The GRASP Taxonomy of Human Grasp Types

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***Abstract*—In this paper, we analyze and compare existing human grasp taxonomies and synthesize them into a single new taxonomy (dubbed "The GRASP Taxonomy" after the GRASP project funded by the European Commission). We consider only static and stable grasps performed by one hand. The goal is to extract the largest set of different grasps that were referenced in the literature and arrange them in a systematic way. The taxonomy provides a common terminology to define human hand configurations and is important in many domains such as human–computer interaction and tangible user interfaces where an understanding of the human is basis for a proper interface. Overall, 33 different grasp types are found and arranged into the GRASP taxonomy. Within the taxonomy, grasps are arranged according to 1) opposition type, 2) the virtual finger assignments, 3) type in terms of power, precision, or intermediate grasp, and 4) the position of the thumb. The resulting taxonomy incorporates all grasps found in the reviewed taxonomies that complied with the grasp definition. We also show that due to the nature of the classification, the 33 grasp types might be reduced to a set of 17 more general grasps if only the hand configuration is considered without the object shape/size.**

***Index Terms*—Hand/wrist posture, human–robot interaction, taxonomies, robotics, human factors.**

I. Introduction

UNDERSTANDING the way humans grasp objects, knowing the kinematic implications and limitations associated with each grasp, and knowing common use patterns is important in many domains ranging from medicine and rehabilitation, psychology, and product design, among many others. In human–computer interaction in general and tangible user interfaces in particular, the hand is used to interact with the technology. In device and interface design, it is not only important to understand grasp posture during normal use, but also how that posture is adjusted according to the task demands [1]–[5]. Haptic feedback is an increasingly important factor in that domain, both as the primary means of the interface [6], or to guide interaction [7]. Grasp-type classifications have also been used in programming by demonstration, where the human action is to be imitated by a robot [8]–[10], as well as an intermediate functional layer mapping human hand grasp kinematics to artificial hands [11]. In prosthetics, hands are often designed with a discrete set of grasp types that they are supposed to accomplish [12]–[14].

The complexity and variety of uses of the human hand makes the categorization and classification of hand function challenging. The hand has 15 joints (not taking the carpal and metacarpal joints in the base of the palm into consideration), which result in more than 20 degrees of freedom [15], [16]. Consequently, directly modeling hand shapes is difficult and involves specifying a large number of parameters. However, the combination of ways in which the hand interacts with grasped objects is much more limited and might be broken down into subclasses. The so-called grasp types are commonly used to describe hand use, and many different grasp classifications have been proposed in the literature ranging from robotics, medicine, and biomechanics (overviewed in depth in Sections II and III).

As we will show in this study, there is little current consensus about the definition of the range of grasp types that humans commonly use. Therefore, this study aims to compare all human grasp taxonomies provided in the literature, find the largest set of distinct grasps, and synthesize them into a single classification. This GRASP taxonomy incorporates all previous grasps defined in the literature, and we therefore argue it the most complete to date. We dubbed the taxonomy (the GRASP taxonomy) after the GRASP project funded by the European Commission within which the initial taxonomy was developed. The first workshop publication of this taxonomy [17] has been widely used. It served as inspiration for a taxonomy of microinteractions [18], assisted in determining human hand capabilities in robotic hand design [19], [20], allowed defining affordances in vision systems [21] and was used in experiments analyzing human hand function [22], [23].

This paper is structured as follows. Section II provides the background, in particular related to the concepts used for classifying or characterizing grasps. In Section III, existing taxonomies are compared, whereas in Section IV, those taxonomies are arranged into a novel classification, the GRASP taxonomy, and a brief overview of each of those grasps and their properties is presented. Finally, Section V discusses the details of the taxonomy, as well as its shortcomings, and Section VI concludes this paper.

II. Background

Movement and function of the hand is not only a product of the internal degrees of freedom of the hand, but also the movement of the body and the arms as well as the contact with the environment. Bullock *et al.* [24] created a high-level taxonomy of movements of the human hand that attempts to capture those

Manuscript received February 3, 2015; revised May 1, 2015 and June 24, 2015; accepted July 7, 2015. Date of publication September 4, 2015; date of current version January 20, 2016. This work was supported by EU IST-FP7-IP GRASP and the National Science Foundation Grant IIS-0953856. This paper was recommended by Associate Editor H. Ludvigsen.

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Digital Object Identifier 10.1109/THMS.2015.2470657

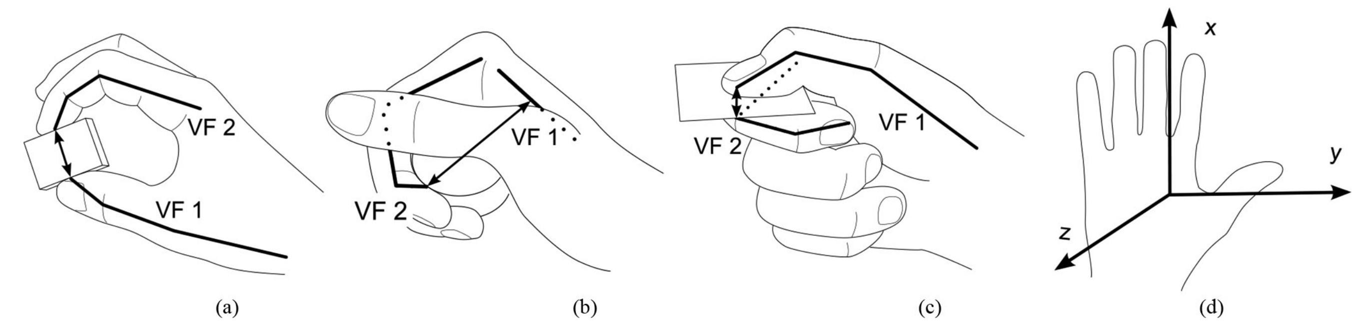


Fig 1. Opposition types of the grasping hand [29]. Figures adapted from [30, p. 34]. The abbreviation VF refers to Virtual Finger, which is explained in Section I-C. (a) Pad Opposition. (b) Palm Opposition. (c) Side Opposition. (d) Hand Coordinate System.

elements. Within their broad classification, the hand function classes of relevance for this study fall into the static and prehensile grasp class (4 according to [24]). This class incorporates manipulation tasks that are prehensile and where the object is in fixed relation with the hand (no in-hand motion). In the remainder of the section, we introduce three important concepts every grasp can be classified with respect to.

