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Performance Characteristics of Anthropomorphic Prosthetic Hands

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Abstract— **In this paper we set forth a review of performance characteristics for both common commercial prosthetics as well as anthropomorphic research devices. Based on these specifications as well as surveyed results from prosthetic users, ranges of hand attributes are evaluated and discussed. End user information is used to describe the performance requirements for prosthetic hands for clinical use.**

Keywords-prosthetics, robotics, hands, terminal devices, review

I. INTRODUCTION

Over the last few decades there have been great strides in the development of novel prosthetic hands and terminal devices that take advantage of the latest technological advances, moving towards more dexterous, realistic hand devices. However, there is still a great gap between the current state of the art and devices that have the ideal combination of being highly functional, durable, cosmetic, and inexpensive. We believe that in order span the gap, a better understanding of the performance needs of anthropomorphic prostheses must be achieved and commonly accepted measures and evaluation protocols established.

In this paper we review the design specifications of a wide range of commercial prosthetic terminal devices and research hands, focusing primarily on devices that are anthropomorphic in structure. We discuss both the physical performance specifications (when available), as well as any justification provided by the developers regarding the scientific basis as to why those measures are appropriate.

Other previous review papers on prosthetic hands have been published, but none focuses on the complete set of design specifications and justification for those to the extent that we have covered here. Additionally, we attempt to discuss the appropriateness of those choices based upon other science and survey results found in literature. Weir provides a thorough discussion of prosthesis design, particularly as it relates to challenges facing amputees and their needs from a more general level, as well as a review of trends in prosthetic hand development [1]. Cipriani et al. [2] and Biagiotti et al. [3] present summaries of the features of current hand designs but do not discuss specific quantitative details, nor how those design choices relate to the science of grasping and manipulation. Biddiss et al. [4] present design priorities as a result of a survey of upper limb prosthesis users but do not state the actual parameters of the devices that were evaluated.

We begin this paper with a summary of the design specifications for a number of commercial and research prosthetic hands and terminal devices, identifying metrics such as weight, grip force, and grasp speed. We then discuss those specifications as they relate to studies in the literature about hand performance. Finally, we present comparisons between the hand characteristics to discuss potential design tradeoffs.

II. SPECIFICATIONS OF CURRENT HANDS

In this section we review the design and performance specifications of a number of the most popular commercial prosthetic hands and terminal devices, as well as research hands intended to be used as prostheses. Tables within the paper will summarize various hand characteristic for five current prosthetic hands and eleven research hands with applications in prosthetics.

The following subsections define and describe each of the properties and specifications listed in the tables, and discuss trends and other interesting aspects that might lend insight into what is an acceptable range of performance for a practical device.

A. *Physical Properties*

1) *Hand Weight*

The human hand has an average weight of 400 grams [5] (distal to the wrist and not including the forearm extrinsic muscles). However, prosthetic terminal devices of similar weight have been described as being too heavy by users [6]. This is primarily because the attachment methods between the prosthesis and the user compound the effects of weight in the terminal device. Although researchers are currently working to alleviate attachment problems through the use of osseointegrated attachment mechanisms, the weight of the prosthesis is a key contributor to interface discomforts and use fatigue. A recent internet survey of myoelectric prosthetic users concluded that 79% considered that their device was “too heavy” [6]. Also, in a similar survey, Biddiss [4] found that users rated the weight of the device as 70 on a scale of 0 (not important) to 100 (most important) in regards to the design priorities of prosthetic hands.

Table I: General Characteristics of Five Current Prosthetic Hands

	Developers	Number of Joints	Degrees of Freedom	Number of Actuators	Actuation Method	Joint Coupling Method	Adaptive grip	Overall Size	Weight
Hosmer Hook [7,8]	Hosmer Corp.	1	1	1	Body Powered	-	No	124 mm long	113-312 grams
SensorHand [9,10]	Ottobock inc.	2	1	1	DC Motor	Fixed pinch	No	Fits inside glove	350-500 grams
Becker Hand (1968) [11,8]	Becker Mechanical Hands Inc.	5	5	1	Body Powered	Spring fingers (act like trunk)	Yes	143 mm long	382-467 grams
i-Limb (2009) [12,13]	Touch Bionics	11	11	5	DC Motors	Tendon Linking MP to PIP	Yes	180-182 mm long, 80-75 mm wide, 35-41 mm thick	450-615 grams
Bebionic (2011) [14]	RSL Steeper	11	11	5	DC Motors	links spanning MP to PIP	Yes	198 mm long, 90 mm wide	495-539 grams

