performed tasks from the SHAP test while their wrist or finger motion was restricted. ROM was reported for trunk and shoulder angles. An alternative outcome measure, the Jebsen test, was used as the basis of participant motion in [13]. Only a limited number of forearm, elbow and shoulder and trunk motion differences were statistically significant for particular tasks. However, participants did report more impairments in self-reporting surveys. In [14], the task was limited to removing an object from a box. Mean joint angles were calculated with/without a wrist splint as a measure of compensatory motion.

A goal of studying the body compensation that stems from wrist impairment is to better inform the design/choice of new prosthetic devices and interventions. Indeed, this approach was taken in [6], where different prosthetic wrist modules were evaluated in amputees. Shoulder joint angles were considered representative of compensatory motion, though no statistically significant difference was noted between the wrist modules.

III. METHODS

A. Study Apparatus

The study involved participants reaching to a set of 49 target locations equally spaced across a 7x7 grid (Fig 2). The grid was constructed from a wooden frame with five plastic PVC pipes reaching between its top and bottom edges. The pipe was wrapped in black matt tape to minimize reflections in the optical motion capture environment. Blue tape was wrapped around these pipes and wooden structures in specific locations to create reaching targets that participants were required to grasp. The vertical cylindrical nature of the targets provides similarities to grasping common objects like cups, bottles and tins from shelves in a kitchen or supermarket.

The grid measures 1.9x1.9m at its outermost edges. The vertical pipes have a diameter of 25mm and the wooden frame members have a cross section of 20x30mm. Targets are spaced at 0.3m intervals horizontally and vertically. The grid is suspended from a modular shelving unit, so that the base of the grid is suspended 0.175m off the ground. Participants stand 0.6m from the grid, with their torso laterally aligned with the central pole. Marks on the floor help participants stay aligned during the study.

The grid is in the center of a symmetrical arrangement of 12 Vicon *Bonita* motion capture cameras arranged at different heights. An additional video reference camera is connected to the Vicon system (Fig 1 was produced with this camera).

Participants wore retroreflective motion capture markers on their pelvis, torso, head and arms in line with the recommendations of the International Society of Biomechanics (shoulder co-ordinate system 2) [16], which are also reflected in [7]. Torso markers were attached to a sleeveless skin-tight (Nylon/Lycra blend) sports shirt (which was available to participants in various sizes), while head markers were affixed to an elastic sports headband. Other markers were attached directly to the skin with double-sided adhesive tape. In addition, three marker 'clusters' were worn on each arm (on the humerus, forearm and back of the hand), as illustrated in Fig 1. The clusters are constructed from thin flexible plastic which are strapped to the user's body with elastic straps. A piece of double-sided tape underneath each cluster prevented it from slipping against the wearer's skin. While the skin based markers mainly contributed to joint angle calculation, the clusters were used for reconstructing markers whose tracking was lost by the Vicon system. Such loss was common, due to the large motion ranges and workspace of this study. In post-processing, joint angles of the trunk, shoulder, elbow and wrist were calculated via the methods of [16].

To impair wrist motion on the participant's dominant arm, a padded orthopedic wrist brace featuring an aluminum internal structure (DonJoy ComfortFORM Wrist Support Brace – DJO Global, Vista CA, USA) was combined with a padded elbow brace with elbow articulation (Orthomen ROM Elbow Brace) by means of a bolt. An additional wooden insert was added to this setup to prevent wrist extension (Fig 4). In all, this combination of orthotic devices effectively limited wrist pronation/supination, radial/ulnar deviation and wrist flexion/extension. Note that the majority of previous work in this area have used wrist brace that do not limit pronation/supination [4], [13], [14]. Note also that though the Elbow brace has the ability to restrict elbow range of motion, the device was set to allow a user's full range of elbow motion. It's primary function was to limit pronation/supination.

Figure 4. A custom bracing system was created for this study by combining an commerical elbow brace with a wrist orthosis, modificed with an additional wooden insert to limit wrist flexion/extension. This arrangment limits motion of all 3DOF of the wrist.

B. Study Procedure

This study procedure has been approved by the Yale University IRB office, protocol number #HSC 1610018511.

