Grasp and Force Based Taxonomy of Split-Hook Prosthetic Terminal Devices

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Abstract — **In this paper, we analyze the use of the body-powered split-hook prosthetic terminal device, which is the most commonly used upper-limb prosthesis. We developed two taxonomies of split-hook use, one on grasp shape and one on force exertion, illustrating the functional capabilities and use cases of the device. Video captured from an amputee using a body-powered split-hook during a number of common activities was used to lend weight to the completeness of the classifications. These taxonomies serve to establish a common language and means of comparing the types of grasps achievable by simple terminal devices to those of advanced myoelectric terminal devices or even human hands. The first taxonomy categorizes the grasp type based on the contacts with the environment while the second is categorized by the method and limitation of force exertion. We discuss the difference between grasps capable of holding objects compared to those that are capable of acquiring objects and the importance of non-prehensile uses of the split-hook. The classification schemes lay the groundwork for further detailed study of split-hook use, and the discussion of the use cases described may help guide terminal device developers to create improved prostheses.**

Keywords—split-hook; terminal device; prosthetic hand

I. Introduction

Although hundreds of prosthetic terminal devices are available, ranging from task specific devices to almost indiscernible cosmetic replicas of human hands [1], the voluntary opening split-hook (shown in Fig. 1) is widely accepted as the most commonly utilized functional terminal device [2]. Even with advanced multi-fingered and multi-DOF myoelectric terminal devices now available on the market, many prosthetists and amputees still turn to the body-powered split-hook due to its proven robustness, performance, low cost, and light weight [3], and many amputees who have learned to utilize the split hook without any major difficulties are reluctant to switch to a newer technology with a long learning curve.

Researchers have long categorized and organized human hand grasp types to better understand and emulate the capabilities of human manipulation. An early taxonomy divides human grasps into six main categories: cylindrical, tip, hook, palmer, spherical, and lateral based on the approximate shape of the hand while grasping an object [4]. This was later extended to a more complex human hand grasp taxonomy by Cutkosky based on the grasp types required in a manufacturing environment [5]. Manipulation taxonomies have also been proposed that classify the relative motion between the object and hand rather than the "shape" of the grasp [6]. The information on human hand use is commonly collected through observation and through the analysis of film collected in a natural use setting. A recent study by Zheng et al. analyzed video footage of human hand use taken during non-structured tasks for machinists and housemaids [7]. By recording each grasping task, the relative distribution of grasp types was measured.

In this paper, we present two sub-classifications of split-hook prosthesis use to enable a better understanding of the functional capabilities and usage of this class of terminal devices. While the specific pose or shape of the hook with relation to the object may help to define the grasp type, it was also observed that within different grasp types there are multiple limitations to the forces that can be exerted on the object. For this reason, we separated our look at the split-hook into two taxonomies. The first is based on the nature of contact with an object, while the second is based on the types of force exertion that can be utilized.

There has been relatively little work related to thorough classifications of split-hook usage that focuses on the function of the device instead of the task. While the majority of studies on prosthesis use to date has primarily involved written surveys of users (e.g. [8]), others have supplemented with follow up visits to the amputee's home to observe the use of the device in the normal and unstructured environment [9]. As far as the authors are aware, all of these studies focus on high-level function (e.g. usage frequency, classes of tasks) without detail on the specific ways in which the device is used. The most relevant study that we were able to identify was performed by Fraser in 1998, in which 66 amputees were videotaped at their homes using their terminal device while performing a set of common tasks [10]. The video was then analyzed and each action involving the terminal device was categorized into a manipulative or non-manipulative category. The secondary categories included, grip, release, hold, transfer, support, steady, etc. While generally a very thorough study, it did not focus on specifics of the device usage and the categorization was broad enough to cover the wide range of devices used, including purely cosmetic terminal devices.

