2018 7th IEEE International Conference on Biomedical Robotics and Biomechatronics (Biorob)
Enschede, The Netherlands, August 26-29, 2018

Analyzing Exfordance Use by Unilateral Upper-Limb Amputees*

Jillian C. Cochran, Adam J. Spiers, *Member, IEEE,* and Aaron M. Dollar, *Senior Member, IEEE*

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.

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.

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

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

*This work was supported by the US Army Medical Research & Materiel Command, grant W81XWH-14-1-0277.

J. C. Cochran, A. J. Spiers and A. M. Dollar are with the Mechanical Engineering Department, Yale University, New Haven, CT 06511 USA (phone: 203-432-5093; e-mail: jillian.cochran@yale.edu, adam.spiers@yale.edu, aaron.dollar@yale.edu).

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.

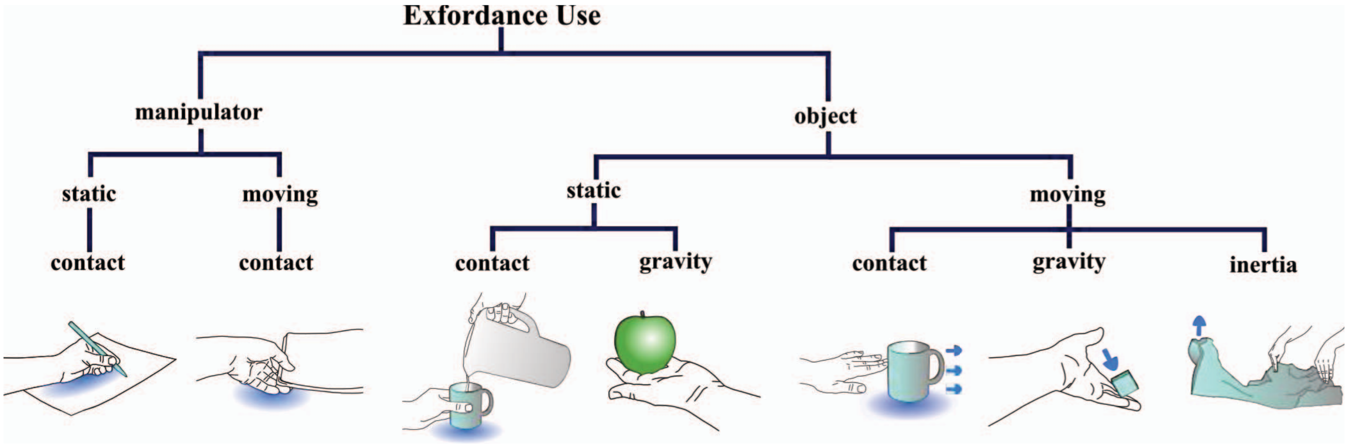

Figure 2. Exfordance use taxonomy. The blue shaded areas highlight contact with the environment, and the blue arrows indicate motion.