(-) Data not applicable to hand

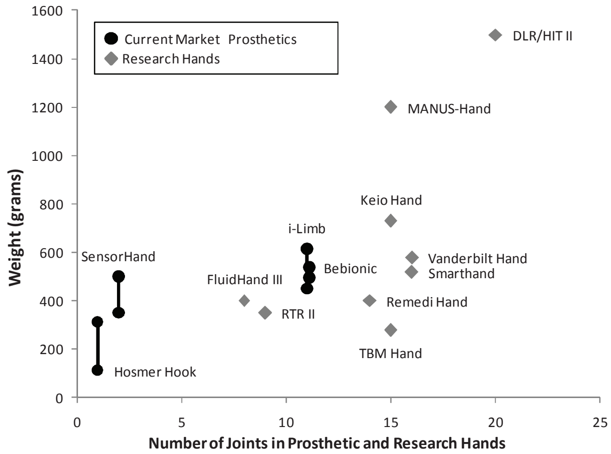

Fig. 1: Distribution of the weights of prosthetic and research hands plotted against the number of joints in each hand.

Table I and Table II show the weight of both current prosthetic hands and research hands designed for use in prosthetics (also highlighted in Fig. 1). A range of 113-615 grams is seen in current commercial prosthetics and 350 to 2200 grams in research based hands. Data presented in the tables are based on values published by the group and do not reflect an absolute 1:1 comparison of weight. For some hands the entire actuation and control system including batteries and wrist attachment is included in the total weight of the hand, while others only consider the weight of the hand itself and not the external computing or power sources for operation. These charts therefore serve as a collection of *published* hand specifications.

Within the prosthetics community there is no set specification for the maximum weight of the prosthesis. Ultimately the weight will depend on required size and capabilities of the hand. According to [15], an adult-sized prosthetic hand should weigh less than 400 grams. Kay and Rakic [16] have set a requirement that the entire hand including cosmetic glove should remain under 370 grams, while other groups, including [17] and [18] feel a 500 gram weight limit is appropriate.

2) *Hand Size*

For an anthropomorphic prosthesis, it is natural for the envelope of the hand to replicate the size and shape that is natural to the user. The SensorHand, iLimb, and Bebionic hands, shown in Table I, are designed to be covered with a silicon glove to enhance the cosmetic appearance of the prosthesis. Given that these gloves are sized according to human hand measurements, the prosthetic hand structure should have a length between 180-198 mm and a width of 75-90 mm to match normal human hand size [12].

3) *Durability/Cycles of Use*

The average myoelectric prosthetic hand user will wear their device in excess of 8 hours per day [6]. Any device must therefore be robust enough to withstand prolonged use and comfortable enough for the user to wear for this amount of time.

Based on work done by [19], between 2500-3000 grasping motions of the dominant hand may be performed over an eight hour period. A study by [20] stated that a typical prosthetic hand will undergo 1200 cycles per day. The predicted grasps of the prosthesis is lower than the able hand since a reduction in functionality will likely result in less frequent use. A report by [18], intended to put forth specifications for electromechanical hands, claimed that a prosthetic should withstand 300,000 grasping cycles and maintain all of its original functionality. However, given the daily expected number of cycles described above, this would put the lifetime of the device at less than one year, which is clearly not long enough.

B. *Actuation Properties*

1) *Type of Actuator*

The most common actuator used in prosthetics today, excluding body power, is a direct current (DC) motor. These motors are small and lightweight and can be packaged in the hand or forearm. In order to reduce the speed and increase the limited torque from these devices, gearing, lead screws, and even harmonic drives may be used. The FluidHand III uses a small DC motor to drive a small hydraulic pump housed within the palm of the hand [21]. Five independent valves then transmit pressure to bellows located at each joint. The advantage of using a pressure based system is the reduced stiffness of each finger joint. Many of the hands incorporate non-backdriveable mechanisms to allow the hand to maintain grip on an object without power being supplied to the motors.