Participants stood on marks made on the floor at a distance of 0.6m from the grid. They were requested to reach to each target on the grid, forming a power grasp and squeezing the target. Following each target they were asked to return to a relaxed position with arms by their sides. Targets were completed one row at a time, in a right to left order, starting with the top right target. Participants were requested to only step away from the start position on the floor if necessary to reach a target and to return to the start position after each grasp. If participants failed to return to the start position for a target then the reaching motion was repeated for that target.

Participants completed the grid reaching task as part of a larger battery of tasks, the data from which is being used for various studies. The additional tasks involved various ADL activities and standardized outcomes measures. It took approximately 30 minutes to affix markers to participants and calibrate the motion capture system. The actual grid reaching procedure took approximately 20 minutes. Participants were reimbursed financially for their involvement.

C. Participants

Four participants (Table 1) took part in this initial run of the study, with the addition of further participants planned for

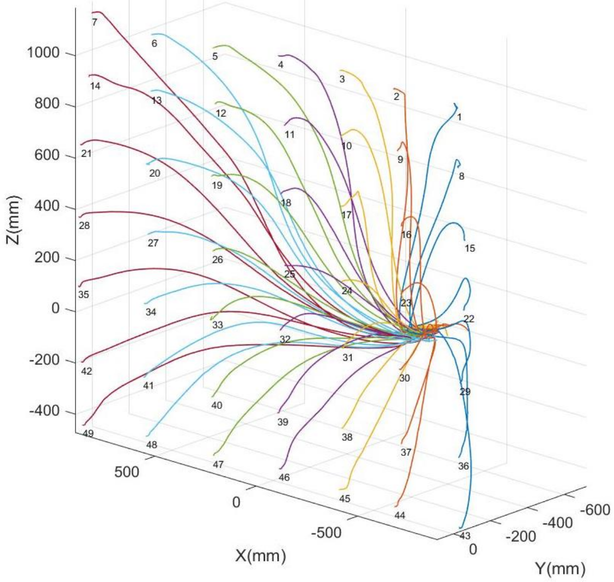


Figure 5. Segmented unimpaired wrist center *(C_{WR})* reaching trajectories for participant P2, showing 49 motions.

future work. All participants completed an initial screening to confirm that they did not suffer from any motion impairments.

IV. DATA PROCESSING

A. Data structure

Marker data was processed using Vicon Bodybuilder and custom Matlab code (based on [16]) to create co-ordinate frames at the center of the wrist, elbow and shoulder of the dominant arm. Additional co-ordinate frames were also created for the pelvis, thorax and head. These frames enabled the extraction of joint angles θ and Cartesian position data C.

B. Segmentation

Reaching data for all targets was recorded in a single Vicon trial for each study condition (with or without arm bracing). This data was then segmented in Matlab based on the lateral position the wrist perpendicular to the plane of the grid (the Y axis in Fig 2). Superfluous motions (such as repeating targets, swinging the arm or scratching the body) were manually removed. Only motions recorded during reaching towards the grid were retained for further analysis. These motions, for the wrist center only *(C_{WR})*, are shown for P2 in Fig 5.

C. Metrics

Several motion metrics were considered for analysis of the captured data, as it was observed that particular variations in reaching patterns may not be captured by a single metric. Fig 6 illustrates trajectories of two joints for participants P1 and P2 in unimpaired and impaired cases. The typical measures of joint ROM will show differences between the impaired and unimpaired conditions for the trunk case. However, little difference would be indicated for the shoulder case. This is despite a large trajectory divergence in the middle of the motion for P1. Following these considerations, the metric of ROM was combined with Cartesian trajectory length when evaluating the motion data.

Table 1. Characteristics of the four participants. Weight is in lbs. 'Dom. Hand' is an abbreviation of dominant hand. Arm length is measured from the shoulder to the tip of the middle finger.

