PROSTHETIC HAND REQUIREMENTS / SPECIFICATIONS

A-priori set of specifications that will be modified along the project. These high-level specifications are from the point of view of the user, not the engineering solution. For instance, "easy to control" would be a desirable engineering requirement that is independent from the properties perceived by the user.

We define the desired:

1. Motions
2. Range of force
3. Size, weight and inertia.
4. Autonomy
5. Durability / reliability (robustness, etc.)
6. Feedback to patient
7. Modularity (flexibility / adaptability to different amputations)
8. Cost.

In this document, we will focus on point 1. These first suggestions will be based on the available surveys found in literature (see references) and the input from those of you with expertise in the field.

1. Desired motions

There are two levels of definition. The first level defines the functional tasks that we consider required for the hand to perform. The second level assigns to those tasks the motion primitives. Many of the functional tasks may lead to the same motion primitive. Finally, motion primitives may be identified with anatomical motions.

For each level, the motions will be organized in two sections: Minimum performance and Maximum performance. The robotic device must be able to deliver the maximum performance, but it must also be flexible to downgrade to minimum performance, according to the degree of amputation and richness of EMG signals of the patient.

1. Literature review

The most widely used grasp taxonomy is that of Cutkosky (1989). He focuses on all aspects of grasping (not manipulation), basing his taxonomy on that of Napier (1956). Below we include some of the definitions that we will use. The grasping taxonomy can be seen in the figure below. However, Cutkosky himself agrees in that it is incomplete, not including grasping actions such as holding a pen for writing.