Table II: General Characteristics of Eleven Research Hands with Applications in Prosthetics

	Developers	Number of Joints	Degrees of Freedom	Number of Actuators	Actuation Method	Joint Coupling Method	Adaptive grip	Overall Size	Weight
TBM Hand (1999) [22]	University of Toronto	15	6	1	DC Motor with Linear Ball Screw	Complient Springs	Yes	146 mm long, 65 mm wide, 25 mm thick	280 grams **
Remedi Hand (2000) [17]	University of Southampton	14	6	6	dc motor (maxon)	Coupled MP, DIP, PIP	No	Simialar to human hand	400 grams
RTR II (2002) [23]	ARTS/Mitech Lbs Pusa Italy	9	9	2	DC Motors	Tendon and free-spinning pulleys	Yes		350 grams
MANUS-Hand (2004) [15]	Spain/Belgium/Isreal	9	3	2	Brushless DC Motors	Fixed Coupling of MP, PIP, and DIP	No^1		1200 grams
DLR/HIT I (2004) [24]	DLR German Space Agency, Harbin Institute of Technology	17	13	13	Brushless DC Motors with planetary drive	1:1 coupling of two distal flexion joints	No	1.5 X Human hand	2200 grams
DLR/HIT II (2008) [24,25]	DLR German Space Agency	20	15	15	Brushless DC motors with harmonic drive	1:1 coupling of two distal flexion joints	No	Human hand size	1500 grams
UB Hand 3 (2005) [26]	University of Bologna, Italy	18	16	16	HiTec Servos	PIP and DIP coupled in ring, little, and thumb	No		
FluidHand III (2009) [21]	Forschungszentrum Karlsuhe GmbH (KIT)	8	8	1 pump, 5 valves	Pressurized fluid	Distrubuted Pressure	Yes	Fits inside glove	400 grams
Smarthand (2009) [2, 27]	ARTS Lab, Pontedera Italy	16	16	4	DC Motors	Tendon/Spring based	Yes	12 mm longer and 8 mm thicker than 50% male	520 grams
Keio Hand (2008) [28]	Keio University, Yokohama Japan	15	15	1	Ultrasonic motor	Single tendon for each finger	Yes	320 mm length (with motor), 120 mm fingers	730 grams
Vanderbilt Hand (2009) [29]	Vanderbilt University	16	16	5	Brushed DC servomotors mounted in forearm	Single cable for each finger	Yes	190 mm long, 330 mm with motors, 75 mm wide	580 grams

(**) Designed for Children, (^{1}) Two DOF of the Thumb controlled through single motor, (blank) Information unavailable

2) *Grip Force*

The grip force exerted by a hand on an object is largely a function of the actuation and transmission method of the hand, the hand configuration, and the size of the object. In particular, prosthetic hands like the Hosmer Hook [7,8] Sensorhand [9,10], and TBM Hand [22], will exhibit different grasp forces depending on the size of the object. The necessary grasp force to maintain an object within a particular grasp is also difficult to predict as it is largely dependent on the friction between the fingers of the hand and the object.

In a precision grasp, the human hand can exert an average of 95.6 N of force [1]. In other grasps such as the power grasp, the forces can reach up to 400 N [1]. According to [1], a study concluded that a grip force of only 68 N was required to carry out activities of daily living. [18] suggests a minimum grip force of 45 N for prosthetic hands for practical use.

Tables III and IV show the published grasp force measurements in three grasp configurations for common prosthetic and research hands. The more dexterous robot hands such as the DLR/HIT II and the UB Hand have a lower grip force than the simpler Sensorhand and MANUS-hand. This may simply be a result of packaging within the space of the hand. With hands that have numerous motors, each one must be small enough to accommodate the space constraints of the hand. Therefore during a precision grasp, the size of the motor that controls the index and thumb flexion is typically smaller in hands with more motors. Fig. 2 shows the relationship between the number of actuators and the published grip force during a precision grasp for multiple prosthetic hands and research hands.