A. Power, Intermediate, and Precision Grasps

Each grasp can be classified by its need for precision or power to be properly executed [25]. The differentiation is very important, and the idea has influenced many authors. The idea was further developed by Landsmeer [26], who distinguishes between "power grip" and "precision handling." In the power grip, there is a rigid relation between the object and the hand, which means that all movements of the object have to be evoked by the arm. For the precision handling, the hand is able to perform intrinsic movements on the object without having to move the arm [26]. As for our study that difference is somewhat mitigated, we only look at static grasps. These are grasps where the object is in a constant relation to the hand. A third category, the intermediate or link grasp [27], [28], was later added. In this class, elements of power and precision grasps are present in roughly the same proportion. This allows for a finer differentiation of grasp types; nevertheless, the basic principles remain the same.

B. Opposition Types

There are three basic directions relative to the hand coordinate frame, in which the hand can apply forces on the object to hold it securely [29]. They differ in terms of the force direction that is applied between the hand and object. According to [30], p. 286], those are figure numbers adapted:

Pad Opposition occurs between hand surfaces along a direction generally parallel to the palm [see Fig. 1(a)]. This usually occurs between volar (palmar) surfaces and the fingers and thumb, near or on the pads. Examples include holding a needle or a small ball. This is the x-axis in the inset in Fig. 1(d).

Palm Opposition occurs between hand surfaces along a direction generally perpendicular to the palm [see Fig. 1(b)]. Examples include grasping a large hammer or screwdriver. This is the z-axis inset in Fig. 1(d).

Side Opposition occurs between hand surfaces along a direction generally transverse to the palm [see Fig. 1(c)]. One holds a key between the volar surface of the thumb and the radial sides of the fingers, or holds a cigarette between the sides of the fingers. This is the y-axis inset in Fig. 1(d).

C. Virtual Finger

In many tasks, several fingers work together as a functional unit, the virtual finger (VF) [31]. Fingers belong to the same VF if they apply forces in a similar direction and act in unison. Depending on the grasp type, one or more fingers or hand parts can be assigned to one VF. The VFs oppose each other in the grasp, as it would be the case for a simple gripper or vice. In the example shown in Fig. 1(a), the thumb (mapped onto VF1) opposes the index finger (mapped onto VF2). In the case of palm opposition [see Fig. 1(b)], the palm of the hand is assigned to VF 1 and the four fingers act against it as VF 2. If one or more fingers are opposing a task-related force or torque, these fingers are assigned VF 3; otherwise, VF 3 will not be assigned [29]. Studies on human grasping found evidence supporting this concept [32], [33].

III. Comparison of Taxonomies

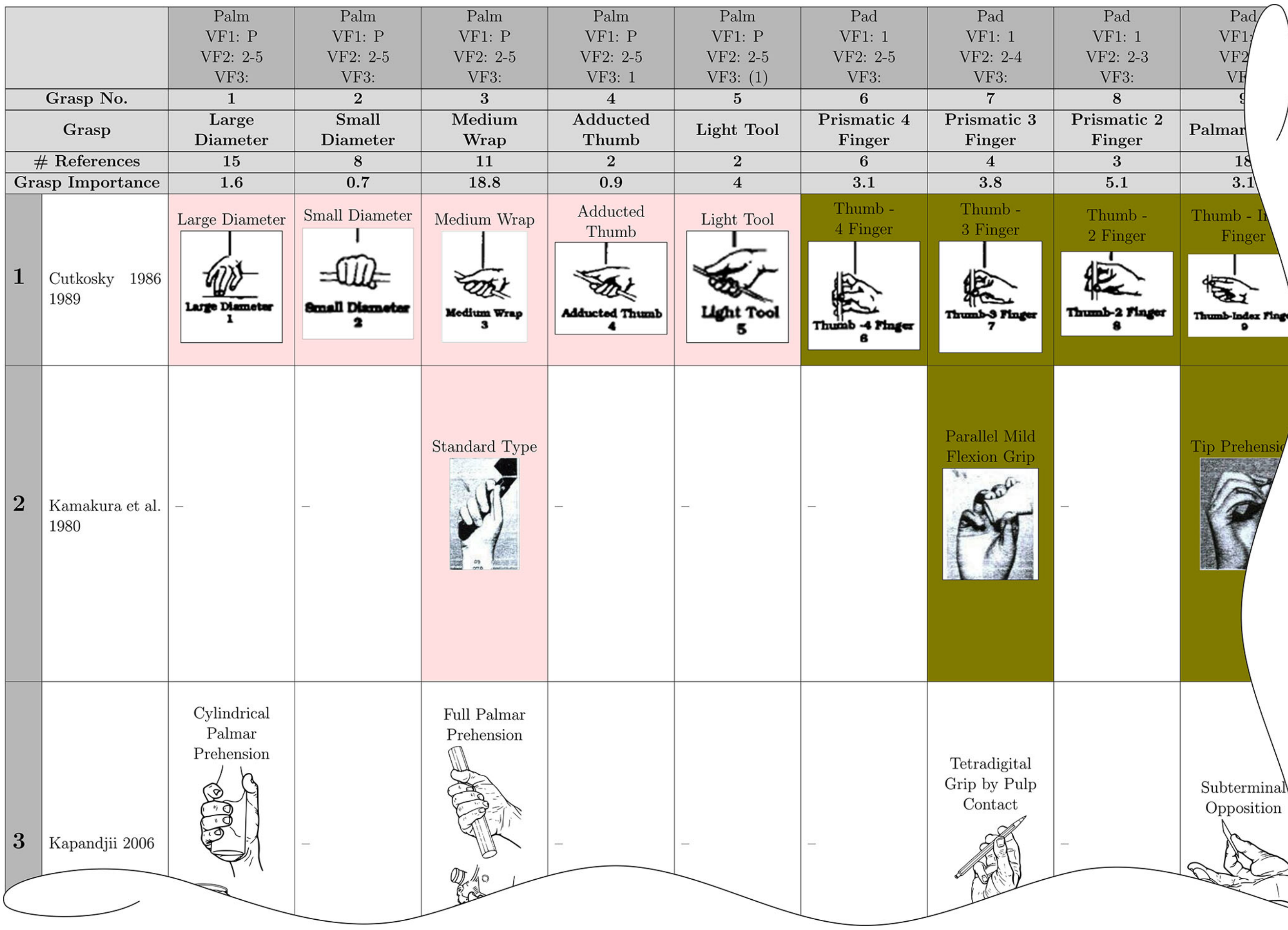
In this section, grasp taxonomies are reviewed, and the overlap and agreement between the listed grasp types is determined. Based on this comparison, a list with all unique grasp types that conform to our grasp definition is compiled.