Participant	Sex	Age	Weight	Height	Dom. Hand	Arm Length
P1	F	24	125	5'6.5"	R	28"
P2	M	29	185	6'2"	R	27"
P3	M	24	160	5'8"	R	24"
P4	M	54	175	5'10"	R	27.5"

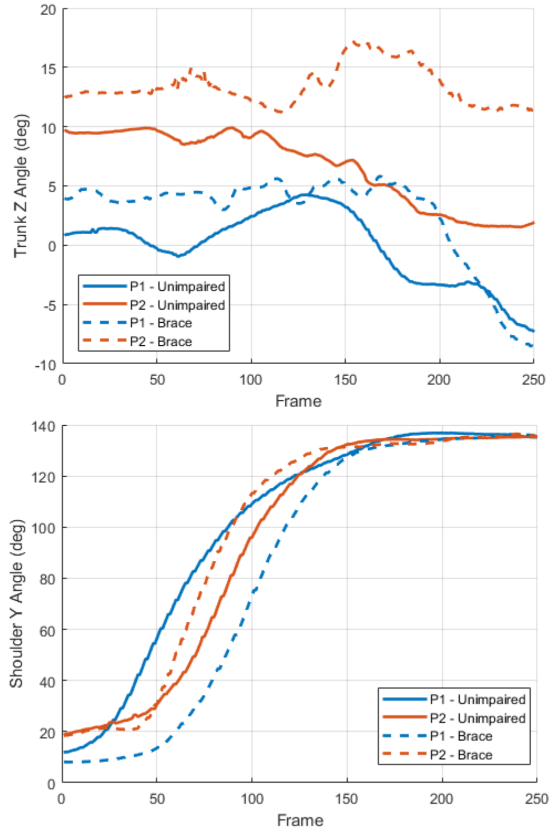


Figure 6. Two joint trajectories for participants P1 and P2 while reaching to target 9 (top plot) and target 1 (bottom plot) from Fig. 5. (Top) The trunk Z trajectories have clearly different ROM. (Bottom) The shoulder Y trajectories have similar start and end points which are also the maximum and minimum values. This would lead to similar ROM measurements, despite the motion patterns being different around the center of motion.

1) Difference in Range of Motion (dROM)

As discussed in Section 2, past studies on body compensation have examined joint ROM as an indicator of body compensation. We take a similar approach in our first metric by measuring range of motion for all joints in unimpaired and impaired (wearing the arm brace) cases, while also considering the difference in joint ROM between the cases.

ROM is calculated for each joint θ_n (n=1 to 10) for unimpaired (R_{Un}) and impaired (R_{Bn}) cases:

$$R_{Un} = \max(\theta_{Un}) - \min(\theta_{Un})$$

$$R_{Bn} = \max(\theta_{Bn}) - \min(\theta_{Bn})$$

The difference is then determined.

$$dROM_n = R_{Un} - R_{Bn}$$

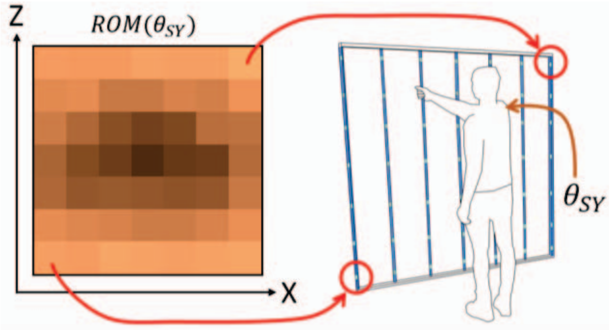


Figure 7. Metrics are represented as 'heat maps', with each square corresponding to joint/body segment behavior while reaching to a spatially equivilant target location on the grid (as viewed from the perspective of the participant). In this example, θ_{SY} refers to shoulder elevation angle while the heat map displays ROM (range of motion).