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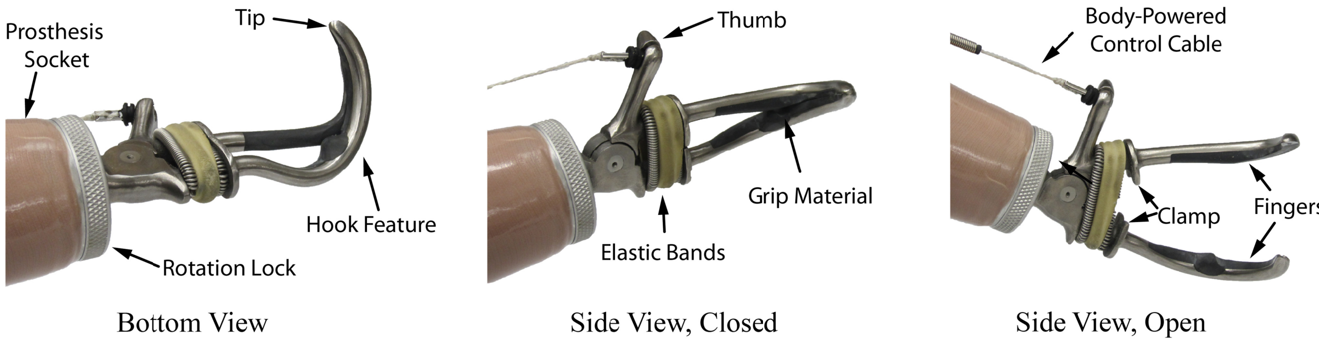

Figure 1. Standard features of the body powered split-hook terminal device. Here, the three views show the classic Hosmer Dorrance 5XTi hook shape and the method of operating the hook using a body-powered control cable.

We are interested in studying the specifics of split-hook type terminal device usage with enough detail to identify specific design shortcomings and areas that can be improved, and therefore would like a detailed classification scheme. We begin this paper with a detailed look at the design of the split hook and methods used to develop the taxonomies. We then present and discuss the taxonomies, including ways to extend it to other device types as well as utilize it to improve and refine future terminal device designs.

II. Methods

A. Description of Split-Hook

The split-hook terminal device has changed little since the original patent was awarded to David W. Dorrance in 1912 [11]. Despite its crude aesthetic appearance, it remains the most popular terminal device for upper limb amputees [2].

In the most basic form, the split hook consists of two titanium or stainless steel fingers shaped to form a hook (see Fig. 1). The inside of the fingers is coated with a layer of Nitrile or Neoprene grip material to increase the surface friction and prevent objects from being scratched by the metal hooks. The grip material has an additional bulge feature (sometimes called the “cigarette notch”) that helps grasp slender, long cylindrical objects similar to a pencil or cigarette. At the base of the fingers there are two opposing grip surfaces called the clamp. These plates have a small cutout in the center to provide additional support and naturally center cylindrical objects along an axis in line with the wrist. The intended purpose of the clamp is to provide a gripping surface on another plane to that of the fingers. Also, the clamp can provide a much larger grip force since the contact points are closer to the pivot point of the device.

The top finger has a long feature protruding perpendicular to the plane of the finger. This feature is called the “thumb” and supports the attachment point for the body-powered control cable and serves as a contact point for grasping similar to the way the human thumb base and palm support the back side of a pencil (see Fig 1, center image). The length of the thumb determines the moment arm of the control cable about the hinge at the base of the fingers. In the voluntary-opening style terminal device, as seen in Fig. 1, the fingers are constantly being held together by a set of elastic bands. A pull of the body-powered control cable, usually accomplished through relative movement of the user’s shoulders or upper arm, overcomes the force of the elastic bands and opens the fingers. The number and strength of the elastic band determines the force placed on an object when it is being gripped in the device. A tradeoff to having a higher number of elastic bands is the increase in fatigue associated with pulling the control cable.

The major benefits of the split hook are attributed to its weight and durability. The standard Hosmer Dorrance 5X split-hook weighs only 213 grams as compared to 400-600 grams for modern myoelectric hands [12]. Also, because of the simple metal construction users do not need to worry about environmental factors such as heat and abrasion [2]. When manipulating smaller objects, the thin profile of the fingers does not obstruct the view of the object. This is an important factor when comparing hooks with functional hands. While we focus the taxonomies on the Hosmer Dorrance 5x style hooks, the results apply to most classes of split-hook type terminal devices. However, small differences such as lack of the “thumb” or additional finger design features may require slight modifications to the results, as described later.

B. Terminology

In order to remove ambiguity, we have defined the terms that will be used within the taxonomy.

- *Prehensile* – The object is intended to be fully supported within the terminal device without the requirement of gravity to hold the object in place.
- *Contact* – Point of interaction between the terminal device and the object or environment.
- *Grip Security* – Ability to maintain the grasp with external disturbances applied to the object.
- *External Force* – A force applied to the external world that would require an equal force to support the terminal device. These types of loads would include pushing, pulling, or lifting.
- *Internal Force* – A force that is created between the fingers of the terminal device. These types of forces include pinching and grasping in a prehensile fashion.