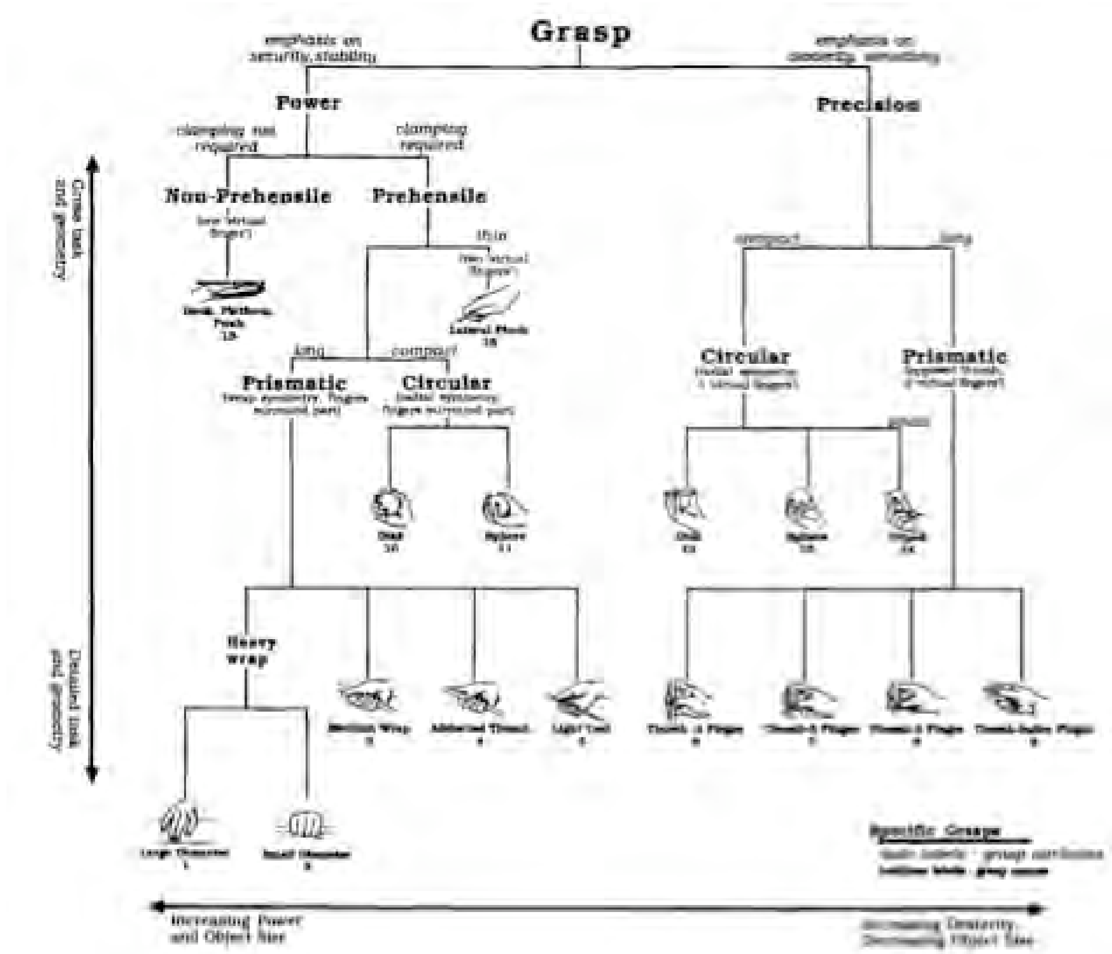


Figure 1: Cutkosky´s (1989) grasping taxonomy

Other concepts that will be used are defined in the figure below.

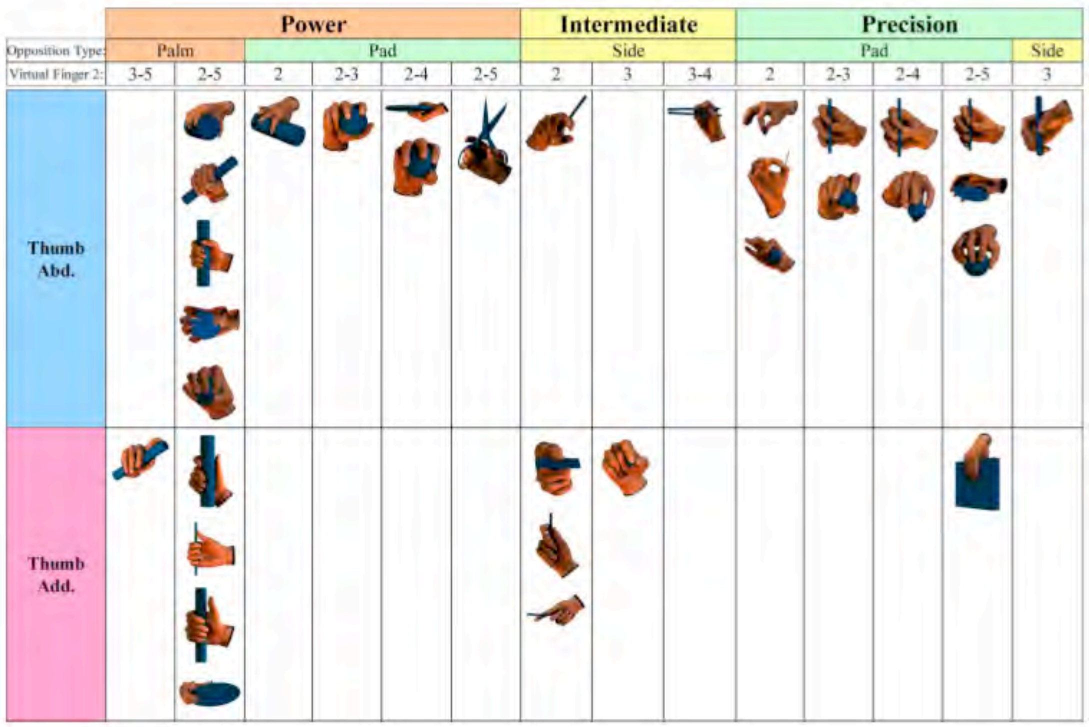
TABLE I
DEFINITIONS OF ANALYTICAL MEASURES USED TO DESCRIBE A GRASP