2) *Cartesian Trajectory Length Analysis*

It was hypothesized that variations in joint motion associated with compensatory movements may result in excessive motion of body segments in Cartesian space. Indeed, the elevation of the elbow is often observed as a compensatory motion in those with limited wrist mobility [5]. It is likely then that the path the elbow traces to reach this pose differs in length from the unimpaired configuration. As such, we propose measuring the Cartesian motion path length of various body segments as the sum of Euclidean distances between body segment positions in the motion data, (X_i, Y_i, Z_i) and $(X_{i+1}, Y_{i+1}, Z_{i+1})$:

$$L_{Un} = \sum_{i=0}^{l} \sqrt{|X_{Ui} - X_{Ui+1}|^2 + |Y_{Ui} - Y_{Ui+1}|^2 + |Z_{Ui} - Z_{Ui+1}|^2}$$

Where l is the number of samples in a targets' reaching trajectory and i is the current sample. This metric is calculated for the unimpaired (L_U) and impaired (braced) (L_B) trajectories. The difference is also calculated.

$$L_n = L_{Un} - L_{Bn}$$

V. RESULTS

A total of 392 reaching motions were recorded, which also captured the joint variables and body segments listed in Table 2. The metrics discussed in Section IV were applied to these variables and have been visualized via spatially relevant heat maps, using the Matlab command *imagesc*. In these plots, each grid square represents motion associated with reaching to the corresponding grid target, as 'viewed' from the perspective of the participant (Fig 7). A mean result, $\overline{P}$, was also calculated by taking the average of corresponding array value across participants. The spatial nature of the data enables visual correlations to be made between the participants and mean result. We apologize that due to the necessary figure size, it has not been possible to place plots on the same page as their first mention in the text.

Table 2. Joint angle and body segment nomenclature. Shaded wrist angles have their motion restricted in the impaired test condition.

Trunk	Shoulder	Body Segments
θ_{TX} Flexion	θ_{SX} Plane of Elevation	C_{Th} Thorax Center
θ_{TY} Rotation	θ_{SY} Elevation	C_{Sh} Shoulder Center
θ_{TZ} Lateral Flexion	θ_{SZ} Internal Rotation	C_{el} Elbow Center
Elbow	**Wrist**	C_{Wr} Wrist Center
θ_{EL} Elbow Flexion	θ_{WX} Pronation/Suppination	
	θ_{WY} Flexion / Extension	
	θ_{WZ} Radial/Ulnar Deviation	

Fig 8 illustrates the ROM for all measured joint angles in impaired and unimpaired condition in addition to the difference in ROM (dROM). These joint angles were determined from ISB standards [16] and are listed in Table 2 along with body segments used in the Cartesian trajectory length metric.

These results indicate patterns of spatial motion distribution which are fairly consistent between participants in both unimpaired and impaired cases. For example, the radial pattern of (θ_{SY}) indicates that participants typically increase their shoulder elevation ROM around the periphery of the workspace, rather than the center. Other distinct patterns are that elbow ROM increases in the lower portion of the workspace while θ_{TX} increases in the upper portion. θ_{TY} and θ_{TZ} are large in opposing quadrants. θ_{SX} and θ_{SY} are high throughout the workspace. The dROM results do not immediately visually indicate consistent patterns of ROM difference between participants, though further statistical analysis will later be applied to confirm this.

Fig 9 shows the Cartesian trajectory length of the four body segments described in Table 2. As in Fig 8, this has been indicated for unimpaired, impaired and the difference. As can be expected, trajectory length increases as participants reach across their body, to targets on the opposite side from their dominant limb. Differences in trajectory length follow this trend, with more variation away from the dominant side. Interestingly, the change seems quite balanced between length increase and decrease. It is also interesting to note that metric patterns are similar across multiple body segments for each participant, but show less similarity between participants.

A. *Statistical Analysis*

Though visual observations regarding patterns of motion may be made from the Figs 8-9, we wished to implement statistical measures to quantify trends.

Table 3 illustrates paired t-tests to determine if significant $(p<0.05)$ statistical differences exist between ROM for unimpaired and impaired motions for the same subject (Fig 8).

Significant motion differences are obviously unanimous for all the wrist DOF, which were subject to motion limitation. For other joints, shoulder elevation θ_{SY} and shoulder plane of elevation θ_{SX} show near unanimous significance. Shoulder

Table 3. Paired t-test p-values for comparing unimpaired and impaired ROM (Fig. 8). Shaded cells indicate $p<0.05$, which implies significant difference between unimpaired and impaired reaching patterns.

