A Grasp Taxonomy for People with C5-7 Spinal Cord Injury

Andrew I W McPherson¹, Keilani Adachi¹, Yuri Gloumakov¹, and Hannah S Stuart¹

¹Department of Mechanical Engineering, University of California

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Abstract

Despite the broad utility of grasp taxonomies to describe manual abilities, no such tool exists for people with spinal cord injury (SCI). This leaves gaps in the practical assessment of assistive devices and tools that people with SCI might use during dexterous manipulation. Here, we evaluate the grasp strategies employed by individuals with C5-7 SCI using six publicly available videos to develop a preliminary taxonomy. The taxonomy was then evaluated for completeness using an egocentric video case study of an author with C5-6 SCI, captured while demonstrating the general tasks observed in the public videos. Twenty-seven grasping strategies are presented in the taxonomy, 14 of which are unique to this work. Though the dataset used to generate this taxonomy is not universally representative of all individuals with SCI, the egocentric case study suggests it closely captures the overall grasp strategies observed in this group. This grasp characterization captures dexterous abilities typically overlooked in technology design and assessment. We therefore propose that it should be used to inform the design of novel grasp assistance.
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Andrew I. W. McPherson, Keilani Adachi, Yuri Gloumakov, and Hannah S. Stuart
Department of Mechanical Engineering, University of California, Berkeley
Berkeley, USA
Email: drewmcpherson25@berkeley.edu, keilaniadachi@gmail.com, yurigloum@berkeley.edu, hstuart@berkeley.edu

Abstract—Despite the broad utility of grasp taxonomies to describe manual abilities, no such tool exists for people with spinal cord injury (SCI). This leaves gaps in the practical assessment of assistive devices and tools that people with SCI might use during dexterous manipulation. Here, we evaluate the grasp strategies employed by individuals with C5-7 SCI using six publicly available videos to develop a preliminary taxonomy. The taxonomy was then evaluated for completeness using an egocentric video case study of an author with C5-6 SCI, captured while demonstrating the general tasks observed in the public videos. Twenty-seven grasping strategies are presented in the taxonomy, of which are unique to this work. Though the dataset used to generate this taxonomy is not universally representative of all individuals with SCI, the egocentric case study suggests that it closely captures the overall grasp strategies observed in this group. This grasp characterization captures dexterous abilities typically overlooked in technology design and assessment. We therefore propose that it should be used to inform the design of novel grasp assistance.

I. INTRODUCTION

Hand dexterity enables people to perform complex manipulation tasks, far beyond capable robotic systems today. Experiencing loss of hand function through limb loss, spinal cord injury/disease (SCI/D) or stroke is devastating [1], impacting one’s ability to work, engage in hobbies and perform even the most basic activities of daily living (ADLs) independently. In the most severe cases, this loss necessitates nearly constant manual assistance from care attendants. Amongst tetraplegics due to SCI, the highest research priority for recovery is to return hand function, even over pain relief, locomotion, bladder/bowel control, and sexual function [2]. In fact, out of 565 participants surveyed, 77 percent believed they would experience a significant improvement in quality of life with improved hand function [3].

As hardware and robotic systems advance, an explosion of new research in hand exoskeletons seeks to aid those with severe loss of hand function. For example, between 2006-2016, “over 140 hand exoskeletons were developed, 48 of which were intended to assist in daily life” [4]. A more recent article evaluates 40 of the most promising recent hand exoskeletons in research, showing the immense progress in the past 20 years [5]. However, only a few of these devices have translated out of the lab and onto the market – Jaeco Power Driven Flexor Hinge orthotic [6], MyoPro by Myomo [7], and the Neoman by Neofect [8] for example. Despite the clear potential benefit, these devices have not found wide community adoption. One potential explanation for the lack of adoption and high device abandonment rates may stem from their unintentional interference with compensatory strategies. With several promising devices poised to enter the market [9], [10], they are at risk of the same fate if not critically evaluated.