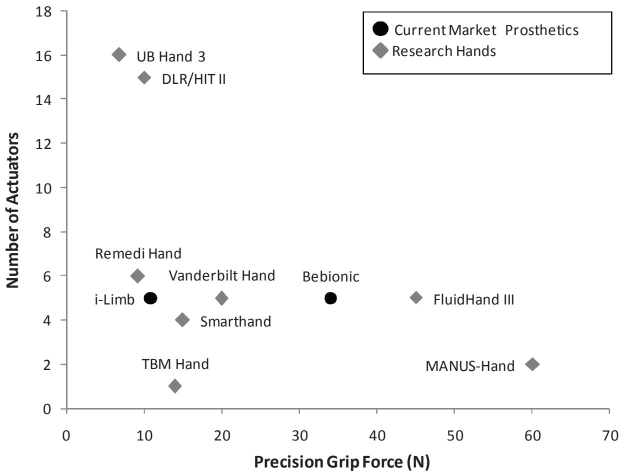

Fig. 2: Precision grip strength of prosthetic and research hands compared to the number of actuators for each hand

3) *Grasp Speed*

According to [6], 100% of females, 76% of males, and 50% of children surveyed would describe the speed of their myoelectric prosthetic to be “too slow.” Although the human hand can exhibit finger flexion speeds of 2290 degrees/sec, the typical speeds for every-day pick and place tasks is 172 to 200

Table III: Grip and Kinematic Characteristics of Four Current Prosthetic Hands

	Grip Force			Range of Motion							
	Precision Grasp	Power Grasp	Lateral Pinch	MP Joints	PIP Joints	DIP Joints	Thumb Circumduction	Thumb Flexion	Finger/grasp Speed	Thumb Circumduction axis	Achievable Grasps
SensorHand [9,10]	-	100 N	-	* 0 to 70°	-	-	-	* 0 to 70°	up to 300 mm/sec at tip	Fixed	Power
Becker Hand (1968) [11, 8]	-		-	-	* 0 to 110°	-	-	* 0 to 20°	-	Fixed	Power, Precision
i-Limb (2009) [12,13]	10.8 N		17-19.6 N	* 0 to 90°	* 0 to 90°	* ≈20°	* 0 to 95°	* 0 to 60°	200 mm/sec	Parrellel with wrist Axis	Power, Precision, Lateral, Hook, Fingerpoint
Bebionic (2011) [14]	34 N (tripod)	75 N		0 to 90°	10 to 90°	* ≈20°	0 to 68°	* 0 to 60°	1.9 sec (power grasp), 0.8 sec (tripod grasp), 1.5-1.7 sec (key grasp)	Parrellel with wrist Axis	Power, Lateral, Hook, Tripod, Fingerpoint

(*) Estimated based on images and videos, (-) Data not applicable to hand, (blank) Information unavailable

degrees/sec [1,30]. Table III and IV show the published grasp speeds of numerous prosthetic hands. Since the data compiled in these tables is based on published information, there are numerous ways the speeds have been described. What is of most concern to the end user, however, is the amount to time it takes to acquire an object in different possible grasp configurations. Some groups, therefore, present grasp speed as a measure of time to open or close the hand. Presenting hand speed data in terms of total time to acquire an object is dependent on the size and shape of the object. The finger flexion speeds for the hands surveyed in this paper ranged from 20 degrees/sec (TBM Hand, 4-5 seconds to close grasp) to 775 degrees/sec (Vanderbilt Hand, 0.4 seconds to close). [18] suggests that a 0.8 sec closing time is sufficient for prosthetic hands. [22] states a slower 1.0-1.5 second closing time is adequate.