	θ_{TX}	θ_{TY}	θ_{TZ}	θ_{SX}	θ_{SY}	θ_{SZ}	θ_{EL}
P1	0.191	0.066	0.533	1.31×10^{-7}	5.4×10^{-5}	6.81×10^{-10}	4.16×10^{-6}
P2	0.067	2.9×10^{-3}	0.482	6.51×10^{-7}	0.062	0.048	1.26×10^{-3}
P3	0.318	0.711	0.751	1.47×10^{-9}	4.94×10^{-11}	0.886	0.06
P4	3.51×10^{-4}	0.049	0.729	0.197	2.61×10^{-10}	0.156	0.75
$\overline{P}$	0.263	0.100	0.465	3.01×10^{-5}	1.24×10^{-13}	6.05×10^{-8}	2.44×10^{-4}

	θ_{WX}	θ_{WY}	θ_{WZ}
P1	4.03×10^{-18}	4.74×10^{-29}	1.26×10^{-22}
P2	6.11×10^{-10}	7.06×10^{-23}	3.24×10^{-26}
P3	7.07×10^{-14}	1.47×10^{-26}	2.48×10^{-19}
P4	3.51×10^{-4}	1.96×10^{-27}	3×10^{-19}
$\overline{P}$	1.54×10^{-23}	2.94×10^{-32}	4.63×10^{-32}