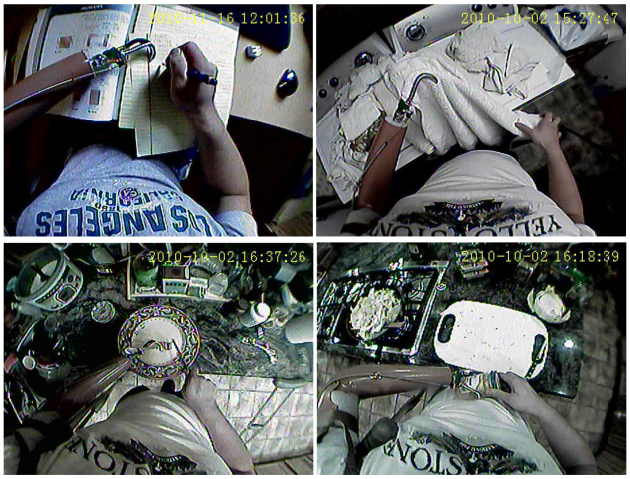

Figure 2. Video frames showing different grasp types exhibited by a unilateral body-powered split-hook user.

C. Method of Establishing Taxonomies

The presented taxonomies were generated after thorough discussions between the authors, one of which is a 10-year user of a Hosmer Dorrance 5X-Ti, voluntary-opening body-powered split-hook. In addition, over 5 hours of video footage was acquired of that author's hook use during numerous activities, including hygienic tasks, laundry, cooking/eating meals, and standard office style work. Fig. 2 shows four sample frames from the video in which the hook is being used to accomplish simple tasks. The video footage was gathered using a head mounted webcam and video recording system similar to the system used in [7], and the user was recorded while in his natural home setting. This video data was studied by all the authors and used to validate the taxonomies, with the authors categorizing each grasp or interaction seen in the video according to the developed classification schemes to ensure that no additional categories were required. The examples depicted in Fig. 3 and Fig. 4 are based on those seen within the recorded video.

III. Results

A. Grasp-based Split-hook Taxonomy

The grasp taxonomy (Fig. 3) attempts to capture any way the split-hook is used to interact with the environment. We first divided the interactions into a non-prehensile or prehensile category, in a similar way to the non-manipulative and manipulative category used by [10]. The non-prehensile category was then subdivided by the locations of contact on the hook. It was shown that almost all surfaces of the hook including the tip, front, thumb, and inner surface were used in a non-prehensile manner. These types of interactions were used to provide stabilizing actions and often in assistance to the able hand. In standard presentations of terminal device grasping capabilities, these important aspects are often overlooked. The rigidity of the hook and the shape help it to perform the non-prehensile type interactions more predictably.

The prehensile category is first sub-divided based on whether the fingers are used. Although the fingers are the main prehensile feature of the split-hook, grasping objects with the outer surface of the fingers was also observed (e.g. the "finger/exterior" grasp, with a roll of tape), as well as within the "clamp". For prehensile grasps with contacts occurring between the fingers, they were again sub-divided based on the number of contacts between the object and the split-hook. These are limited to two contacts (usually for "precision grasps" on small objects), four contacts (often for long, thin objects, and often involving both the fingers and an additional feature such as the "thumb"), or area contacts, where a large portion of the entire grip material surface was in contact with the object, which is sometimes used in combination with the "clamp". The entire taxonomy is organized from left to right based on an increase in object grasp security which is strongly correlated to the number of contacts between the hook and the object.

Note that a few particular grasps, marked with an asterisk in Fig. 3, typically cannot be achieved without the use of the contralateral hand or terminal device. Partly due to their complexity and the geometry of the objects used in them, these grasps generally require proper position of the object with respect to the split-hook and were not achievable when trying to pick up an object directly from a table or drawer. For example, the common "Thumb/Fingers" grasp, used to hold an eating or writing utensil, requires specific positioning of the utensil that is not generally achievable without placing it in the grip using the other limb.

B. Force-based Split-hook Taxonomy

The split-hook force exertion taxonomy (Fig. 4) shows the different methods and limitation of exerting load on the environment. The first categorization separates the force exertion based on external or internal forces. This division is very similar to the division of non-prehensile or prehensile functions since all prehensile grasps require internal forces. The second sub-categorization is based on the factor that limits the amount of force that can be exerted on the environment. This includes the prosthesis suspension system, the elastic bands, and the control cable.