Compliance	What is the effective compliance (inverse of stiffness) of the grasped object with respect to the hand? The grasp compliance matrix is a function of grasp configuration, joint servoing, and structural compliances in the links, joints, and fingertips [6].
Connectivity	How many degrees of freedom are there between the grasped object and the hand? Formally, how many independent parameters are needed to completely specify the position and orientation of the object with respect to the palm [17]?
Force closure	Assuming that external forces maintain contact between the fingers and the object, is the object unable to move without slipping when the finger joints are locked? Formally, a grasp satisfies force closure if the union of the contact wrenches has rank 6 [17], [22].
Form closure	Can external forces and moments be applied from any direction without moving the object, when the fingers are locked? Formally, there is form closure, or complete kinematic restraint, if the intersection of all unisense contact twists is a null set. Thus seven frictionless point contacts are in general required to achieve form closure on a rigid body [13], [17].
Grasp isotropy	Does the grasp configuration permit the finger joints to *accurately* apply forces and moments to the object? For example, if one of the fingers is nearly in a singular configuration, it will be impossible to accurately control force and motion in a particular direction. Formally, the grasp isotropy is a function of the condition number of the grasp Jacobian matrix [12], [17]. Li and Sastry [14] define similar grasp quality measures that are functions of the singular values of the grasp Jacobian.
Internal forces	What kinds of internal grasp forces can the hand apply to the object? Formally, the internal grasp forces are the homogeneous solution to the equilibrium equations of the object. Thus internal grasp forces can be varied without disturbing the grasp equilibrium [12], [17].
Manipulability	While not consistently defined in the literature, a useful definition is: Can the fingers *impart arbitrary motions* to the object? Thus a manipulable grasp must have force closure and a connectivity of 6. In addition, the rank space of velocities due to the finger joints must span the space of velocities transmitted through the contacts [12].
Resistance to slipping	How large can the forces and moments on the object be before the fingers will start to slip? The resistance to slipping depends on the configuration of the grasp, on the types of contacts, and on the friction between the object and the fingertips [5], [10]–[12].
Stability	Will the grasp return to its initial configuration after being disturbed by an external force or moment? At low speeds, the grasp is stable if the overall stiffness matrix is positive definite [6], [21]. At higher speeds, *dynamic stability* must be considered [19].

Figure 2: Cutkosky´s (1989) definitions for describing grasping

A more complete effort on classifying hand grasping motions has been done for OttoBock by Feix et al. (2009) and can be found at http://web.student.tuwien.ac.at/~e0227312/ . They review taxonomies up to date (they have a good literature review) and try to summarize them in a comprehensive set with minimum grasp types. Their definition of grasping is that of a force-closure grasp without manipulation, hence some of Cutkosky´s grasps are ruled out. I included in the appendix the taxonomy comparison. See their final taxonomy in Figure 3 (the numbers in the second table correspond to the descriptions in the Appendix). We will use their denomination for most of the grasps. A more complete table, with names and description, is included in the Appendix. In the Appendix find also the summary of taxonomies from other authors.

In this figure, they distinguish grasps as using palm against fingers, using finger pads against each other, or using the sides of the fingers. In addition, they classify the grasps by abduction / adduction of the CMC thumb joint. By doing this classification, some of the grasps can be grouped and the total set of grasps reduced to 17 basic motions, which could be adapted to different object sizes.



	Power						Intermediate			Precision				
Opposition Type:	Palm		Pad				Side			Pad				Side
Virtual Finger 2:	3-5	2-5	2	2-3	2-4	2-5	2	3	3-4	2	2-3	2-4	2-5	3
Thumb Abd.		1 2 3 10 11	31	28	18 26	19	23		21	9 24 33	8 14	7 27	6 12 13	20
Thumb Add.	17	4 5 15 30					16 29 32	25					22	

Figure 3: Final taxonomy from Feix (2009)

In what follows, we describe the hand motion requirements for amputees, from different surveys.

Pylatiuk, Schulz and Doderlein (2007) created an internet survey for prosthetic hand users, which includes an assessment on the level of amputation. The data are to be used in the design and redesign of the Univ. of Karlsruhe prosthetic hand. They found that the prostheses were used for at least 8 hours daily. Among the main problems they found the weight, the lack of control on the grasping speed, the noise. One of the interesting things of this survey is its focus on the desirable activities to be performed with the prosthesis. They found an interest in all of these activities: personal hygiene, using cutlery, dressing and undressing, operation of domestic devices, and handicraft (all of these over 60%), and a little less on opening/closing doors (about 60%) and writing (about 40%). Asked about other manipulation features, they ranked very high pointing with index, move individual fingers (like to operate a keyboard), and having wrist motion.The desirable feedback feature was mainly force, followed by temperature (much less). Other concern was the maintenance of the covering glove.

For the Karlsruhe hand, they focus on "increasing the number of grasping patterns achievable" by adding force feedback, a better cosmetic appearance and a lighter weight. In particular, the achievable grasping actions are cylindrical power grasp, precision grasp, lateral pinch, hook grasp. Additionally, a manipulation function is included: individual flexion/extension of the index finger. The total weight does not exceed 860 gr. (Pylatiuk et al. 2004)

Fig. 4 A-C: Prehension patterns: Hook grasp (left), lateral pinch (middle), precision grasp (right)

Fig. 4 D and E: Prehension patterns: Extended Index (left), cylindrical grasp (right).