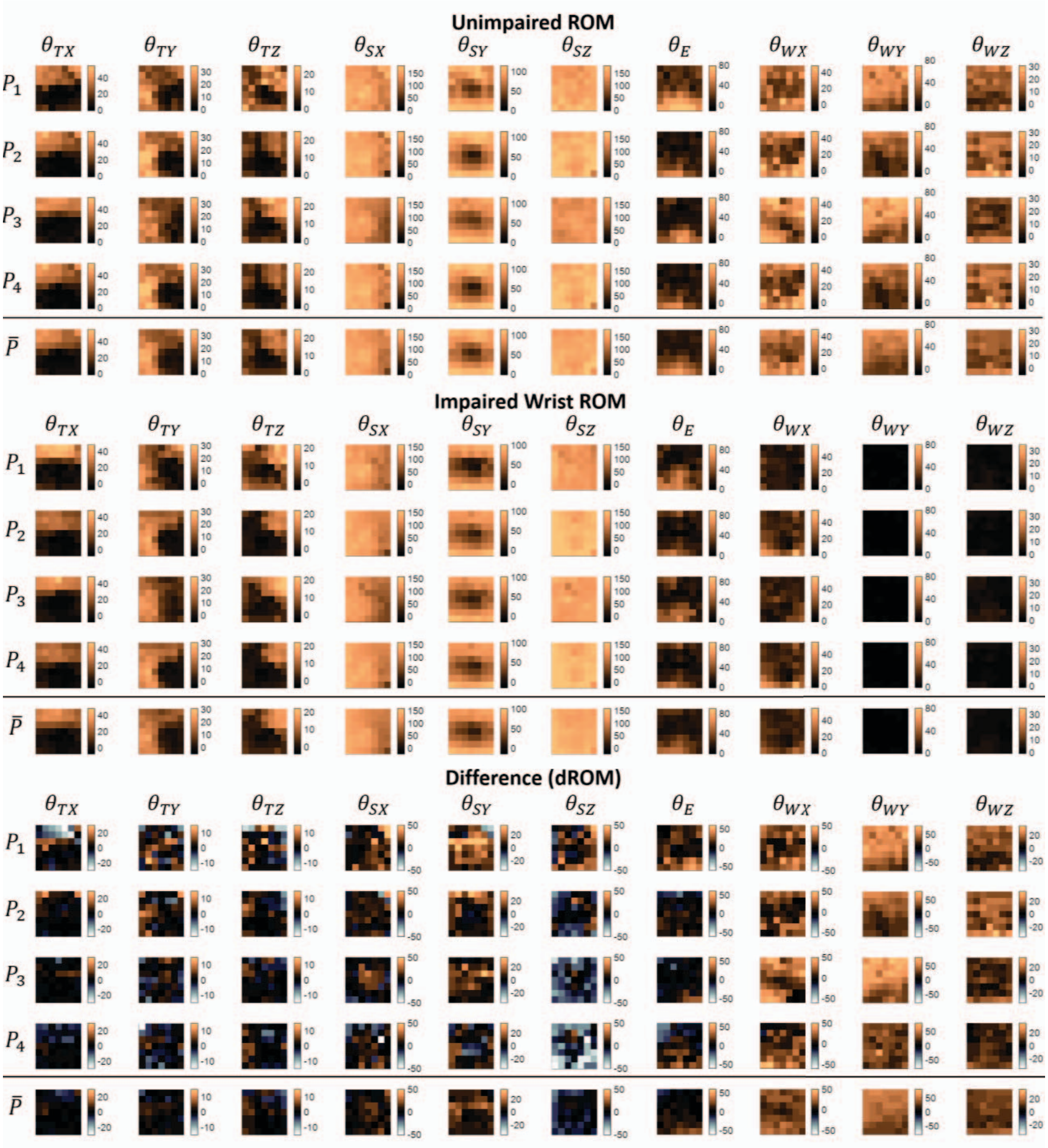


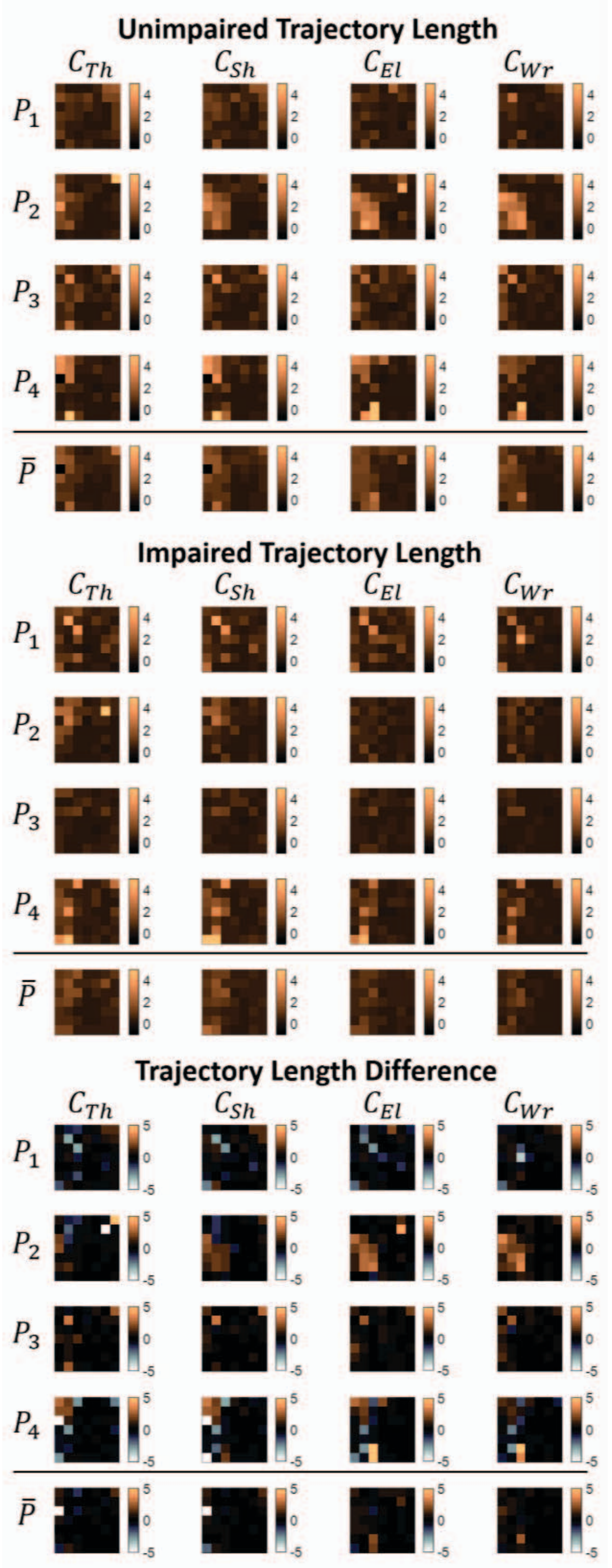
Figure 8. Range of Motion (ROM) for each joint during unimpaired reaching, impaired reaching and the difference between the two (dROM). Lighter colors in the Unimpaired and Impaired cases correspond to greater range of motion. In the dROM case darker colors are close to zero, and therefore indicate little difference, with lighter colors also indicating magnitude and sign of dROM, i.e. whether the difference resulted in greater (copper) or less (white) ROM. Note that the joints have the same color scale for both impaired and unimpaired ROM cases, though this is different in the dROM case.