The suspension system consists of the entire apparatus used to fixate the prosthesis to the amputee, including the prosthetic socket and body powered harness. Since a tradeoff exists between how tightly the prosthesis is attached and the level of comfort, the amount of loading during pushing, pulling, or lifting is limited. The achievable loads within this category are also limited by the strength of the user.

The internal gripping forces of the voluntary-opening split hook are generally determined by the elastic bands (the number and stiffness of which are chosen by the user according to their preferences, needs, and abilities), but can also be modulated by a balance of tension in the body-powered control cable and the elastic bands. When an object is grasped and all tension is released from the control cable, the maximum force exertion is dependent on the elastic bands, the location of the object within the hook, and the size of the object. For a standard amount of elastic band

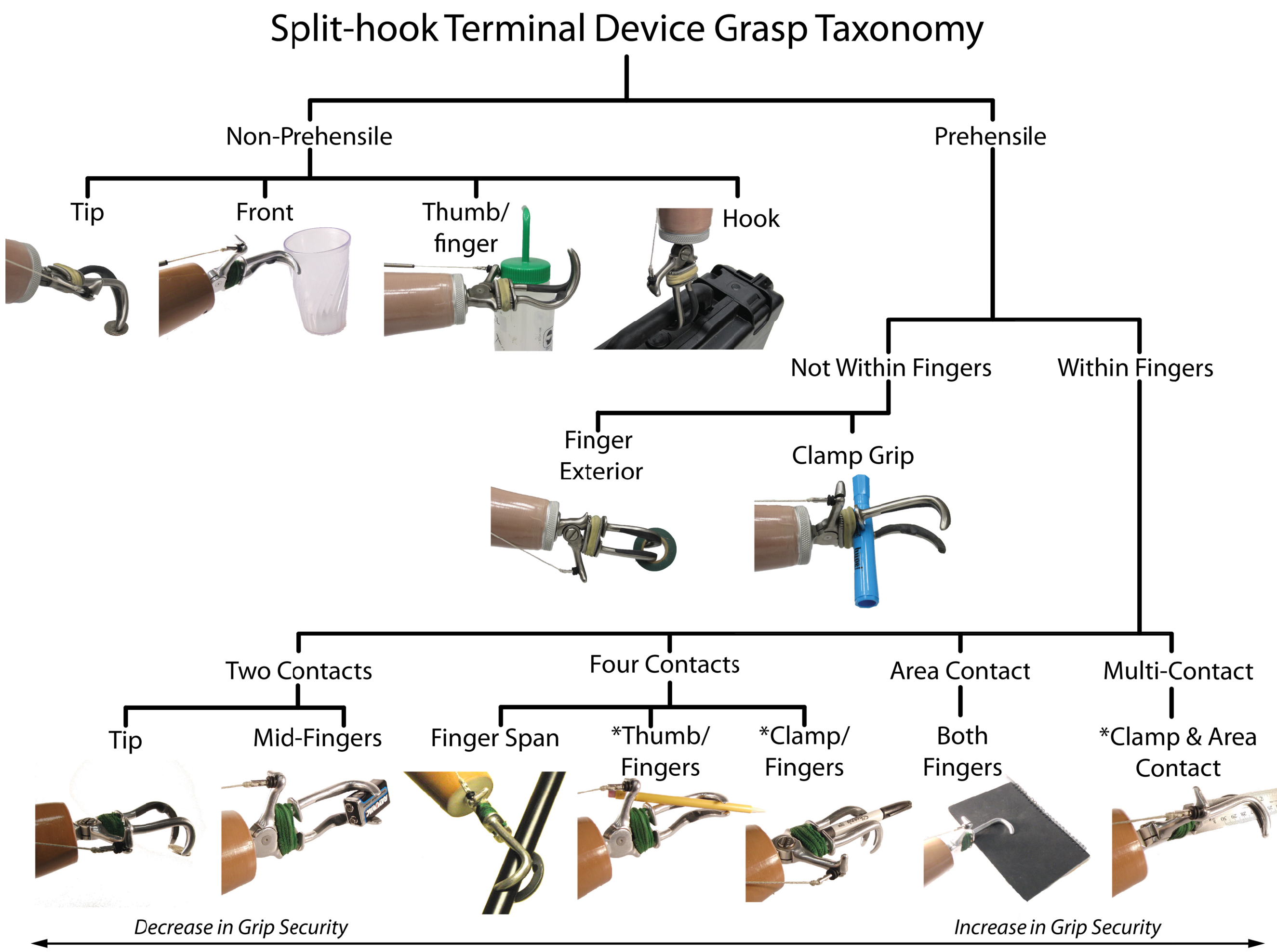

Figure 3. The Split-Hook grasp taxonomy shows all observed uses for the voluntary-opening split-hook as controlled by a body-powered control cable and harness. *Grasps only observed by placing the object within the hook using the able hand.