A. Grasp Definition

In order to proceed, it is important to define the range of human hand movements considered in the comparison. In the remainder of this paper, the following definition is used to determine whether a grasp fits into the analysis.

"A grasp is every static hand posture with which an object can be held securely with one hand, irrespective of the hand orientation."

The definition implies that the grasp stability has to be guaranteed irrespective of the relative force direction between hand and object. Specifically, this means that the grasp can withstand forces in all directions with a magnitude greater than zero. By



		Palm VF1: P VF2: 2-5 VF3:	Palm VF1: P VF2: 2-5 VF3:	Palm VF1: P VF2: 2-5 VF3:	Palm VF1: P VF2: 2-5 VF3: 1	Palm VF1: P VF2: 2-5 VF3: (1)	Pad VF1: 1 VF2: 2-5 VF3:	Pad VF1: 1 VF2: 2-4 VF3:	Pad VF1: 1 VF2: 2-3 VF3:	Pad VF1 VF2 VF
Grasp No.		1	2	3	4	5	6	7	8	9
Grasp		**Large Diameter**	**Small Diameter**	**Medium Wrap**	**Adducted Thumb**	**Light Tool**	**Prismatic 4 Finger**	**Prismatic 3 Finger**	**Prismatic 2 Finger**	**Palmar**
# References		**15**	**8**	**11**	**2**	**2**	**6**	**4**	**3**	**18**
Grasp Importance		**1.6**	**0.7**	**18.8**	**0.9**	**4**	**3.1**	**3.8**	**5.1**	**3.1**
1	Cutkosky 1986 1989	Large Diameter	Small Diameter	Medium Wrap	Adducted Thumb	Light Tool	Thumb - 4 Finger	Thumb - 3 Finger	Thumb - 2 Finger	Thumb - In Finger
2	Kamakura et al. 1980	–	–	Standard Type	–	–	–	Parallel Mild Flexion Grip	–	Tip Prehensi
3	Kapandjii 2006	Cylindrical Palmar Prehension	–	Full Palmar Prehension	–	–	–	Tetradigital Grip by Pulp Contact	–	Subterminal Opposition

Fig. 2. Comparison of the grasp listings from 22 taxonomy publications found in the literature. Due to the size (22 publications × 47 grasp columns) only an excerpt of the comparison table is shown. Rows store all grasps from one publications, whereas columns store similar grasps. The sheet allows for direct comparison of the grasp types by all publications. The full table is available as supplementary material and can be downloaded at grasp.xief.net.

scaling the maximal grasp force theoretically, all disturbances can be withstand.

The definition rules out:

In-hand motion: Movements that invoke object motion without global hand motion are excluded because the object is not in a constant relationship to the hand.

Bimanual tasks: Only one hand is to be used.

Gravity-dependent grasps: They do not fit the definition, because the hand orientation is vital to the grasp stability. If one turns the hand, the object may fall down, which is not independent of the force direction. Grasps listed in the reviewed taxonomies that are excluded here are, among others, the Hook Grasp and the Flat Hand Grasp. We chose to exclude those grasps as most taxonomies are centered on prehensile grasps and because adding nonprehensile grasps would greatly increase the complexity of the taxonomy. Related to the classification in Bullock *et al.* [24], our classification excludes the whole nonprehensile category (category: C NP), because the environment provides the reaction force in those grasps. This would include motions such as flipping a light switch, rolling a ball on the table or pressing a key with a finger.

It is interesting to note that grasping a glass of water still fits into that definition. The glass is sensible to the orientation of the hand, but this is not because the grasp would lose its stability if the hand rotates. Just the water would be poured out. The orientation of the hand is constrained by the object itself, not by the grasp stability.

B. Comparison Table

We compared 22 comparable taxonomies (see [14], [15], [27], [28], [34]–[52]), covering a broad range of domains. To facilitate comparison, all grasp taxonomies were registered in a comparison table, where columns store equivalent grasps, and rows store all grasps defined by an author. Grasps were considered equivalent if the overall hand configuration, the grasped object size, and the contact surfaces were similar. Due to the size of the table, only part is shown in Fig. 2. Overall, 211 relevant grasp examples were found in the reviewed literature sources. Those grasp examples could be arranged into 47 different grasp types. Of this set, five grasps violated the grasp definition and were, therefore, excluded (e.g., hook grasp, platform grasp, push grasp). Some grasps are only minor variations and were, therefore, not regarded as different grasp (eight instances). For example, the Panoramic Pentadigital Grip (see [15]) was regarded to be similar to the precision disk grasp, and the Index Roll Position 2,

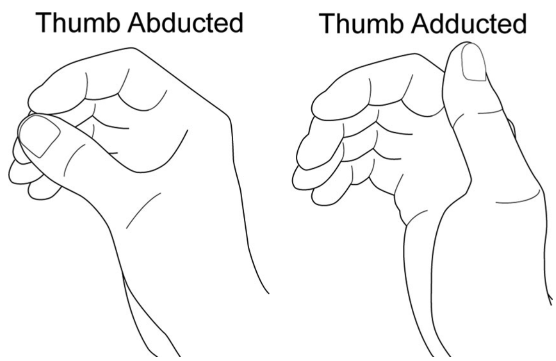


Fig. 3. Positions of the thumb used in the taxonomy. The thumb can either be either abducted or adducted. In the abducted position, the thumb is able to oppose the fingertips. The adducted position allows us to either apply forces on the side of the fingers or it moves the finger "out of the way."