Figure 4: Karlsruhe hand grasping actions (Pylatiuk 2004)

Kyberd et al. (2007) did a survey of 156 upper-extremity prosthesis users in Sweden and UK. About 40% of them wore active prostheses. Most participants reported wearing the prostheses during 8 or more hours. Among other activities, they reported using them (ranked) for work, driving and sports. The level of satisfaction with the prostheses in this survey is quite high, but the survey did not include subjects who stopped using the device. The biggest problems (less than 6/10 ranking) reported were on sensory feedback, adaptation to objects properties (which is more or less the same), and precision-demanding activities (fine manipulation), followed (less than 7/10) by glove issues, ability to release objects and force-demanding activities. Identified areas for improvement were mainly related to movement and grip function: (ranked) precision-demanding activities, sensory feedback, reliability, force-demanding activities, weight and sound. Also for improvement were appearance (glove) and fit of socket.
The results of this survey are to be applied in the ToMPAW project (http://www.oandp.org/jpo/library/2007_01_015.asp). Final recommendations were: quiet operation, a wider range of grip shapes and good control of the grip force (e.g., not too high an initial grip force), reliable operation, free from breakdowns and interference from electrical noise, and intuitive control.

Pons et al. (2005) define the specifications for their MANUS hand based on a survey performed among prosthesis users (200) and professionals for prosthesis fitting and rehabilitation (150). Their results ranked the biggest problems as aesthetics, discomfort, weight, functionality, maintenance, noise and skin problems, while the professionals added price and autonomy to the list. They listed as motion needs the following graspings: tip, hook, precision, cylindrical or power, and lateral. Also tactile feedback was identified as a desirable quality. From here, a very detailed set of specification for the MANUS hand was elaborated, including range of motion and velocity, forces and torques, desirable types of grasping, weight, noise and battery time. See Table 1 in the above citation.

Dudkewicz et al. (2004) designed a survey to try to predict the factors for successful prosthetic rehabilitation. About 70% of the patients reported difficulties with prostheses usage. The main problems were discomfort with the fitting, weight of the prosthesis, cosmetic issues, and limited hand motion. It has to be mentioned that most of the patients in this study used cosmetic prostheses only.

Datta, Selvarajah and Davey (2004) report in their survey of 62 patients, a rejection rate of approx. 34% for prostheses. The number of powered-prostheses users in this survey was very low, so the results are not so relevant to us. The patients reported benefits in (ranked) driving, recreation, DIY(?), employment, cooking, dressing and personal care.

Sherman (1999) did a random survey among US veterans (45 individuals responded, with only 11 upper-limb amputees). The main finding in this survey as compared to others is the consistent fitting problems: pain in the stump, skin breakdown, etc.

Atkins, Heard and Donovan (1996) performed a survey with more that 1,500 upper-limb amputees responding to it. Out of those, 1020 were body-powered prostheses and 438 corresponded to externally powered prostheses. Their results indicate similar needs for both groups.
Areas for improvement were wrist motion, control of coordinated motion for more than one joint, and sensory feedback. Desired improvements in motion were individual finger control, whole thumb motion, and sensory feedback. The top activities to be performed with the prostheses were (ranked) opening doors, typing, use of cutlery, dressing activities (buttons, shoelaces), and use of tools (hammer). Main maintenance problems were batteries and cable repair. Most users reported the price of the electrically-driven prostheses as excessive.

From the point of view of the design, Schaffer and Dillman (2001) designed a humanoid robot wrist. Their strategy was to accomplish human motion functionality by studying and copying as faithfully as possible the biomechanics of the articulation surfaces of the wrist. In order to assess the motion of their wrist, they compare their joint trajectories to Andrews (1979). However, the high variability among individuals for the same kinematic task makes this assessment tool just qualitative. See Cutkosky (1989) for a qualitative assessment; Cole and Abbs (1986) for finger-thumb grasp variability; Ansuini et al. (2006) on variability of same grasp and same object depending on the end task; Magnus et al. (1999) on variability of grasping for same geometry but different friction conditions, Friedman and Flash (2007) for a detailed study and summary on this topic. Performance indices have been defined, see Davidson (2004) for a review.