tension, the grip force at the fingers is between 45-70 N for 1-3 cm sized objects. The grip force of a 1 cm sized object in the clamp can reach 140 N. In Fig. 4, the hook is shown crushing a peanut within the clamp feature. The user can also overpower the strength of the elastic bands and exert a load with the outside of the fingers. The limiting factor in this type of grasp is the tension in the body powered control cable, minus the force required to open the fingers due to the elastic bands, as shown in Fig. 4 separating a stiff rubber band.

Often more delicate and fine movements of the fingers are required. In this case, the user can alter the position and force on the control cable such that a much smaller grip force is placed on the object than that of the elastic bands alone. Ultimately, the grip force exerted on the object is the difference between the load in the control cable and the tension stored in the elastic bands. With a high degree of concentration, the user is able to grasp delicate objects like a small spring, or a compliant drink lid, as shown in Fig. 4 (far right). However, due to the required tension on the cable, it can be difficult for the user to keep that pose while moving their arm in space. The force-based taxonomy is sorted from left to right by the level of user concentration required to perform each category of force exertion.

IV. Discussion

The two taxonomies presented in Fig. 3 and 4 show that the split-hook is used to perform a wide array of grasp and interaction types. Although the grasp taxonomy was not based on the objects being grasped, it can be seen that the achievable prehensile grasps ecompass a large set of common object sizes and geometries. Furthermore, the array of achievable grasp types hold many objects in multiple orientations, depending on the requirements of the task intended to be performed.

A. Object Acquisition versus Holding

A major feature of grasp utilization relates to the difference in acquisition methods for each particular grasp type. Some of the grasps are unachievable without careful prepositioning of the object prior to closing the split-hook. For example, the four-contact, thumb/finger grip, as seen in Fig. 2 (bottom) securing a fork, is only achieved if the able hand positions the fork within the hook. This is the case for most grasp types involving multiple contacts with the thumb

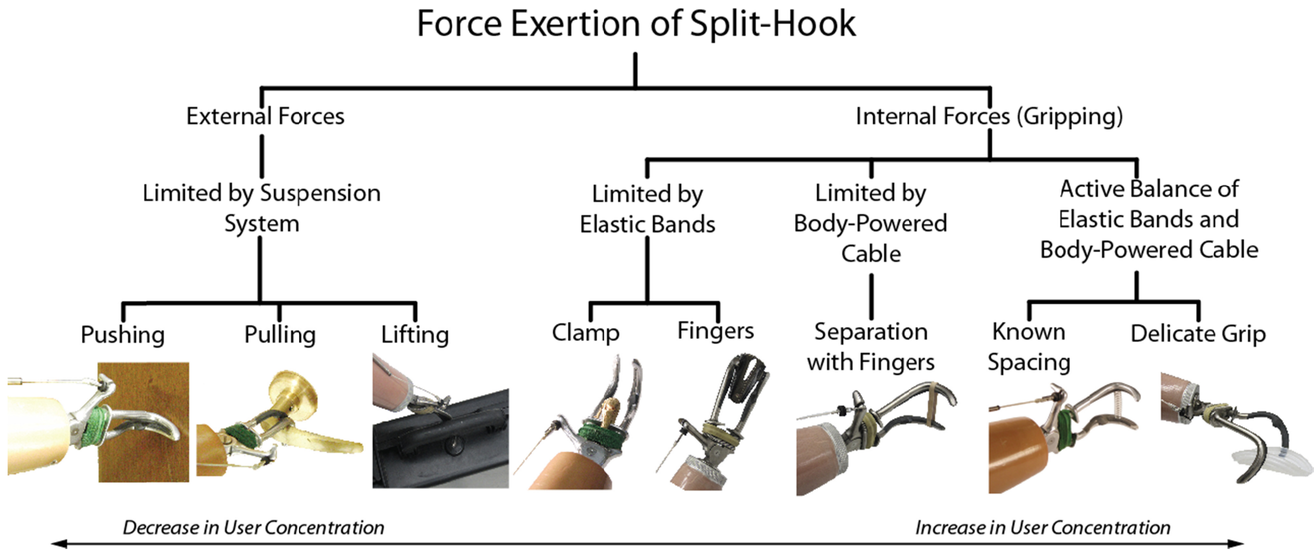

Figure 4. The split-hook force taxonomy shows the methods of force exertion utilized by split-hook users. The organization is based on the limitation to the maximum force exerted and the amount of user concentration required to achieve that particular task.