While loss of hand function is known to impact daily independence [1], people with tetraplegia can still demonstrate impressive dexterity through various compensatory adaptations. We believe that devices designed to support hand function often inadvertently impede these abilities, thus leading to the observed difficulty in technology adoption. In order to design wearable devices that are more appealing, inventors and clinicians must characterize the existing ability of potential users and understand the technology has on it. This study presents the initial development of a new assessment tool for this purpose.

A. Background on grasp taxonomy use

Looking to the adjacent field of prosthetics, which has likewise seen a renewed interest and focus towards innovation, some efforts have sought to better understand the current function and use of prosthetics through the development of taxonomies [11], [12]. A large body of work is already dedicated to defining normative hand functionality through a rigorous robotics lens, such as the grasp taxonomies [13], [14]. Such grasp taxonomies are helpful in creating a common language to speak of the grasp behaviors an individual or machine can perform. This serves as inspiration to design effective, flexible devices while also providing a basis for evaluation.

To date, no such taxonomy exists for tetraplegics who do not have voluntary use of their fingers. There are clinical evaluation tools such as the TRI-HFT, SHFT, B&B Test [5], and GRASSP [15] to evaluate patient’s hand function, though these do not fully characterize how patients perform grasping/ manipulation strategies in the home. We seek to generate the first-ever grasp taxonomy for people with C5-7 SCI.

In recent years, several research groups have acknowledged the value of developing a grasp taxonomy for this population but cite the “variability in grasping strategies that occurs as a result of different levels and severities of injuries” [16] as reason no such taxonomy exists. Egocentric video capture is proposed as a potential alternative solution and a powerful new evaluation tool for clinicians and researchers to evaluate...
hand and device use in unstructured environments. This has particular promise with the development of new ML tools for grasp/hand detection to reduce the laborious manual video tagging process for data analysis [17], [18]. In fact, this population has already demonstrated its openness to the use of this tool [19]. Initially generated using publicly available video data, the taxonomy presented herein was refined through an egocentric video case study.

B. Overview

Introduced in this manuscript is a new grasp taxonomy for individuals with C5-7 SCI. Section II provides a description of the video selection process employed to generate the initial grasp classification and corresponding grasp taxonomy. This is followed by outlining the method used to evaluate the YouTube video samples and the egocentric video case study by the author. Sec. III-A presents the resulting taxonomy, and the egocentric case study. The results are discussed in Section IV and observations made. Conclusion and future work in Section V highlights the need to perform a set of evaluations of currently available hand orthotics and their benefit and cost to the user’s ability to perform ADLs independently.

II. METHOD OF DEVELOPING TAXONOMY

A. Video selection

To develop an initial grasp taxonomy for individuals with C5-7 SCI, publicly available video footage found on YouTube was selected for evaluation. A total of 6 videos were selected showing five different individuals demonstrating activities of daily living. Each video self-reported having an SCI between C5-7. Through visual inspection, the authors confirm each individual can perform tenodesis grasp [20] [21], thus demonstrating some voluntary control of wrist flexor muscles with little to no voluntary function in wrist extensors or fingers. Functional tenodesis grasp was used as an inclusion requirement given it is unique to, and widely used by this population for prehensile and enhanced grasping.

Additionally, all videos were selected because they demonstrate a wide variety of primarily hand-based manipulation strategies in a short period of time, resulting in a high number of “grasp” classifications. Grasp is used liberally here to mean any manipulation of an object, not just in-hand prehensile grasping, and will be defined as such throughout this paper. Grasp and manipulation will be used interchangeably. Fig. 1 presents example frames from each video depicting a variety of grasping behaviors. Video 1 demonstrates brushing teeth [22], Video 2) making hot tea [23], Video 3) putting on makeup [24], Video 4) filling gas [25], Video 5) preparing food [26], and Video 6) putting on jeans.

B. Analysis of data for taxonomy construction

We use the software package PythonVideoAnnotator to tag the start and end frames of all relevant manipulation tasks in each of the 6 videos. These preliminary tags were used to demarcate use of the right hand, left hand, thumb, mouth, and other body parts for object manipulation or fixturing in order to capture the general categories relevant to the taxonomy development. If a bimanual grasp was observed, it was broken into its constituent parts.