internal rotation and elbow motion show significance in half of participants and the mean. The trunk DOF have the least significant differences.

Table 4 illustrates the same method of paired t-tests for Cartesian trajectory length of the four body segments. The results show that the elbow and wrist trajectories underwent a significant length change, with slightly more occurrence in the elbow. This matches the hypothesis of Section IV.2. The trajectory of the thorax and shoulder did not undergo a significant length change.

Table 4: Paired t-tests for Cartesian trajectory length of body segments

	C_{TH}	C_{Sh}	C_{El}	C_{Wr}
P1	0.409	0.515	$1.98\text{x}10^{-2}$	0.460
P2	0.869	0.058	$4.98\text{x}10^{-4}$	$2.25\text{x}10^{-3}$
P3	0.004	0.002	$4.81\text{x}10^{-5}$	$4.3\text{x}10^{-4}$
P4	0.340	0.512	0.412	0.774
$\bar{P}$	0.898	0.381	$9.27\text{x}10^{-3}$	$9.08\text{x}10^{-3}$


Unimpaired Trajectory Length

Impaired Trajectory Length

Trajectory Length Difference

Figure 9. Cartesian path length metric for the thorax, shoulder center, elbow center and wrist center. Units are cm.

A second statistical measure was implemented to determine if spatial patterns of reaching motion were consistent between the four subjects for different variables, metrics and conditions. This comparison necessitates preserving the spatial grid structure of the data, to allow comparison of workspace behavior. This then excludes the use of common tools like ANOVA. Instead, a linear mixed effects model was fit to the data, using the Matlab command *fitlme*.

For each variable to be tested (e.g. dROM for Trunk Angle θ_{TX} from Fig 8), the response variable of model was defined as the array of mean participant metric results (e.g. the arrays illustrated by $\bar{P}$ in Fig 8-9), while input data was individual participant arrays for each metric.

If participants provide a similar response to a metric, then we expect a slope of 1, when assessing the relationship between the mean across participants ($\bar{P}$) and each participant (P_1-P_4). We accommodated a linear mixed effects model for each metric's variables where we use each participant as a random effect and fixed the intercept to 0. Here, our null hypothesis is that participants behave similarly, and thus the slope is 1; if rejected, then the participants are statistically different. A Gaussian cumulative distribution function was used with the model estimates to calculate a p-value, where ($p<0.05$) rejects the null hypotheses. These p-values for all variables in all metrics are shown in Table 5 and 6, where values of ($p\geq 0.05$) have been highlighted to indicate the data shows a comparable pattern across participants.

Table 5 indicates that participant ROM patterns across the workspace were similar for all trunk and shoulder joints in the unimpaired and impaired cases. The value of dROM is naturally signed (Section IV.C.1), though we have also provided an unsigned value in Table 5, to examine difference magnitude but not direction. Interestingly, the similarities observed for the trunk and shoulder in the unimpaired and impaired cases are less pronounced in the dROM cases.

Though this may seem counter-intuitive, visual inspection of Fig 8 confirms that though the spatial patterns of unimpaired and impaired reaching are similar, there are subtle and seemingly unpredictable variations across participants.

Table 6 provides a linear mixed effects model approach for the Cartesian trajectory length data. Interestingly, in Table 6 we observe similarity only in the impaired, braced condition, implying that individuals had similar strategies for dealing with the loss of wrist motion, though as Fig 9 illustrates, this was through via both increasing and decreasing Cartesian trajectory length for different parts of the workspace.