or clamp. Preposition of objects is observed in able human hand manipulation when one grasp type is used to pick up the object before within-hand manipulation transitions the object into a more stable or useful grasp. With the lack of within hand manipulation in the split-hook, the object must be placed in the hook in the exact position for use which places a large demand on the contralateral hand or terminal device for much of the practical function of the hook. This shows that not only is the grasp important, but the method of acquiring it in order to determine its relevance and practical usage to both unilateral and bilateral amputees doing unilateral and bilateral tasks.

The necessity for careful prepositioning prior to achieving a useful grasp position may lead to the high incidence of non-prehensile uses of the split-hook or other terminal devices. In fact, the most common grasps seen in the video of the split-hook user were non-prehensile grasps, with within-finger two-contact grasps the next most common. Similar results were found by Fraser [10]. If a unilateral amputee requires the use of the able hand to assist the terminal device in holding or using an object, then it may be easier to simply perform the task completely with the able hand. Perhaps since non-prehensile functions do not require this additional effort and require very little user concentration, they are performed more frequently.

B. Modifications of Hooks/ New Hook Designs

Designers have seen limitations to the traditional split-hook design and proposed alternative features or actuation methods [1]. We can easily see how the features added to the hook could expand, or fill in, the grasp taxonomies presented in this paper. Fig. 5 shows two additional hook types including the "Work Hook" (middle) and the Sierra voluntary closing hook (right) [1]. The work hook was appropriately named based on the addition of the large cylindrical opening between the fingers. This opening was intended to grasp the handle of a broom or shovel. When we look at the grasp taxonomy in Fig. 3, we see that this offers a more robust alternative to the four-contact finger-span grasp type.

While the work hook partially addresses it, one major limitation to the capabilities of the split hook is the lack of a robust medium and large diameter power grasp (often called "wrap grasps" as they involve a large amount of contact between grasper and object to support large loads). These power grasps make up a large portion of grasps for human hands, yet are not capable of being performed using the standard split-hook. The lack of a large power grasp was made up for by utilizing the split-hook wearer's body and often sandwiching large cylindrical items between the hook or prosthesis socket and their chest or stomach.

When looking at the force exertion capabilities of the split-hook, it is clear that there are limitations based on the nature of any voluntary opening terminal device, the most important of which is the inability to close tighter on an object than the limitation imposed by the elastic bands. If the device were a voluntary closing split-hook, the load could be directly specified by the tension in the body powered cable. One drawback is that this tension would need to be maintained while holding an object. The Sierra voluntary closing hook lacks the clamp feature but does offer the ability to exert larger forces within the fingers of the hook. The voluntary-closing operation gives the benefits as described above but also features a lock that will hold the hook in position when the tension is released from the control cable (although this locking feature can be a bit cumbersome and sometimes unreliable).

In addition to these changes in the split hook designs, numerous task specific hook-type terminal devices are sold. These types of devices do not attempt to span the entire space of required grasp types, but focus solely on a particular aspect such as holding a baseball glove or fishing rod [1].

Figure 5. Basic Hosmer 5X hook (left) compared to the "Work Hook" (middle) and the Sierra Hook (right) [1].

V. CONCLUSIONS AND FUTURE WORK

Using the split-hook taxonomy, we can easily compare the functional use of the hook with both human hand and other prostheic hand use. Although the split-hook has the ability to perform a wide variety of functions, it lacks in the ability to acquire all the grasps without assistance from the able hand and the ability to exert forces is limited by the nature of the voluntary opening control strategy. We believe that the presented taxonomies can allow for more detailed grasp analysis in order to compare and better understand the function of numerous terminal devices. Although we have classified the types of grasps achievable by the split-hook, we would like to get a better understanding of the importance of each grasp type based on the frequency of use or the types of grasped objects that are more important than others. This analysis has been performed for able hands in [5,6,7], but non-prehensile functions of the hand were rarely classified and recorded. To do so with terminal devices, we would like to extend our video analysis for a much greater number of subjects and tasks, as well as to include logging of grasp type and duration to enable calculations of statistical distribution of grasp type utilization. This would add an additional element related to the importance of each grasp listed in the taxonomy and therefore allow for a more informative decision making process for the designer of prosthetic hands depending on the usage and functionality required by the end user.

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