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

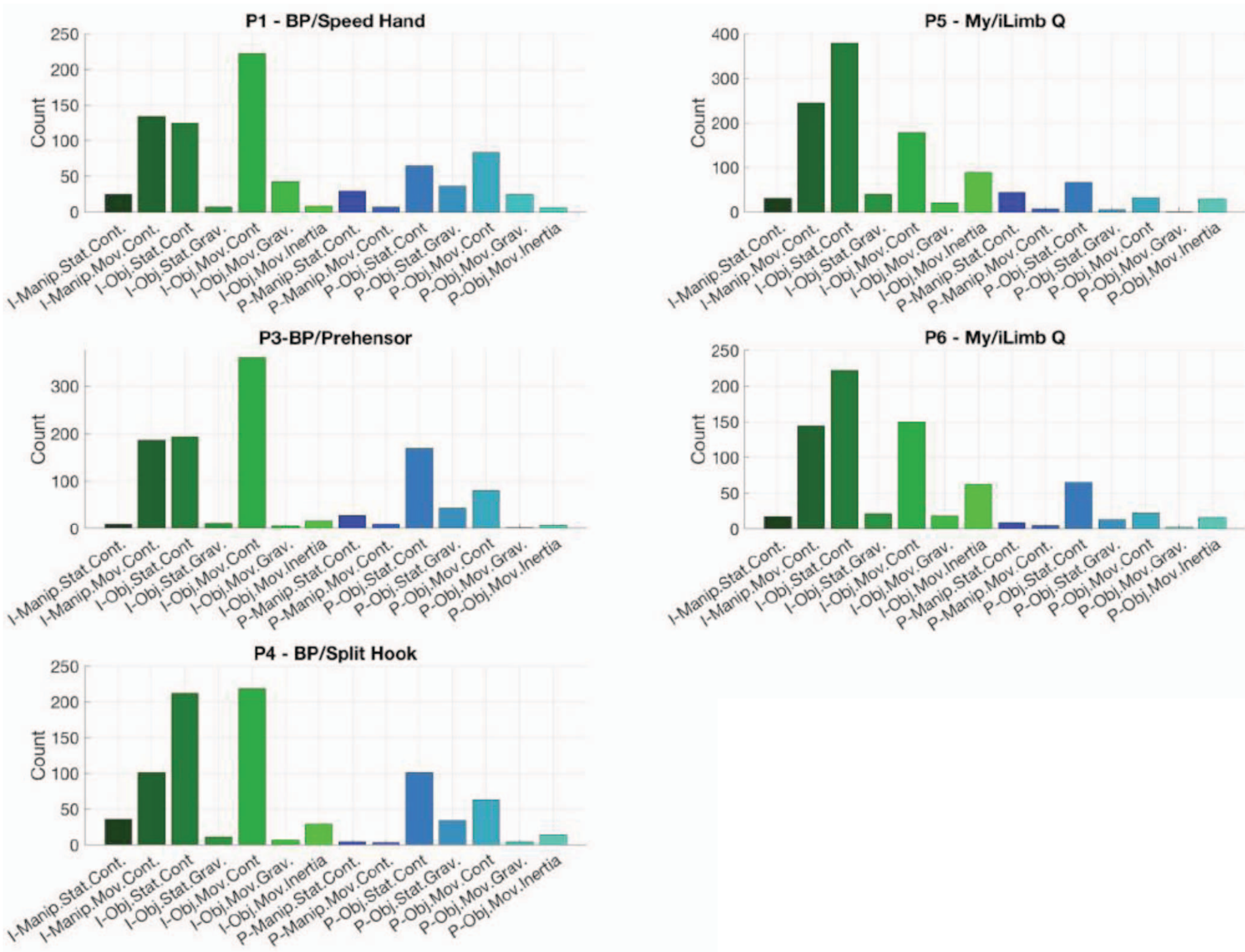

Figure 3. Frequency of exfordance tags for each category during 35 minutes of video for each participant. 'I' refers to intact hand and 'P' to prosthetic.

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

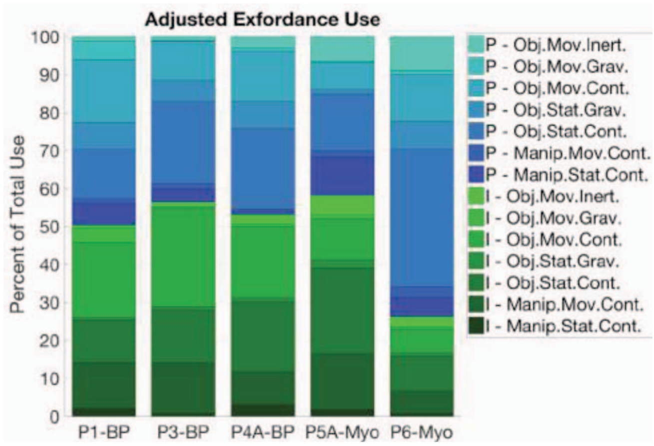

Figure 4. Exfordance use as calculated by (1) for each participant. 'I' refers to intact, 'P' to prosthetic.