C. *Kinematic Properties*

1) *Achieveable Grasps*

The typical activities of daily living (ADLs) conducted by an amputee can be accomplished using a finite set of predefined grasps. These grasp patterns include power (used in 35% of ADLs), precision (used in 30% ADLs), lateral (used in 20% ADLs), hook, tripod, fingerpoint, and gesturing (i.e. counting) [2]. For a detailed description of these grasp patterns please refer to [19]. Table III and Table IV show the ability of each hand studied within this paper to form these grasp patterns without considering contact forces with the object. In order for a hand to accomplish all seven grasping patterns (including counting), each individual finger flexion motion must be controlled with an independent actuator that is not coupled to the other fingers. The analysis shown in Tables III and IV allows for the thumb circumduction axis to be passive and changed by the user, as is the case with the TBM hand, iLimb, and Bebionic hand. Many hands such as the TBM hand, attempt to accomplish as many patterns as possible with fewer than five individual actuators. This hand utilizes a single actuator with passive movement of the thumb circumduction axis to accomplish five of the seven common grasp patterns.

2) *Joint coupling methods*

In many of the hands studied in this paper, there are more joints than number of actuators. Often, numerous joints will be coupled to act as a single compound motion where only the actuator position, for example, must be known to determine the position of all joints which are coupled together. A distinct set of movements that can be described by a single parameter is considered a single degree of freedom. The four fingers of the MANUS-Hand are considered one degree of freedom (despite having 8 joints) since they are directly coupled to one another. Another way of coupling is through adaptive underactuation, in which a single actuator controls a number of independent degrees of freedom [31]. In this sense the single actuator parameter cannot be used to describe the position of the joints since they are dependent on the contact state of each finger link with the object. These mechanisms are considered adaptive because when they are used in a hand, they allow multiple links of the fingers to passively adapt to the shape and location of an object with a single actuator. Examples of adaptive finger designs include a single tendon that is routed across multiple joints as in the Vanderbilt Hand, and RTR-II, or the compliant spring connections used in the TBM hand and Smarthand.

The advantage of using adaptive finger designs is that the interaction force between the finger and object is more distributed, and the mechanism can take a greater range of configurations for the same number of actuators. [32] concluded that while the contact forces are higher when using a fixed coupling fingered prosthetic, the joint torques of adaptive fingered hands are comparable to the joint torques of human hands. The major disadvantage is that the only way to achieve a particular finger configuration is to rely on object contact.

Although some commonly used prosthetic hands, including the Becker Hand, allow for adaptability in grasping, a study by Bergman [33] in 1992 claimed that a conventional non-adaptive prosthesis showed "significantly better results" regarding width of grip, force of grip, and scores in a standardized grip function test when compared to a similar adaptive prosthesis.

3) *Thumb Design*

The thumb accounts for up to 40% of the entire functionality of the human hand [34] and therefore the design of the thumb in any anthropomorphic prosthetic hand is extremely important. In most of the prosthetic hands described in this paper, the thumb is actuated in flexion/extension (simple closing or opening) and along the circumduction axis. The circumduction rotation of the thumb is the movement required