From the preliminary tag set, we then added more descriptive labels to each grasp event to include both body part used, contact surface, and task function. These descriptively labeled images were constructed into an initial grasp taxonomy. If a manipulation strategy was employed that did not fall under a previously labeled strategy, a new element was added to the taxonomy. Once a set of grasping strategies seen in the videos was fully defined into the grasp taxonomy, the authors evaluated the taxonomy to consolidate any duplicates or minor variations to refine the taxonomy similar to the method used in [14]. We checked the taxonomy for completeness by reviewing the videos and using it to again label the specific behaviors observed with the newly refined corresponding
categorized grasps. This was an iterative process until the taxonomy fully described the breadth of behaviors observed in the videos. A researcher who had not yet reviewed the videos independently performed a set of labeling at this stage using the final taxonomy to validate their agreement.

C. Egocentric video Case Study

One limitation of using publicly available video footage is that this data was self recorded and likely cropped or shortened, therefore some manipulation behaviors may be absent or not reflect the real time duration. To evaluate this initially developed taxonomy, an author with C5-6, ASIA A, SCI collected egocentric video data wearing a GoPro Hero 4 silver, head-mounted camera (GoPro, San Mateo, CA, USA), positioned to capture the hands and arms in a wide angle view while performing ADLs as shown in Fig. 2. This data was used as a case study to validate that the manipulation tasks observed for this individual were fully described in the taxonomy. Effort was made to perform the same tasks as the evaluated YouTube videos, for tasks the author could perform in addition to other common ADLs not observed in the online videos. A consent form was acquired from the participant.¹

III. RESULTS

A. C5-7 SCI Manipulation Taxonomy

From the videos analyzed, there was 20 minutes and 41 seconds of active, grasp-dense footage, resulting in 348 total manipulation event tags. Each video shows a unique activity, specifically: brushing teeth, making hot tea, putting on makeup, filling a car with gas, preparing food in the kitchen, and putting on jeans. The resulting grasp taxonomy is thus presented in Fig. 3. All of the strategies outlined in blue in the figure were not previously described in the literature to the author’s knowledge. Given the wide array of compensatory strategies developed in the absence of voluntary prehensile grasping, this taxonomy serves as a critical tool to describe observed behaviors.

The taxonomy developed from this data set is laid out with the top row broken down by the major body parts involved

¹The Center for the Protection of Human Subjects deemed that no Internal Review Board review was necessary because this data collection involves a single case study (self-study by one author) that does not produce generalizable knowledge.
in the grasping action. Grasp security increases as a general theme from left to right, most notably within each numbered subcategory but also in a general trend across the top row categories. The rightmost column of categories, separated by the dashed line, are not connected representing the combined actions **environment feature use**, **bimanual grasping**, and **tenodesis**, respectively. These three categories are not directly connected to the taxonomy tree as they constitute a two-part manipulation, which can be described by a combination of other manipulation elements. How and why environment-assisted and bimanual grasping are used warrants its own independent investigation, and thus is out of the scope of this work. Similarly, **tenodesis** is not directly connected, as it is present in all the grasps in the taxonomy **hand** branch; both in **prehensile** grasps to strengthen the grip directly, and in **non-prehensile** with wrist extension to stabilize the wrist. The remainder of this section describes the taxonomy elements from left to right in Fig 3.

Starting from the left, in the main taxonomy, some of the least secure actions are to push or support an object with the head, central body, and legs: **Push/Support with Face**
- An object is supported or pushed with the face or head;
**Push/Support with Trunk** - The object is supported or pushed with the trunk;
**Push/Support with Lap** - An object is placed on, supported or pressed against the lap usually, or legs. All of these strategies may occur as part of a bilateral grasp or on its own. For example, quite commonly one may place an object on one’s lap to carry it, or less frequently, press a jar between the stomach and table edge while unscrewing the lid with both palms.

The **hand** is considered more secure than the central body and makes up the largest portion of the taxonomy. The **hand** is broken down into two further subcategories of **Non-Prehensile** and **Prehensile**.

