A TAXONOMY FOR COMMERCIALLY AVAILABLE MYOELECTRIC TERMINAL DEVICES

Eric J. Earley, PhD[1,2], Cristina Piazza, PhD[3], Kristi L. Turner, DHS, OTR/L[4]

[1]*Bone-Anchored Limb Research Group, University of Colorado Anschutz Medical Campus, Aurora, CO, USA*

[2]*Department of Orthopedics, University of Colorado Anschutz Medical Campus, Aurora, CO, USA*

[3]*Department of Computer Engineering, Technical University of Munich, Germany*

[4]*Center for Bionic Medicine, Shirley Ryan AbilityLab, Chicago, IL, USA*

ABSTRACT

The number of myoelectric prostheses available commercially has grown rapidly in the past decade, displaying a range of design philosophies and capabilities. As a result, the terms "myoelectric prosthesis," "bionic hand", or "multifunction prosthesis" commonly used to describe such devices fail to account for these different prosthetic designs. Here, we propose a myoelectric prosthesis terminal device taxonomy, which aims to describe the full span of prosthetic designs. We then categorize commercially available myoelectric prosthetic terminal devices to identify the subset of categories most frequently represented in the market, thereby expanding the ability to perform cross-study comparison and meta-analysis of myoelectric prosthesis performance.

INTRODUCTION

For people with limb loss or limb difference, myoelectric prosthetic hands represent the current standard of prosthetic care. While some prostheses are capable of only rudimentary opening and closing, reminiscent of the body-powered prosthetic hooks available throughout the 20th century, other modern "bionic" prosthetic hands are capable of emulating more complex hand movements, with features including thumb adduction and independent finger actuation. The number of myoelectric prosthetic hands entering the market has increased drastically in the past decade [1, 2]. While this provides a wealth of options for those with limb loss and limb difference, it also presents a challenge when it comes to comparing the capabilities of each hand, especially with respect to their degrees of freedom.

With the increased flexibility and versatility of these modern myoelectric prosthetic hands, the previous classifications of opening and closing the hand were insufficient to describe the new grasping styles that are now possible. There was a need for a grasping taxonomy which strove to classify the nearly infinite combinations of finger and hand positioning in a manageable number of prehensile patterns which are commonly used throughout daily life [3]. Related work near the end of the 20th century, namely the development of the Cutkosky grasping taxonomy [4] and postural synergy analysis [5], served as a foundation and inspiration for identifying the common grasp which multifunction prostheses would strive to mimic. While the control of individual fingers of a prosthetic hand can be done within research settings [6], most multifunction instead implement a subset of these grasping patterns as "presets", available for the user to access via pattern recognition control [7], gesture control, or a mobile app. These grasping styles subsequently influenced the development of several standardized outcomes to be able to characterize the benefits of the additional mechanical complexity (and cost) of these devices. For example, the Southampton Hand Assessment Procedure (SHAP) requires its various tasks to be performed using six specific grasps [8]. However, the ability for a prosthetic hand to achieve any of these grasps is wholly dependent on its mechanical design and its available degrees of freedom.

Given the vast difference in grasping capabilities across devices which share the label "myoelectric prosthesis," and the ever-expanding number of myoelectric prostheses available on the market, there is a clear need for a taxonomy which can categorize these devices based on their common functionality and their mechanical degrees of freedom. Thus, in this paper we propose such a terminal device taxonomy with two aims. First, we aim to describe the full span of possible prosthetic designs, such that any myoelectric prosthetic hand can be clearly classified. Second, we aim to perform a market analysis of commercially available myoelectric prosthetic terminal devices, to categorize these prostheses according to the proposed taxonomy, and to identify the most common categories. By identifying the subset of categories most frequently represented in the market, we aim to expand the ability to perform cross-study comparisons and meta-analysis of myoelectric prosthesis performance according to common functionality, rather than grouping study outcomes by a growing list of individual devices.