Full Roll Position 1, and Full Roll Position 2 (see [43]) all are very similar to either the tip or palmar pinch. Finally, the only difference of the Reverse Transverse Palmar Grasp (see [49]) to the cylindrical grasp is the global orientation of the object and was, therefore, not regarded as new grasp. After this reduction in grasp types, the final number of valid grasp types is 33.

The grasp type recalled by the largest amount of authors with a coherent name was the "Lateral Grasp (grasp #16 in Fig. 3)," with 19 entries. This might be due to the fact that this grasp is very specific and was not further divided into multiple "sub" grasps. In comparison, full hand wrap grasps are split into at least three different grasps [medium wrap (#3), large diameter (#1), small diameter (#2)] that are all relatively similar. As they were regarded to be different by many publications (11 publications list at least two of them), they were kept separate. Twenty-one publications list at least one of those three grasps, which shows that those three grasps combined are equally frequent. Finally, 18 publications contain at least one full hand wrap grasp, a thumb-index precision grasp [palmar pinch (#9), tip pinch (#24)], and the lateral grasp (#16).

The numbers of grasps listed vary to a large degree; some classifications only name three grasps [35], [44], and the publication with the largest amount of grasp types names 21 [15]. While some size differences can be attributed to the differences in application, where potentially not the full spectrum of hand use is supposed to be covered, a large factor is also the precision by which those different grasps are described. Some authors explicitly state that the few grasps listed are prototypical and should be adapted based on the situation. Furthermore, there is no consensus on how to treat different sizes and shapes of objects. While Cutkosky [53] distinguishes grasps also by object size, many other authors do not. This also accounts for some variation in the numbers of grasps listed. In our comparison, we consider the object size to correspond to the size shown in the picture, as we assume this is the prototypical grasp the author had in mind.

Some taxonomies [15], [45], [51] are defined in a hierarchical way, which allows for selecting a desired level of precision. For the scope of this paper, we always selected the maximal number of different grasps, thus selecting the finest differentiation of grasps. Hierarchical taxonomies could allow for a more precise comparison, because the number of grasps becomes a parameter, allowing comparison at the same level of granularity. However, as only few taxonomies are arranged that way we did not pursue this idea further.

C. Analysis of Power and Precision Grasps

Of the 22 authors represented in the survey, nine classified their grasps as power, intermediate, or precision (PIP) grasps. The first taxonomy included in our comparison to incorporate such a distinction is [28], whereas it appears that more publications adopted the categorization in recent years. Of the ten publications after 1985, only three did not also classify their grasps according to power, precision, and intermediate (optionally). Overall, both power and precision grasps were equally present with 40 and 41 listings, respectively. Intermediate grasps were less common, being listed eight times.

In this section, we determine the consensus of the allocation of the PIP categories. In order to compare assignments, at least two publications need to define the category for a particular grasp. This is the case for 19 grasps. The assignments showed a large consensus; the assignment completely agreed in 13 of the 19, where all authors classified the grip into the same category. Interestingly, the lateral grasp (#16) was classified either as precision grasp [40], [46], [47], [49], intermediate [27], [28], or power grasp [45], [51]. This reinforces the view that this grasp takes an intermediate stage between power and precision, a fact Iberall [29] also acknowledges. This "in between" state of the grasp is represented within our taxonomy since it is put into the intermediate category. Some inconsistency was found in the tripod grasps ["real" tripod (#14) and writing tripod (#20)]; Kamakura *et al.* [27] classified them as intermediate grasps, apart from that it was classified as precision. We follow the majority of publications and label those grasps as precision grasps. Furthermore, in our view, the need for power in those grasps is very little; hence, classifying them as precision also makes sense from this point of view.

IV. Synthesis of Grasp Taxonomies

After determining which grasps were valid according to our grasp definition, those grasps had to be arranged into a systematic categorization. After much deliberation and analysis of different ways to arrange the grasps, an arrangement in a matrix was chosen. The resulting taxonomy is depicted in Fig. 4. Columns are arranged according to power/precision requirements. The next finer differentiation depends on whether the opposition type is Palm, Pad, or Side Opposition. The opposition type is also defining the VF 1: In the case of Palm Opposition, the palm is mapped into VF 1; in Pad and Side Opposition, the thumb is VF 1. The only exception to this "rule" is the Adduction Grasp, where the thumb is not in contact with the object.

The position of the thumb is used to differentiate between the two rows. As shown in Fig. 3, the thumb CMC joint can be in an either adducted or abducted position. This is a new feature introduced in the GRASP taxonomy.

Compared with the taxonomies in the literature, our taxonomy has a greater extent. The publications with the largest number