**Non-Prehensile** is further broken by function **Support**, **Push**, **Hook**, and then appearance as emphasised in [13]. There is a specific difference in functional behavior between the use of the **support** and **push** designations. The support behavior observed imparts no motion and occurred as part of a bilateral task where an action was performed on the object, such as supporting a bowl while pouring in or stirring contents. Push, by contrast, imparts motion on the manipulated object, i.e. pushing a door open or a button. **Hooking** is the third non-prehensile strategy observed in this population, used to passively lift/carry/pull objects with geometrically caged features. This could be picking up a bag by the handle or pulling open a drawer.

1) **Support with Dorsal Face** - Dorsal Face is used to stabilize an object without motion. This may occur as part of a bimanual task or other manipulation strategy.

2) **Support with Interosseous Space** - Interosseous space can provide more stable contact for certain object shapes. It is also not as dependent on wrist extensor strength as the dorsal face, and can allow for better contact force by enabling the use of more biceps strength.

3) **Support with Palm** - Palm may be used with fingers open or closed and can include both contact on the palm and back of the fingers. Contact is more often on the proximal portion of the palm given voluntary wrist flexion is not possible.

4) **Push with Hypothenar Eminence** - Hypothenar Eminence is used to apply gross pressure on an object if unable to move the torso to allow for other strategies or approach angles.

5) **Push with Knuckle(s)** - Different knuckles of the dorsal side of the hand are used to push with a finer point of contact when sufficient surrounding space allows.

6) **Push with Finger(s)** - Individuals may use fingers for fine pressure with fingers either passively limp or extended fully/hyper-extended, providing greater stiffness and force application. This can allow individuals to perform finer motor tasks without voluntary finger motion, though less stable than knuckles.

7) **Push with Palm** - Palm gives a large surface to push and conforms to the object for large pressure application. However, the angles at which the palm can be used is limited without contorting the torso. It can be used with active or passive wrist extension.

8) **Push with Dorsal Face** - The dorsal face is used similarly to the palm but in different angles/orientations, again when unable to reposition or contort one’s torso.

9) **Hook with Dorsal Face** - The dorsal face with wrist extended forms a groove at the wrist, commonly used to retain or pull objects with hooks, loops, clothing, etc., such that it will not slip off the metacarpophalangeal (MCP) joints. This is most common as it does not require the opening of digits, which can be difficult due to contractures of the fingers.

10) **Hook with Finger(s)** - The finger hooking strategy is dependent on the stiffness of the fingers and thus may have limited strength for some people, though still useful for some.

11) **Hook with Thumb** - The thumb hook is another effective passive strategy for hooking small loops, key rings etc.

**Prehensile** grasping, applying enough friction to arrest the object overcoming its inertia and gravity, usually achieved through active grasping with fingers and/or thumb, is not achievable in the normal sense given this population does not have voluntary finger motion. However, the unique grasps seen in this group take advantage of the structure of the hand and tightness of the joints and tendons to passively achieve prehensile grasping, strengthened using tenodesis. Thread grips are generally used for small cross-sectional objects such as writing or eating utensils. Either one might be selected based on the ease with which one can enter the threaded grasp, the desired angle an object is wished to be held, or firmness of grip needed. Prehensile **pinch** is used for smaller lighter objects, while **wrap** grasp is used for larger cross-sectional, potentially heavier objects.
1) **Thread Through Fingers** - Largely dependent on the stiffness or contractures of the fingers, small cross-sectional longer objects can be threaded between any three fingers in the radial-ulnar direction.

2) **Thread Through Finger(s) and Thumb** - Object is threaded at an angle, contacting between any two fingers and supported by the thenar web space (Purlicue). This provides three points of contact for a stable grasp, though at an angle and less secure than the previous grasp.

3) **Pinched Between Fingers** - The object must be thin and pressed between two fingers in the Sagittal plane.

4) **Pinched between Finger Pad(s) and Thumb** - Pinch is between the thumb tip or nail and one or more finger pads. This is very dependent on hand form and tendon stiffness and is usually only effective for small light objects.