METHODS

The genesis for creating the terminal device taxonomy arose during conversations regarding the development of a data entry sheet for the Assessment of Capacity for Myoelectric Control (ACMC) [9], wherein evaluators would be asked to indicate the prosthetic setup being used. In earlier iterations of this sheet, evaluators could select from a small number of myoelectric prosthetic hands commonly used in research. However, when revisiting this sheet for current use, we noted that it would become cumbersome to list every type of prosthetic hand; furthermore, doing so would also require frequent updates for the sheet to stay up-to-date with the latest technological developments. Instead, developing a smaller list of prosthetic hand categories that can broadly differentiate between the different types of myoelectric prostheses would both reduce the complexity of filling out the sheet for the evaluator, and also future-proof the list against requiring frequent updates to account for new prosthetic hands entering the market or research space.

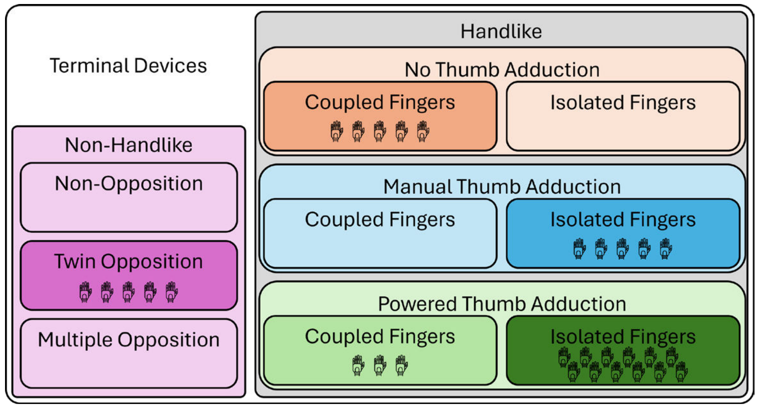

Figure 1: The proposed terminal device taxonomy features two higher-order taxa, *Handlike* and *Non-Handlike*, determined by the appearance and function of the device. Each higher-order taxon is further separated into several lower-order taxa. Icons within each taxon represent the number of commercially available prostheses categorized accordingly; taxa with greater representation are colored darker.

Development of the Taxonomy

Thematic analysis of common commercially available myoelectric prostheses provided a foundation for the taxonomy. We noted three broad categories that we wanted to account for in the taxonomy: prosthetic hooks and grippers, simple (open/close) prosthetic hands, and multifunction prosthetic hands. Next, particular focus was paid to grouping the different types of multifunction prosthetic hands, in which we noted two dimensions of categorization: thumb adduction and finger coupling. Finally, through a review of commercially available and research prostheses, we iterated upon the taxonomy as flaws were discovered which failed to categorize a prosthetic design.

The full taxonomy is shown in **Figure 1**. The following sections introduce the two overarching taxa (categorizations), followed by their unique lower-order taxa.

Non-handlike terminal devices are prostheses which do not seek to emulate the appearance or function of the human hand, but instead performs grasping actions through other configurations. Non-handlike terminal devices can be separated into three categories:

- Twin opposition: two opposing surfaces are used to grasp objects, such as the traditional split-hook design.
- Multiple opposition: three or more opposing surfaces are used to grasp objects. Designs often take inspiration from industrial grippers.
- Non-opposition: objects are handled without opposition, instead employing other mechanisms such as suction or wrapping around the object.

Handlike terminal devices are prostheses which seek to emulate the appearance of the human hand, and to varying degrees emulate the natural function and degrees of freedom of the hand. Handlike terminal devices can be categorized across two dimensions of mechanical degrees of freedom. First, devices can be separated into three categories describing the ability of the prosthetic thumb to adduct:

- No thumb adduction: the thumb is positioned in an abducted position, suitable for palmar grasping. It may flex, but cannot be rotated into an adducted position for lateral grasping.
- Manual thumb adduction: the thumb can be positioned in an abducted or adducted position, but must be rotated manually. Thumb flexion is still powered.
- Powered thumb adduction: thumb flexion and adduction are both powered.

Second, devices can be separated into two categories describing the coupling or independence of the prosthetic fingers:

- Isolated fingers: all five fingers are mechanically independent and could theoretically be adapted to actuate individual fingers, even if the fingers are normally controlled to move together (e.g. if using grasp-based pattern recognition).
- Coupled fingers: some or all fingers are mechanically coupled, such that they cannot be actuated independently.