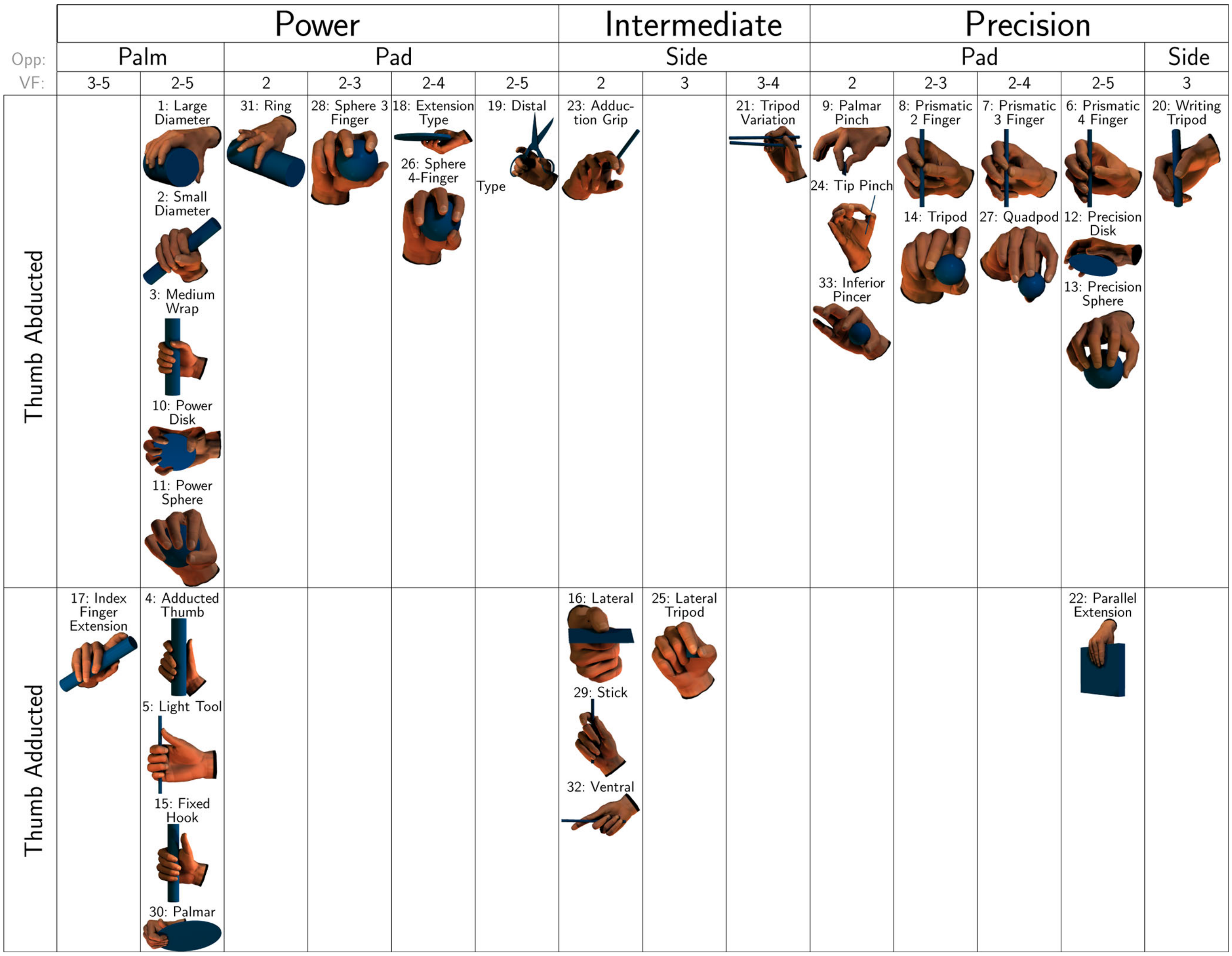


Fig. 4. GRASP taxonomy that incorporates all previous grasp classifications. The grasps are classified in the columns according to their assignment into power, intermediate and precision grasp, the opposition type, and the VF assignment. The assignment of the rows is done be the position of the thumb that can be in an abducted or adducted position.

of relevant grasps are [15] and [49], with 21 and 20 grasp types, respectively. The taxonomy of Cutkosky [53], which is widely used in the field of robotics, lists 15 different grasps. Even this very basic comparison shows the difference to our taxonomy, which incorporates a higher number of grasp types.

A. *Merging of Grasps Within One Cell*

Many grasps have similar properties (opposition type, thumb position, etc.); therefore, some cells are populated with more than one grasp. The difference between the grasps within one cell is mainly the shape of the object. This offers the possibility to reduce the set of all 33 grasps down to 17 grasps by merging the grasps within one cell to a corresponding "standard" grasp. Depending on the task, this offers the possibility to choose between two different levels of accuracy of the grasp classification.

As a comparison, the classification of Cutkosky [53] has 15 different grasp types that fit into our definition of a grasp. This is close to the amount of grasps the reduced taxonomy has. However, our comparison shows that even though the number of grasps is nearly the same, the classification is very different. When their grasps are classified according to the presented scheme, the grasps only populate seven cells. As Cutkosky mainly differentiates grasps by the object properties, this reduction is only natural. The differentiation between object properties is done within one cell.

On the other hand, the 14 grasps of Kamakura *et al.* [27] have no multiple entries in one cell. In this study, humans were observed grasping 98 different objects with static grasps. That is very close to natural human hand usage, and therefore, it is reassuring that the GRASP taxonomy has a similar result. Nevertheless, it is difficult to judge whether the selected objects represent an exhaustive set of objects humans encounter in everyday life.

B. *Completeness of the Taxonomy*

It is also important to determine the completeness of the taxonomy. As this taxonomy is only based on the literature, it is impossible to answer this question based on those literature sources alone. However, since the initial publication of this taxonomy [17], there has been a study that recorded the frequencies of grasp types during the work of two housekeepers and two machinists [54]. For each subject, 7.45 h or about 4700 grasps were analyzed. They used the GRASP taxonomy as basis for their grasp definition. Their results show that all grasp types except the Tripod Variation (#21) and the Distal Type (#19) were used. Both of those grasps are certainly used, but very specialized and thus were not observed in their set of activities. A similar study [55] that used a different categorization (which also incorporated nonprehensile grasps) found that 3.3% of the grasps could not be assigned into one of their categories. As their grasps are only a subset of grasps from the GRASP taxonomy, our taxonomy will most likely also cover a broader range of hand movements.

In the GRASP taxonomy, there are cells that are not populated with any grasp. For some cells, imagining a grasp is possible, for example, grasping a stick (e.g., cigarette) between the middle and the ring finger would change the categorization to "Intermediate/Side/VF2: 3, thumb abducted." However, so far, the need has never arisen to add those potentially uncommon grasps. It appears that the existing categorization is sufficient. Furthermore, some cells cannot technically be populated. For proper tip opposition, the thumb has to be abducted, as otherwise the thumb is not able to act against the fingertips. This excludes most of the Pad/Thumb adducted combinations. The only grasp that is listed in this combination is the Parallel Extension Grasp (#22), in which the thumb is in some intermediate position between abduction and adduction. As the opposition is done partly by the side of the thumb, we then put the grasp into the adducted category.

C. *Statistics of the Cells in the Taxonomy*

Fig. 5 was created to further analyze the properties and statistics of the grasps and cells in the taxonomy. It uses the frequency and interrater data from [54] and [56] and arranges the information according to the taxonomy. As the interrater analysis was performed only on part of the data [54], only the most common grasps provide reliable statistics. Therefore, confusion data for grasps with a frequency of less than 5% are omitted.