5) **Lateral Pinch** - Pinched between the thumb pad and side of the index finger. This is limited by much the same factors as the previous pinch, though it can accommodate a slightly larger variation of objects.

6) **Wrap** - Power wrap grasp for objects that fit snugly in the palm between thumb and fingers, partially dependent on finger stiffness. This can provide a firm grasp for the right shape/size object. The wrap grasp was also observed without the thumb as a palmar grasp, though providing a less secure grip. Not all people observed could perform the wrap grasp, given some had a permanent fist due to finger contractures.

The arm is broken into two sub-actions that involve it clamping the object in some way to grasp, lift, and support objects that are often too large or unsteady for other body parts to perform. This is listed as more secure because this population has greater voluntary control of the arm and shoulder muscles, allowing for greater motion and force application.

1) **Clamp in Elbow** - Unimanual manipulation that allows for distal pick and place of larger objects. The object is squeezed in the crook of the elbow, between the bicep and forearm. This can be used to retrieve an object from a side location, which can be a difficult manipulation task for many in this group given restricted approach angles from the wheelchair and a reduced ability to reach across the sagittal plane for bimanual grasping.

2) **Push/Support with Arm** - Here, an object is pressed or clamped against the body, a surface or object in the environment with the arm. This can secure the object from falling or while performing other actions on it like holding down food while cutting it with the other hand.

For many with tetraplegia, the mouth is the most secure prehensile gripping strategy and, for many, the most widely used for strong and precise tasks. It is hard to overstate how integral the mouth can be for strategies such as holding, tearing, unscrewing, etc. However, there are some environmental factors that affect one’s willingness to use their mouth, such as cleanliness or discomfort with others staring.

1) **Bilabial Pinch** - This prehensile gripping is used for more delicate tasks and materials when not wanting to damage or moisten the object surface or taste/ingest its contents.

2) **Interdental Pinch** - The strongest of the prehensile manipulation strategies, the inter-dental pinch is the only one fully innervated, and even in the normative population the jaw can provide a strong clamp force [28].

The combined action column on the right, separated by dashes, presents distinct behaviors that are not fundamental elements of the taxonomy but rather are commonly used strategies for manipulation, made up of one or more elements from the grasp actions.

**Environment** - Environmental Feature Use or Exfordance [29] is regularly used by this population, most commonly noted in the videos to either stabilize the object in a bilateral fashion or to secure a grip for unimanual prehensile grasping. Given the loss of voluntary finger movement and often contractures, the fingers remain closed for many unless forced open, which was observed when the environment was used to push an object into the hand for grasping. Also, sliding objects such as a credit card or plate partially off the edge of a surface was used to initiate both non-prehensile and prehensile manipulation strategies.

**Bimanual** - Bimanual strategies are also left out of the central taxonomy given they are made up of two or more grasping action elements. However, it is worth noting that for many in this group, given varying levels of voluntary control of the arms, chest, and torso, their effective working area of bimanual tasks is kinematically constrained. Within this range however, one of the most common bimanual grasping strategies is pressing the object between both palm faces. Additionally, manipulation is also limited to gross transfer actions of mid-sized to larger objects.

**Tenodesis** - Tenodesis is observed across all the prehensile strategies with wrist extension performed to tighten the tendons to increase grasping force and finger stiffness regardless of grasp type or hand/finger orientation. Additionally, wrist extension, the voluntary action in tenodesis was observed to enhance the non-prehensile strategies by stabilizing the wrist. It was further observed that wrist supination was used to take advantage of gravity-assisted grasping and carrying, as the object mass would extend the wrist in addition to tenodesis. This allowed for the grasping of objects that were either too heavy for just the wrist alone, would otherwise passively stretch and open the fingers, or would fatigue the wrist if held for long. This use of extrinsic (i.e. gravity [30]) and intrinsic (i.e. muscular) wrist extension to enhance grasp security of different action categories is left as a topic for future study.