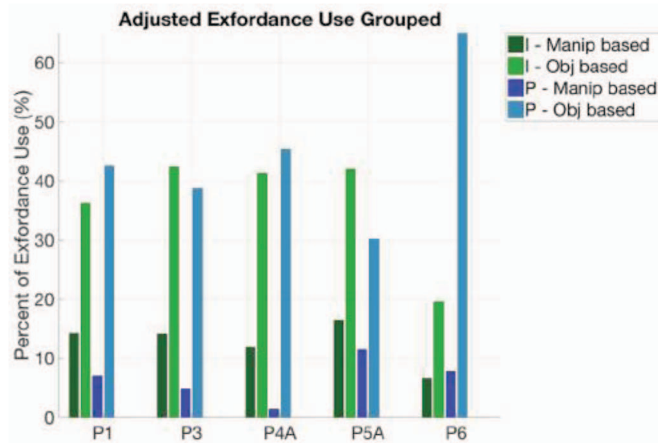

Figure 5. Exfordance use as calculated by (1) grouped based on whether the exfordance involves the manipulator or object.

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

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

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

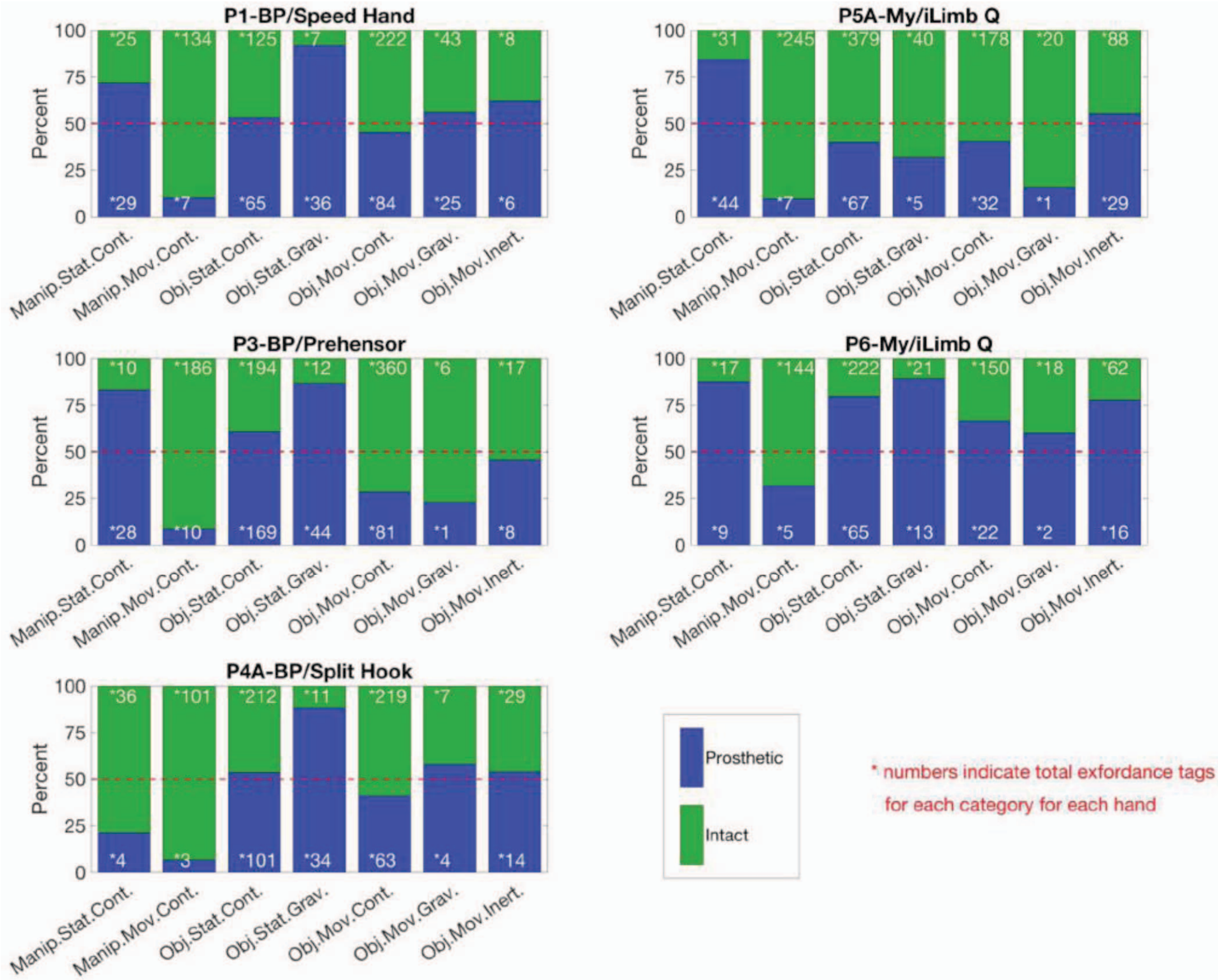

Figure 6. Proportion of exfordance use per category per hand after adjusting for hand activity according to (2).

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.

Acknowledgment

The authors would like to thank Karli Cecil and Aude Bunel for their effort applying the UPM and exfordance use taxonomies to the videos.

References

[1] M. Kazemi, J. S. Valois, J. A. Bagnell, and N. Pollard, "Human-inspired force compliant grasping primitives," *Auton. Robots*, vol. 37, no. 2, pp. 209–225, 2014.

[2] L. Y. Chang, G. J. Zeglin, and N. S. Pollard, "Preparatory object rotation as a human-inspired grasping strategy," in *2008 8th IEEE-RAS International Conference on Humanoid Robots, Humanoids 2008*, 2008, pp. 527–534.

[3] J. J. Gibson, *The Ecological Approach to Visual Perception*. 1986.

[4] A. J. Spiers, L. Resnik, and A. M. Dollar, "Analyzing at-home prosthesis use in unilateral upper-limb amputees to inform treatment & device design," *2017 Int. Conf. Rehabil. Robot.*, pp. 1273–1280, 2017.

[5] M. Bonilla *et al.*, "Grasping with Soft Hands," in *IEEE-RAS International Conference on Humanoid Robots*, 2014, vol. November, pp. 581–587.

[6] C. Eppner and O. Brock, "Planning grasp strategies That Exploit Environmental Constraints," *Proc. - IEEE Int. Conf. Robot. Autom.*, no. June, pp. 4947–4952, 2015.