As presented in Section IV-A, the grasps within each cell can be merged to one prototypical grasp when the full precision of the taxonomy is not needed. Generally, grasps within one cell are similar and, therefore, might be more likely to be confused. Using the confusion and frequency data presented in Table I, it becomes clear that this is not the case. There is no consistent pattern on which grasps are confused. Additionally, many cells contain only one grasp, making in-cell confusion impossible.

Most of the cells in the taxonomy have a significant frequency/duration share associated with them. This shows that every populated cell in the taxonomy also contains at least one grasp that is relevant for real-life usage. Some of the uncommon cells [adduction grip (#23), distal type (#19), and tripod variation (#21)] contain a single specialized grasp. Even though that grasp might not be common, it is clearly used in specialized cases that are important.

If the grasps within one cell of the taxonomy are to be merged, one approach would be to pick the most common grasp of this cell as the prototypical example. This way, the most relevant grasp of each cell is kept, while being able to reduce the total number of grasps. Using this set of 17 grasps, they still cover 83.4% of the duration and 75.8% of the frequency of the full dataset.

D. *Grasp-Type Properties*

After the initial publication [17], there have been a set of follow-up studies that made direct use of the GRASP taxonomy. Bullock *et al.* [54], [56] used the taxonomy as basis for classifying real-life grasp types performed by two machinists and two housekeepers. Additionally, the properties of the manipulated objects [57] and tasks [58] were analyzed. The information from these publications is used to compile a list of grasps from the GRASP taxonomy and augment each grasp with a set of properties as shown in Fig. 5. The table presents an overview over the properties of each of the grasps for real-life usage, which is slightly different to the initial publications, where the focus was never to determine the properties for each grasp type separately.

It is important to keep in mind that the shown properties are relevant for those environments, and it is still unclear to what extent those results can be extrapolated to all human hand usage. However, this is an exhaustive analysis of human grasping in real life and, therefore, still can provide valuable insights. Comparable studies [39], [55], [59]–[61] use a different grasp classification and, therefore, cannot provide these data on a per-grasp basis.

1) Object and Task Properties: Regarding the object mass, Fig. 5 highlights that most grasp types in fact are applied to relatively lightweight objects, with most grasps used on objects lighter than 500 g. A similar observation can be made regarding the grasp size (the size of the object that defines the hand aperture), where the majority of grasps needs hand openings of 5 cm or less. This shows that for most grasp types, the hand is not operating at its limit in terms of force and aperture. The data also show that the properties of objects that are usually grasped can vary to a larger degree. For each grasp, there is a range of object mass and object size.

Regarding the rigidity of objects, most grasps are dominated by rigid objects, where the grasp force is not deforming the object. Major exceptions from this trend are the power sphere (#11) and precision disk (#12), both of which are mainly used for floppy objects (objects that deform easily under gravity). The grasp force can either be dominated by weight of the object ("weight") or the force needed to exert on the environment ("interaction"). The table shows that for most grasps, the grasp force is dominated by the weight of the objects; only the index finger extension (#17), precision disk (#12), and writing tripod (#20) are strongly dominated by the interaction.

2) Frequencies of Grasp Types: Apart from the frequency data shown in Fig. 5, there are some other publications [39], [55], [59]–[61] that determine the importance of individual grasps via their occurrence in real life. Due to the different definition of grasps, it is difficult to compare the results directly. Regarding