Taxonomic Categorization of Commercially Available Prosthetic Terminal Devices

A list of commercially available prosthetic terminal devices is provided in **Table I**. The list was populated using an online database [10] supplemented by the authors' knowledge of devices that were omitted from the database. In total, 30 prosthetic terminal devices were identified; devices created only for research purposes, which are not commercially available, are not included.

Table I: Taxonomic Categorization of Commercially Available Prosthetic Terminal Devices

Non-Handlike Terminal Devices		
Fillauer MC Standard ETD	Twin opposition	
Fillauer ProPlus MC ETD	Twin opposition	
Fillauer ProPlus MC ETD2	Twin opposition	
Ottobock AxonHook	Twin opposition	
Ottobock Greifer	Twin opposition	
Handlike Terminal Devices	***Thumb Adduction***	***Finger Coupling***
Aether Biomedical Zeus Hand	Manual	Isolated
Atom Limbs Atom Touch	Powered	Isolated
BionIT Labs Adam's Hand	Powered	Isolated
BrainRobotics Prosthetic Hand	Powered	Isolated
COVVI Nexus Hand	Powered	Isolated
Fillauer MC ProPlus Hand	None	Coupled
Makers Hive KalArm	Manual	Isolated
MaxBionic MeHand	Powered	Isolated
Mobius Bionics Luke Arm	Powered	Coupled
Motorica Manifesto Hand	Powered	Isolated
Open Bionics Hero Arm	Powered	Isolated
Össur i-Limb Access	Manual	Isolated
Össur i-Limb Ultra	Powered	Isolated
Össur i-Limb Quantum	Powered	Isolated
Ottobock bebionic Hand	Manual	Isolated
Ottobock Michelangelo Hand	Powered	Coupled
Ottobock MyoHand VariPlus Speed	None	Coupled
Ottobock SensorHand Speed	None	Coupled
OYMotion OHand	Manual	Isolated
Prensilia MiaHand	Powered	Coupled
Psyonic AbilityHand	Powered	Isolated
Robo Bionics Grippy	None	Coupled
TASKA Hand Gen2	Powered	Isolated
Unlimited Tomorrow TrueLimb	None	Coupled
Vincent Systems Vincent Evolution	Powered	Isolated

RESULTS

Of the 30 identified commercially available prosthetic terminal devices, the majority (25) are handlike in design, and half (15) feature powered thumb adduction. Of these, most (12) feature isolated finger actuation, indicating the general trend for multifunction hands over the past decade. Although every hand with no thumb adduction or manual thumb adduction had coupled and isolated fingers, respectively, there was a subset of hands with powered thumb adduction and coupled fingers. This is likely intended to reduce the number of motors via underactuation, relying on the fact that prominent grasping synergies typically involve some degree of finger coupling [5].

DISCUSSION

Overall, we identified five categories which describe the commercially available prosthetic terminal devices:

- Non-handlike terminal device
- Hands without thumb adduction
- Hands with manual thumb adduction
- Hands with powered thumb adduction and coupled fingers
- Hands with powered thumb adduction and isolated fingers

The proposed taxonomy shown in **Figure 1** features several taxa which are not commercially represented. We do not recommend including these in the list of categories above, however we believe their presence in the taxonomy represents the possibility of prosthetic terminal device design. Indeed, examples of each of these taxa may be found in the literature, and have simply not been developed into a commercial product.

For handlike devices, a case can be made for the inclusion of *semi-coupled* fingers as a new taxa, which refers to devices where some, but not all, fingers are coupled. For example, the Mia hand couples the middle, ring, and little fingers, but the index finger actuates independently from these three fingers. However, for the purposes of a concise categorization listed above, we grouped all hands were finger coupling.

One aspect which is not considered in this taxonomy is the method used to control a prosthesis. For example, in a recent study, a prosthesis with fully isolated fingers (Ottobock bebionic) was set up to couple the middle, ring, and little fingers as one unit, and to control the index and thumb flexion independently [6]. The taxa for coupled and isolated fingers represent the limits of prosthetic function; A prosthetic hand designed with the ability to move fingers independently (isolated fingers) can be adapted to move them together (coupled) using the control system. However, a hand originally designed to move fingers only together (coupled) cannot be adapted to control the fingers independently.. For grasp-based pattern recognition, depending on the grasps available to the user, the distinction between coupled and isolated fingers may disappear, in which case the categories listed above could be further reduced from five to four.

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