[7] N. C. Dafle *et al.*, "Extrinsic dexterity: In-hand manipulation with external forces," in *Proceedings - IEEE International Conference on Robotics and Automation*, 2014, pp. 1578–1585.

[8] T. Asfour, J. Borràs, C. Mandery, P. Kaiser, E. E. Aksoy, and M. Grotz, "On the dualities between grasping and whole body loco-manipulation tasks," *Int. Symp. Robot. Res.*, pp. 1–19, 2015.

[9] L. Y. Chang and N. S. Pollard, "Video survey of pre-grasp interactions in natural hand activities," in *Robotics: Science and Systems (RSS) 2009 Workshop on Understanding the Human Hand for Advancing Robotic Manipulation*, 2009, no. June.

[10] C. Eppner, R. Deimel, J. Álvarez-Ruiz, M. Maertens, and O. Brock, "Exploitation of environmental constraints in human and robotic grasping," *Int. J. Rob. Res.*, vol. 34, no. 7, pp. 1021–1038, 2015.

[11] Y. Wang and C. L. MacKenzie, "The role of contextual haptic and visual constraints on object manipulation in virtual environments," *Proc. SIGCHI Conf. Hum. factors Comput. Syst. - CHI '00*, vol. 2, no. 1, pp. 532–539, 2000.

[12] L. U. Odhner, R. R. Ma, and A. M. Dollar, "Precision grasping and manipulation of small objects from flat surfaces using underactuated fingers," *Proc. - IEEE Int. Conf. Robot. Autom.*, pp. 2830–2835, 2012.

[13] M. R. Dogar and S. S. Srinivasa, "A Framework for Push-Grasping in Clutter," in *Robotics: Science and Systems*, 2011, pp. 1–6.

[14] I. M. Bullock, T. Feix, and A. M. Dollar, "Finding small, versatile sets of human grasps to span common objects," *Proc. - IEEE Int. Conf. Robot. Autom.*, pp. 1068–1075, 2013.

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