Indeed, though human motion is optimized to some quantity, it is rarely a straight line when motion against gravity is involved [10]. The emergent compensation away

Table 5. Statistical measure of similarity between participant ROM data using a linear mixed effects model. Variables where *p≥0.05* (indicating correlation between participant movement patterns) have been shaded.

	θ_{TX}	θ_{TY}	θ_{TZ}	θ_{SX}	θ_{SY}	θ_{SZ}
Unimpaired	0.638	0.884	0.830	0.947	0.135	0.996
Impaired	0.812	0.788	0.939	0.998	0.188	0.956
dROM	5.88×10^{-131}	4.67×10^{-151}	5.63×10^{-50}	2.32×10^{-63}	8.67×10^{-54}	1.23×10^{-128}
|dROM|	0.225	1.75×10^{-17}	0.005	9.39×10^{-21}	0.053	0.150

	θ_{EL}	θ_{WX}	θ_{WY}	θ_{WZ}
Unimpaired	0.711	7.42×10^{-6}	0.934	0.799
Impaired	1.71×10^{-9}	0.627	3.75×10^{-5}	0.658
dROM	6.68×10^{-46}	1.64×10^{-19}	0.950	0.713
|dROM|	0.081	1.24×10^{-14}	0.950	0.737

Table 6. Statistical measure of similarity between participant ROM data using a linear mixed effects model. Variables where $p \geq 0.05$ (indicating correlation between participant movement patterns) have been shaded.

	C_{TH}	C_{Sh}	C_{El}	C_{Wr}
Unimpaired	0.005	0.003	0.072	0.010
Impaired	0.211	0.067	0.244	0.070
L_n	1.1×10^{-129}	1.4×10^{-139}	1.97×10^{-136}	2.26×10^{-103}
$\lvert L_n \rvert$	8.05×10^{-30}	9.15×10^{-22}	3.15×10^{-44}	7.87×10^{-30}

from these non-linear trajectories may therefore be difficult to predict and non-consistent across various individuals.

VI. CONCLUSION

This paper has proposed the extension of compensatory motion investigations beyond isolated activities of daily living and into discretely sampled workspaces. The dense resulting data has been displayed via a novel method that allows visual comparison of the effect of target location on various metrics. In addition to the standard measure of joint ROM, we have also measured Euclidean path length of four body segments in Cartesian space. The results visually indicated how regions of the workspace influence individual joint ROM, joint-level trajectories or Cartesian path changes when the user is moving naturally, or when wrist motion is impaired in 2DOFs. Though clear ROM and Euclidean patterns are present for un/impaired reaching motions (showing gradual metric change throughout the workspace), the difference metrics provides less clear spatial patterns, with limited observable similarity between participants.

Statistical approaches (Tables 4-7) were implemented to quantify, unimpaired/impaired variable differences and correlation between participants. Significant ROM changes were identified for all joints except the trunk. Significant Cartesian trajectory length changes occurred for the elbow and wrist, which matched general observations of wrist-less prosthetic user behavior. Measures of similarity across participants showed consistent ROM for the trunk and shoulder in impaired and unimpaired cases though this was less so for the compensatory (dROM) cases. In terms of Cartesian length, participants seemed to show similar braced motion strategies but were uncorrelated otherwise. The general trend of correlation in un/impaired cases but not in compensation (difference) is interesting and unexpected. It seems that though participants have comparable reaching strategies, the differences between these strategies is subject to some noise (θ_{SY} in Fig 8 is a clear example).

These initial findings indicate the value of spatial workspace sampling, as metrics change considerably depending on workspace location. The typical approach of measuring body compensation for a task at single location may lead an investigator or therapist to overlook varied data in neighboring locations.

Secondly the impact of increasing wrist mobility (via interventions such as rehabilitation, surgery or prosthetic devices) on reducing gross changes in joint ROM and trajectory length have been shown. The results may also be used in guiding therapists in understanding which areas of the workspace has the most motion demands on different aspects of the body.

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