All surveys seem to collect information on pre-selected tasks and hence the scope of tasks is limited by the survey maker. In addition to the above references, we base our requirements on the recommendations of our EMG group (Schoen et al., 2009). In this report, they point out the differences that will have to be taken into account based on the type of amputation and the available signals. Things that seem to be a priority are force feedback and incremental control of flexion motion, especially in pad pinch grips of thumb and index or middle fingers, and in the full thumb motion, abduction/adduction and opposition.

2. Motion specification

Unlike most of the surveys reviewed above, we want to define a broad scope of tasks including static grasping, manipulation, and free manipulation.

Static grasping: grasping action in which the fingers will be fixed once the object is grasped, and subsequent actions will be done by the wrist or arm. (Mostly power grasp)
Manipulation: change of position and orientation of a grasped object. (Usually happens after a precision grasp)
Free manipulation: free motion of individual fingers, may contact objects or other fingers at some point, but without the aim of holding them.

In addition, in the minimum performance we may not require incremental motion control, which will be required for the maximum performance for the thumb, index and middle fingers. Table 1 shows the desirable functional tasks for minimum and maximum performance of the hand.

Table 1: Desired functional tasks

TABLE 1: FUNCTIONAL TASKS		
FUNCTIONAL TASK	MINIMUM PERFORMANCE	MAXIMUM PERFORMANCE
Eating /Use of cutlery	- Table-plate-mouth motion for spoon, fork. - Table-to-mouth cup motion.	- Combined fork + knife motion. - Opening bottle. - Use of chopsticks.
Personal Hygiene	- Combing hair, brushing teeth.	- Handling scissors. - Washing? (wet hand)
Dressing /Undressing	- Handling of clothes - Zips, buttons.	- Tie shoelaces.
Operation domestic devices / Cooking	- Holding devices - Button pushing (index finger)	- Button pushing (thumb). - Controlled object holding (trajectory/speed).
Handicraft	- Power holding (hammer) - Precision holding (nail)	- Screw operation.
Opening doors	- Knob operating	- Door key operating.
Writing	- Type writing, individual	- Type writing, all

	finger. - Handling paper.	fingers. - Handwriting.
Hand communication	- Index finger pointing	- Sign language.
Vehicle driving	- Steering wheel holding / operating.	
Sports	- Racket, poles holding. - Ball handling.	

In Table 2 we list the grasps corresponding to the desirable functional tasks, according to Feix (2009), for minimum and maximum performance. We also assess whether the task requires wrist manipulation or fine (finger) manipulation. Last column describes the free manipulation for the tasks.

Table 2: Targeted grasps for functional tasks, minimum performance.

TABLE 2: CORRESPONDENCE WITH GRASPS				
FUNCTIONAL TASK	GRASP PRIMITIVES	Wrist man.	Finger man.	Free man.
Eating /Use of cutlery	Adducted thumb (4), Large diameter(1)	YES	NO	NO
Personal Hygiene	Adducted thumb(4), small diameter(2)	YES	NO	NO
Dressing /Undressing	Palmar pinch(9), parallel extension(22), tip pinch(24)	NO	NO	NO
Operation domestic devices / Cooking	Large, small diameter(1,2), medium wrap(3), adducted thumb(4)	NO	NO	Pointing index
Handicraft	Large, small diameter(1,2), medium wrap(3), tip pinch(24)	NO	NO	NO
Opening doors	Sphere 3 or 4 finger (26 or 28), medium wrap(3)	YES	NO	NO
Writing	Parallel extension(22), palmar pinch(9).	NO	NO	Pointing index
Hand communication	NO	NO	NO	Pointing index
Vehicle driving	Small diameter(2)	NO	NO	NO
Sports	Adducted thumb(4), power sphere(11)	YES	NO	NO

Table 3 is similar to Table 2 but for maximum performance.

Table 3: Targeted grasps for functional tasks, maximum performance.