Table IV: Grip and Kinematic Characteristics of Eleven Research Hands

	Grip Force			**Range of Motion**							
	Precision Grasp	**Power Grasp**	**Lateral Pinch**	**MP Joints**	**PIP Joints**	**DIP Joints**	**Thumb Circumduction**	**Thumb Flexion**	**Finger/grasp Speed**	**Thumb Circumduction axis**	**Achievable Grasps**
TBM Hand (1999) [22]	14 N			0 to 90°	10 to 50°	10 to 50°	Thumb -45 to +70 (from perp to palm plane)		90° in 4-5 sec	Parrellel with wrist Axis	Power, Precision, Lateral, Hook, Tripod
Remedi Hand (2000) [17]	9.2 N			0 to 81°					Full Thumb motion in 2.5 sec	* 10° towards thumb from wrist axis	Power, Precision, Lateral, Hook, Tripod, Fingerpoint, Counting
RTR II (2002) [23]							* 0 - 90°			* 45° towards littlefinger from wrist axis	Power, Precision, Lateral
MANUS-Hand (2004) [15]	60 N			* 0 to 45°	* 0 to 55°	* 0 to 70°	* 10 to 85°		Full Grasp in 1.2 sec	* 45° towards thumb from wrist axis	Power, Precision, Lateral, Hook
DLR/HIT I (2004) [24]	7 N						* 0 to 90°		180°/sec	Parrellel with wrist Axis	Power, Precision, Lateral, Hook, Tripod, Fingerpoint, Counting
DLR/HIT II (2008) [24,25]	10 N			0 to 90°	0 to 90°	0 to 90°	-20 to 20° [2]	Same as fingers		none	Power, Precision, Lateral, Hook, Tripod, Fingerpoint, Counting
UB Hand 3 (2005) [26]	6.8 N			0 to 90°	0 to 90°	0 to 90°		Same as fingers	Full closure in 0.36 seconds	Fixed rotation but finger adduction /abduction	Power, Precision, Lateral, Hook, Tripod, Fingerpoint, Counting
FluidHand III (2009) [21]	45 N			* 0 to 90°	* 0 to 80°	* ≈35°	* 0 to 90°		1 sec closing time	* 10° towards little finger from wrist axis	Power, Precision, Lateral, Hook, Fingerpoint
Smarthand (2009) [2,27]	15 N	40 N		0 to 90°			0 to 120°		1.4 sec for full open or close, thumb flexion in 0.67 sec	* 40° towards littlefinger from wrist axis	Power, Precision, Lateral, Hook, Tripod, Fingerpoint, Counting[3]
Keio Hand (2008) [28]		37 N					90°		Full closure in 0.8 sec	none	Power, Precision
Vanderbilt Hand (2009) [29]	20 N	80 N		0 to 90°	0 to 90°	0 to 90°	-10 to 80°		775°/sec, 0.4 sec to close	* 15° towards littlefinger from wrist axis	Power, Precision, Lateral, Hook, Fingerpoint

(2) Abduction/adduction of thumb but not true rotation about circumduction axis, (3) No Independent control of fingers 3-5, (*) Estimated based on images and videos, (-) Data not applicable to hand, (blank) Information unavailable

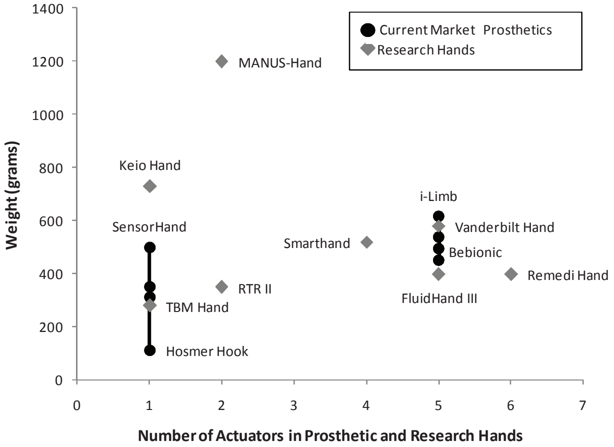

Fig. 3: Distribution of hand weight compared to the number of actuators in the hand

to alternate between a lateral grasp and a power or precision grasp. An analysis of human hand kinematics shows an average circumduction motion of 90.2 degrees, which is achieved through a combination of three joints at the base of the thumb [35].

As can be seen in Tables III and IV, the circumduction axis of current hands is not always oriented parallel with the wrist axis. By angling this axis towards or away from the little finger, thumb flexion and circumduction rotation can be jointly approximated in a single DOF. This can be beneficial to achieve desired hand openings and a more anthropomorphic motion for precision, power, and lateral grasp patterns while keeping complexity low. The coupling can also help the timing of the grasp if all of the fingers are actuated simultaneously. Further discussion of the role of the thumb circumduction axis can be found in [16] and [35].

III. HAND CHARACTERISTIC COMPARISON AND DESIGN TRADEOFFS

The information presented in this paper might be used to compare the tradeoffs made in the design of prosthetic and research hands.

A. *Number of Actuators and Hand Complexity*

Based on the data presented in Table I and II, a comparison can be made between the weight of each hand and the number of actuators used. Fig. 3 shows that although there may be an increase in weight of the hand associated with the number of actuators, the coupling of multiple joints to one or two motors can still greatly increase the weight of the hand, as illustrated with the Keio and MANUS-Hand. Fig. 1 shows that the total number of joints in the hand is strongly correlated to the weight of the hand, regardless of coupling methods.