Nr.	Name	Type	Opp. Type	Th. Pos	VF	Lit. Ref.	Prev. [54]	Mass [g] [57]	Size [cm] [57]	Rigidity [57]	Force [58]
1	Large Diameter	Pow.	Palm	Abd.	VF 2: 2-5 VF 3:	15	F: 1.7 % D: 1.5 %	0 500 1,000	0 5 10 15	ri sq	wt
2	Small Diameter	Pow.	Palm	Abd.	VF 2: 2-5 VF 3:	8	F: 0.7 % D: 0.3 %	0 500 1,000	0 5 10 15	ri sq	wt in
3	Medium Wrap	Pow.	Palm	Abd.	VF 2: 2-5 VF 3:	11	F: 12.7 % D: 23.8 %	0 500 1,000	0 5 10 15	ri sq	wt in
4	Adducted Thumb	Pow.	Palm	Add.	VF 2: 2-5 VF 3: 1	2	F: 1.0 % D: 0.9 %	0 500 1,000	0 5 10 15	ri	wt in
5	Light Tool	Pow.	Palm	Add.	VF 2: 2-5 VF 3: (1)	2	F: 4.8 % D: 3.6 %	0 500 1,000	0 5 10 15	ri	wt in
6	Prismatic 4 Finger	Pre.	Pad	Abd.	VF 2: 2-5 VF 3:	6	F: 4.0 % D: 2.0 %	0 500 1,000	0 5 10 15	ri sq	wt
7	Prismatic 3 Finger	Pre.	Pad	Abd.	VF 2: 2-4 VF 3:	4	F: 4.2 % D: 3.5 %	0 500 1,000	0 5 10 15	ri	wt
8	Prismatic 2 Finger	Pre.	Pad	Abd.	VF 2: 2-3 VF 3:	3	F: 6.4 % D: 4.3 %	0 500 1,000	0 5 10 15	ri	wt
9	Palmar Pinch	Pre.	Pad	Abd.	VF 2: 2 VF 3:	18	F: 3.9 % D: 2.3 %	0 500 1,000	0 5 10 15	ri fl	wt
10	Power Disk	Pow.	Palm	Abd.	VF 2: 2-5 VF 3:	3	F: 0.2 % D: 0.1 %	0 500 1,000	0 5 10 15	ri sq	wt in
11	Power Sphere	Pow.	Palm	Abd.	VF 2: 2-5 VF 3:	13	F: 6.3 % D: 4.8 %	0 500 1,000	0 5 10 15	fl	wt in
12	Precision Disk	Pre.	Pad	Abd.	VF 2: 2-5 VF 3:	3	F: 7.1 % D: 18.8 %	0 500 1,000	0 5 10 15	fl	in
13	Precision Sphere	Pre.	Pad	Abd.	VF 2: 2-5 VF 3:	7	F: 0.2 % D: 0.2 %	0 500 1,000	0 5 10 15	ri fl	wt
14	Tripod	Pre.	Pad	Abd.	VF 2: 2-3 VF 3:	9	F: 8.4 % D: 6.1 %	0 500 1,000	0 5 10 15	ri	wt in
15	Fixed Hook	Pow.	Palm	Add.	VF 2: 2-5 VF 3:	2	F: 0.4 % D: 0.4 %	0 500 1,000	0 5 10 15	ri	wt in
16	Lateral	Int.	Side	Add.	VF 2: 2 VF 3:	19	F: 8.9 % D: 5.9 %	0 500 1,000	0 5 10 15	ri fl	wt in
17	Index Finger Extension	Pow.	Palm	Add.	VF 2: 3-5 VF 3: 2	4	F: 3.4 % D: 5.6 %	0 500 1,000	0 5 10 15	ri	wt in
18	Extension Type	Pow.	Pad	Abd.	VF 2: 2-5 VF 3:	3	F: 3.6 % D: 1.8 %	0 500 1,000	0 5 10 15	ri sq fl	wt in
19	Distal Type	Pow.	Pad	Abd.	VF 2: 2-5 VF 3:	3	F: 0 % D: 0 %	no data	no data	no data	no data
20	Writing Tripod	Pre.	Side	Abd.	VF 2: 2 VF 3:	8	F: 0.7 % D: 1 %	0 500 1,000	0 5 10 15	ri	wt in
21	Tripod Variation	Int.	Side	Abd.	VF 2: 3-4 VF 3:	2	F: 0 % D: 0 %	0 500 1,000	0 5 10 15	ri	no data
22	Parallel Extension	Pre.	Pad	Add.	VF 2: 2-5 VF 3:	7	F: 2.0 % D: 2.3 %	0 500 1,000	0 5 10 15	ri sq	wt in
23	Adduction Grip	Int.	Side	Abd.	VF 2: 2 VF 3:	4	F: 2.2 % D: 0.9 %	0 500 1,000	0 5 10 15	ri	wt in
24	Tip Pinch	Pre.	Pad	Abd.	VF 2: 2 VF 3:	13	F: 0.3 % D: 0.1 %	0 500 1,000	0 5 10 15	ri fl	wt in
25	Lateral Tripod	Int.	Side	Add.	VF 2: 3 VF 3:	2	F: 10.4 % D: 5.1 %	0 500 1,000	0 5 10 15	ri fl	wt
26	Sphere 4 Finger	Pow.	Pad	Abd.	VF 2: 2-4 VF 3:	1	F: 0.2 % D: 0.2 %	0 500 1,000	0 5 10 15	ri fl	wt in
27	Quadpod	Pre.	Pad	Abd.	VF 2: 2-4 VF 3:	2	F: 0.3 % D: 0.2 %	0 500 1,000	0 5 10 15	ri sq fl	wt
28	Sphere 3 Finger	Pow.	Pad	Abd.	VF 2: 2-3 VF 3:	1	F: 1.5 % D: 0.7 %	0 500 1,000	0 5 10 15	ri sq	wt in
29	Stick	Int.	Side	Add.	VF 2: 2 VF 3:	1	F: 1.2 % D: 0.8 %	0 500 1,000	0 5 10 15	ri	wt in
30	Palmar	Pow.	Palm	Add.	VF 2: 2-5 VF 3:	2	F: 0.6 % D: 0.2 %	0 500 1,000	0 5 10 15	ri	wt in
31	Ring	Pow.	Pad	Abd.	VF 2: 2 VF 3:	1	F: 2.0 % D: 2.0 %	0 500 1,000	0 5 10 15	ri	in
32	Ventral	Int.	Side	Add.	VF 2: 2 VF 3:	1	F: 0.4 % D: 0.2 %	0 500 1,000	0 5 10 15	ri	wt
33	Inferior Pincer	Pre.	Pad	Abd.	VF 2: 2 VF 3:	1	F: 0.6 % D: 0.3 %	0 500 1,000	0 5 10 15	ri sq	wt
						Descriptions	F... Frequency D... Duration	Mass of the object in grams.	Size of the object that defines the hand opening, in cm.	ri... rigid fr... fragile sq... squeezable fl... floppy	wt... weight in... interaction

Fig. 5. Overview of the properties from each grasp in the taxonomy. The properties are taken as the average properties for all instances with the grasp. Please note that while we give the statistics for all grasps, the statistics of rare grasps are unreliable. One should focus on grasps with a frequency (see F in the Prev. column) greater than 5%. Rigidity defines the compliance of an object, whereas the force category is "weight" if the mass of the object defines the grasp force or "interaction" when the task requires a different grasp force. More details are given in Section IV-D. Data come from publications as indicated in brackets in the column headers; it is based on observing two housekeepers and two machinists during their regular work.

TABLE I
FREQUENCY AND DURATION FOR EACH GRASP

Grasp Nr.	Frequency%	Duration %	Confusion 1	Confusion 2	Confusion 3
1	1.7	1.5			
2	0.7	0.3			
3	12.7	23.8	5: 13.8%	1: 8.8%	25: 2.2%
4	1.0	0.9			
5	4.8	3.6			
6	4.0	2.0			
7	4.2	3.5			
8	6.4	4.3	9: 27.1%	16: 26.7%	7: 7.7%
9	3.9	2.3			
10	0.2	0.1			
11	6.3	4.8	12: 20.3%	25: 10.5%	16: 7.5%
12	7.1	18.8	11: 4.2%	16: 0.7%	6: 0.3%
13	0.2	0.2			
14	8.4	6.1	16: 69.7%	25: 6.9%	8: 1.4%
15	0.4	0.4			
16	8.9	5.9	14: 41.8%	8: 8%	9: 4.8%
17	3.4	5.6			
18	3.6	1.8			
19	0.0	0.0			
20	0.7	1.0			
21	0.0	0.0			
22	2.0	2.3			
23	2.2	0.9			
24	0.3	0.1			
25	10.4	5.1	11: 13.5%	14: 13%	5: 12.9%
26	0.2	0.2			
27	0.3	0.2			
28	1.5	0.7			
29	1.2	0.8			
30	0.6	0.2			
31	2.0	2.0			
32	0.4	0.2			
33	0.6	0.3			