TABLE 3: CORRESPONDENCE WITH GRASPS				
FUNCTIONAL TASK	GRASP PRIMITIVES	Wrist	Finger	Free man.

		man.	man.	
Eating /Use of cutlery	Adducted thumb (4), Large diameter(1), index finger extension(17), tripod(14), tripod variation(21), ventral(32)	YES	YES	NO
Personal Hygiene	Adducted thumb(4), small diameter(2), distal type(19)	YES	NO	NO
Dressing /Undressing	Palmar pinch(9), parallel extension(22), tip pinch(24),	YES	YES	NO
Operation domestic devices / Cooking	Large, small diameter(1,2), medium wrap(3), adducted thumb(4), fixed hook(15) lateral(16),	YES	YES	Pointing index, thumb abd/add.
Handicraft	Large, small diameter(1,2), medium wrap(3), tip pinch(24), stick(29)	YES	YES	NO
Opening doors	Sphere 3 or 4 finger (26 or 28), medium wrap(3), lateral(16)	YES	NO	NO
Writing	Parallel extension(22), palmar pinch(9), writing tripod(20)	YES	YES	Individual finger pointing, finger abd/add.
Hand communication	NO	NO	NO	Full dof
Vehicle driving	Small diameter(2)	NO	NO	NO
Sports	Adducted thumb(4), power sphere(11)	YES	NO	NO

In Table 4 we try to identify finger motion primitives for each of the grasping / manipulation actions, in order to define the minimum / maximum degrees of freedom for the prototype hand.

(to be done once the tasks are agreed and identified).

2. Power Consumption and Autonomy

From some of the above-mentioned surveys, the desired autonomy of the hand should be of at least 8 hours.

3. References

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4. Appendix

The first document is Feix (2009) list of grasps. Classified as

- type (power, precision, intermediate),
- opposition type: basic direction in which the human hand applies forces
    i. pad opposition: force between finger pads.
    ii. palm opposition: digits applying force against palm.
    iii. side opposition: force between sides of fingers.
- Virtual finger assignments: call virtual finger to the opposing surfaces exerting the force. (P = palm, 1-5 = thumb-little finger).
- It also includes the number of times the grasp has been described in literature.

The second document is a summary of the grasps found in literature.

Nr.	Name	Picture	Type	Opp.Type	Thumb Pos.	VF1	VF2	VF3	#
1	Large Diameter		Power	Palm	Abd	P	2-5		10
2	Small Diameter		Power	Palm	Abd	P	2-5		3
3	Medium Wrap		Power	Palm	Abd	P	2-5		6
4	Adducted Thumb		Power	Palm	Add	P	2-5	1	2
5	Light Tool		Power	Palm	Add	P	2-5	(1)	2
6	Prismatic 4 Finger		Precision	Pad	Abd	1	2-5		4
7	Prismatic 3 Finger		Precision	Pad	Abd	1	2-4		4
8	Prismatic 2 Finger		Precision	Pad	Abd	1	2-3		2

9	Palmar Pinch		Precision	Pad	Abd	1	2		12
10	Power Disk		Power	Palm	Abd	P	2-5		3
11	Power Sphere		Power	Palm	Abd	P	2-5		8
12	Precision Disk		Precision	Pad	Abd	1	2-5		5
13	Precision Sphere		Precision	Pad	Abd	1	2-5		6
14	Tripod		Precision	Pad	Abd	1	2-3		8
15	Fixed Hook		Power	Palm	Add	P	2-5		2
16	Lateral		Intermediate	Side	Add	1	2		12
17	Index Finger Extension		Power	Palm	Add	P	3-5	2	4

18	Extension Type		Power	Pad	Abd	1	2-4		1
19	Distal Type		Power	Pad	Abd	1	2-5		2
20	Writing Tripod		Precision	Side	Abd	1	3		6
21	Tripod Variation		Intermediate	Side	Abd	1	3-4		1
22	Parallel Extension		Precision	Pad	Add	1	2-5		5
23	Adduction		Intermediate	Side	Abd	1	2		3
24	Tip Pinch		Precision	Pad	Abd	1	2		9
25	Lateral Tripod		Intermediate	Side	Add	1	3		1
26	Sphere 4 Finger		Power	Pad	Abd	1	2-4		1

27	Quadpod		Precision	Pad	Abd	1	2-4		2
28	Sphere 3 Finger		Power	Pad	Abd	1	2-3		1
29	Stick		Intermediate	Side	Add	1	2		1
30	Palmar		Power	Palm	Add	1	2-5		1
31	Ring		Power	Pad	Abd	1	2		1
32	Ventral		Intermediate	Side	Add	1	2		1
33	Inferior Pincer		Precision	Pad	Abd	1	2		1