**B. Egocentric Case Study**

To initially evaluate and validate the taxonomy, the author with SCI recorded more than three hours of egocentric videos performing the general tasks seen in the videos to the best of their abilities. For example, making tea as the author...
would normally, not trying to replicate the specific motions but simply executing the general task. The footage was reviewed, evaluating whether all manipulation strategies in the author’s data were represented in the taxonomy. Through this review, all manipulation strategies observed adequately fell within the taxonomy categories except for the clamp in elbow (Arm, 1), which was then added. This suggests the presented taxonomy, by and large, covers the manipulation strategies commonly seen within C5-7 tetraplegic individuals. However, it may be supplemented with additional grasp types as more scenarios and individuals are observed with a larger dataset in future work.

IV. DISCUSSION

The taxonomy presented in Fig. 3 shows how diverse the grasp strategies employed by this specific population are, with 14 of the 27 strategies not appearing in previous taxonomies. Some of this diversity can be attributed to the liberal definition of grasping used in this work, but also the restricted motion of the individual in their wheelchair and loss of hand function that forces the use of new approaches not seen in normative grasping. For example, all surfaces of the hands are used in the non-prehensile strategies, given reduced hand function, arm strength and mobility; this is counter to the normative population, that preferentially uses the palmar side of the hand for contact.

Given this wide range of behaviors and contact points, we assert that it is imperative to critically evaluate how a proposed assistive device for ADLs might unintentionally inhibit any of these strategies, and how the device makes up for this. For example, a hand exoskeleton, such as one that aims to improve prehensile grasping, e.g., [31], that covers the dorsal side of the hand may hinder the use of strategies involving it, such as the dorsal support, push, and hook non-prehensile strategies. New product features may emerge from this taxonomy framework, such as more emphasis on the profile, robustness, and contact friction of hardware that is not located on the palmar side of the hand. If the palm is covered, the user must similarly retain the ability to push a manual wheelchair push rim, etc. For manipulation strategies that the device does inhibit, sufficient function that compensates for these lost strategies should be demonstrated or alleviated in functionally relevant ADL tasks. It is not enough to say that a device meant for generalized use increases normative function alone, when overall manipulation function may be reduced in the context of manipulation strategies the individual used before the intervention was introduced.

V. CONCLUSION

Many factors contribute to the lack of translation of assistive hand device research to everyday use in the home, both from the business and research sides. These devices often only address a small set of specific tasks or functions. This is valuable in the scientific process for testing technology innovations, but can inadvertently hinder the execution of other tasks. This is a potential oversight, to not recognize the rich set of compensatory manipulation strategies this population employs, and the human ingenuity to find new ways to complete tasks. Without considering this, devices may be abandoned if, while trying to augment one type of dexterity, they do so at the cost of another – obstructing functional compensatory strategies. This grasp taxonomy for people with C5-7 SCI seeks to bridge the research-application divide through both better understanding the end-user, and creating a tool to critically and quantitatively evaluate new technology within the context of daily living through video observations.

A. Limitations and future work

This study uses a limited-sized data set and a limited number of participants, taken from online self-posted videos. Despite this, the authors’ initial validation shows that the few tasks performed, in fact, account for the most commonly observed manipulation strategies. Through the observation of more participants, there are likely to be more, less-common strategies observed and expanded manipulation taxonomies. As has been suggested, an individualized taxonomy, autonomously generated with personal egocentric data will describe an individual most precisely [17]; however, for the purpose of design interpretation and evaluation, our initial generalized taxonomy for this population is a beneficial start. Future work will explore this further to evaluate the taxonomy completeness with a larger unedited data set of more participants, and add to it if necessary.

In the present study, we do not directly present or compare the frequency of grasp usage across tasks or individuals. In part this is because the videos were edited by the content creators for public instruction or entertainment and thus may not precisely represent the time duration and frequency as it naturally occurred. Despite this, we saw a large percentage of grasps used to bring an object into the person’s bi-manual functional range of motion [32] followed by the use of non-prehensile, bi-manual strategies to perform the desired object manipulation task. We therefore believe that this grasp use frequency and order are interesting factors to characterize with complete data sets, like that collected in [33]. Such quantitative analyses must be included in future work in order to prove out the utility of the taxonomy proposed in this preliminary work.

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