Figure 4 shows the relationship between the total number of joints and the number of actuators for the hands presented in this paper. Hands lying on the dotted line, such as the UB Hand 3 and the Hosmer hook, have a single motor for each joint of the hand with no coupling between joints. The hands

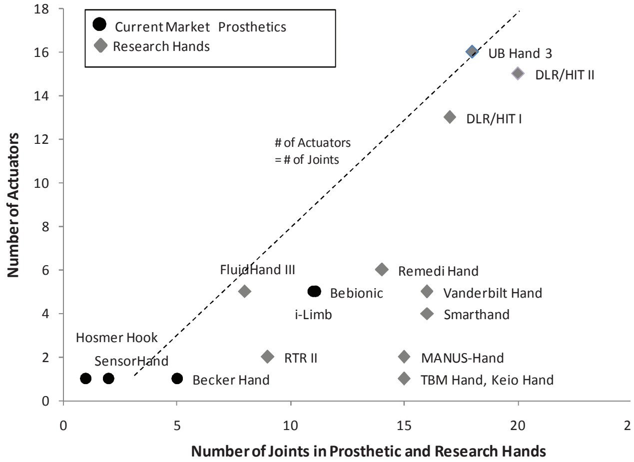

Fig. 4: Comparison between the number of actuators and number of joints in common prosthetic and research hands

that fall to the right of the dashed line indicate that they contain some form of coupling between joints. A large group of research hands are contained in the range of 15 to 20 joints, which approaches the number of joints in the human hand (~30).

B. Hand Weight and Grasp Force

The Sensorhand by Otto Bock has the highest precision grip force to weight ratio of all the hands studied, and the DLR/HIT II hand, the lowest. Besides these outliers, both the research and prosthetic hands have similar precision grip force to weight ratios. Fig. 5 compares the hand weight and precision grasp strength of all the hands studied in this paper.

IV. CONCLUSIONS AND FUTURE WORK

The information presented in this paper serves as a compilation and review of published hand characteristics and performance limits by prosthetic hand developers. Within this paper, we focused on the mechanical characteristics of hands, without treatment of sensing, controls, electronics, and power requirements and techniques.

Since a hand, like any other tool, has many uses, sufficient performance for one application might not be appropriate for another. It is therefore difficult to establish exact mechanical and performance requirements. Ultimately the selection of hand characteristics and specification is a choice between tradeoffs in complexity, dexterity (achievable grasps), weight, and control methods. Furthermore, all of these measures are subject to the patients' exact needs, including the nature and level of their amputation, as well as level of activity, professional needs, and others.

However, a set of standards for performance, including techniques for evaluation of anthropomorphic hand designs, both on the bench and in the clinic, would be beneficial. It is clear from this review that the current performance standards used by hand designers span a wide enough range that many would be considered unacceptable in a practical device. Working towards a common set of standards (or range of standards) would help maximize the likelihood that the extensive research efforts in this area might be implemented in a successful commercial device that will improve the lives of the population it is meant to serve.

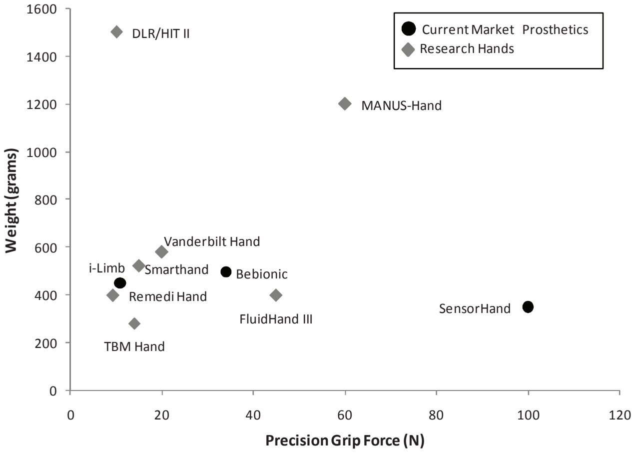

Fig. 5: Distribution of hand weight compared to the amount of grip force the hand can exert in the precision grasp configuration

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