For each grasp, the frequency (Freq) and duration (Dur) is given, based on observing housekeepers and machinists [54], [56]. For grasps with a frequency greater 5%, also the confusion data is given for the top three confused grasps. The number corresponds to the grasp number, whereas the percentage value represents the proportion of times the other grasp was classified. It is based on two raters analyzing the same video and calculating the confusion matrix and looking at the top three off-diagonal terms.

precision grasps executed with thumb and index, the frequencies can vary to a large degree. According to [39], the pulp pinch ("The object is held between the thumb and the index and/or the middle finger") is used 20% of the time, whereas the pulp (#9) and tip pinch (#24) combined make up for only 4.2% in the work of Bullock *et al*. In a study of manufacturing tasks, Lee and Jung [60] found that a pinch between the thumb and index finger is used, 6.7% (mean left and right hand), which is a similar value to that found by Bullock *et al*. Comparing those numbers to that found by Vergara *et al.* [55] is difficult as they have a very general definition of the pinch grasp ("Thumb and fingertips (one or more) are used, and usually the thumb as well). According to their definition, all pad grasps are classified into pinch grasp, a group that contains 11 grasps in the GRASP taxonomy. They found this group in 38.3% of the instances, which is a significant proportion. Adding the frequencies shown in Table I of the corresponding 11 pad grasps gives a sum of 37%, which is close to the results from Vergara *et al.*

Keller *et al.* [61] look only at the frequencies of tip pinch (#24), palmar pinch (#9), and lateral (#16) in order to estimate their importance for prosthetic applications. They found that de-

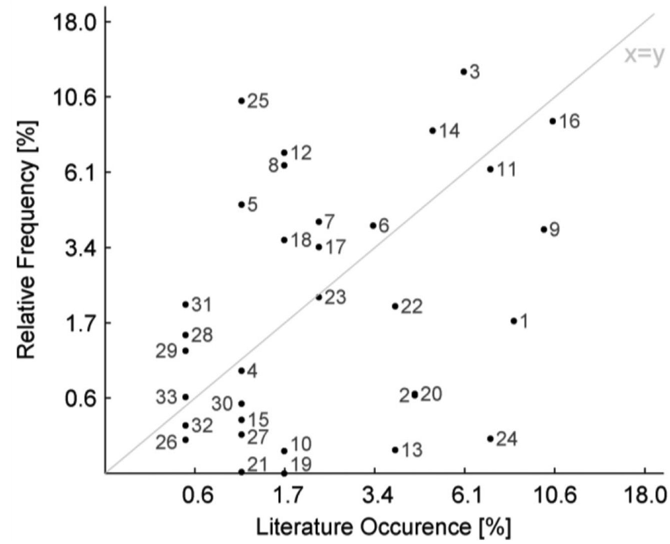


Fig. 6. Comparison of the frequency of grasps. The x-axis represents the occurrence of grasps in the literature. The y-axis shows their relative frequency based on a video analysis [54], that is based on observing housekeepers and machinists. It compares the prevalence of a grasp in the literature with the observed frequency in those real-life environments. The Pearson correlation between the x- and y-axis is 0.36. Both axes have a logarithmic scale.

pending on the task (pick-up or hold-for-use), either the lateral grasp or the palmar grasp (#9) is more prevalent with about 60%, whereas the other has 34%. Finally, the tip pinch (#24) is less common. The low prevalence of the tip pinch (#24) is in accordance with Bullock *et al.*, where this grasp is also uncommon.

Kilbreath and Heard [59] observed the routine of elderly adults. They define only two grasps (digital grasp and whole hand grasp); therefore, their study does not have enough granularity at the grasp-type level. However, they also included non-grasping movements. Their results show that grasps are the most prevalent hand function, where in 60% (right hand) and 48% (left hand) of the time, a grasp was observed.

3) Perceived Versus Real Frequency of Grasps: Comparing the occurrences of grasp types in the literature and the empirically measured frequency provides an alternative view on the grasp data. If a grasp type is listed in every taxonomy that is published, it has high literature prevalence. This prevalence can be compared with the real-life frequencies from the study that makes use of the GRASP taxonomy [54]. This study is based on observing two housekeepers and two machinists while performing their regular work. The comparison (see Fig. 6) shows that there is little correlation between the number of references in the literature and the observed grasp frequency. The Pearson correlation between those two sets is 0.36. This means that a grasp that is referenced often in the literature is not necessarily observed often in those scenarios.

Both the palmar (grasp #9) and the tip pinch (grasp #24) have a perceived prevalence much higher than their actual frequency. The palmar pinch (#9) has a literature occurrence rate of 10% and the tip pinch (#24) 7%. In reality, however, they make up for only 4% of the grasp instances. On the other end of the spectrum, the lateral tripod (grasp #16) has a prevalence based on literature of 1%, whereas it is used in 10% of the instances.

V. Discussion

In this study, we reviewed existing taxonomies and created a novel classification that consists of 33 grasp types. Depending on the level of required granularity, they can be reduced to a set of 17 more prototypical grasps. There are a couple of interesting observations, which will be discussed in the remainder of the section.

The classification in the taxonomy depends not only on the hand pose, but also the type of contact between hand and object. For example, the medium wrap (#3) and the prismatic 4 finger (#6) have a similar hand shape, but the first has additional palm contact, whereas the latter has only fingertip contact. Therefore, the opposition type is different (palm versus pad).

Classifying grasps based on those additional parameters simplifies classification for the human, but for automated grasp recognition systems, those additional parameters can be difficult to obtain. Depending on the approach, this would require two different measurement modalities. For example, using a glove that measures only the joint angles might not be sufficient, since it would also need to measure contact in order to correctly classify the grasps in the taxonomy. Specialized taxonomies, for example, based only on the contact configuration [45] could be useful in particular applications. However, the presented taxonomy provides a common terminology and can be the basis for more specialized taxonomies.

As the thumb is the most important digit, usually opposing the four fingers, the position of the thumb is introduced as a new feature. It provides an additional classification parameter to distinguish grasps. In order for the thumb to oppose the fingers, the thumb has to be in abducted position. This fact is also reflected in the taxonomy, where most pad grasps are classified as thumb abducted. The thumb is adducted only in cases where the opposition is between the thumb and the side of the finger (e.g., lateral grasp) or the thumb is not involved in opposition at all (e.g., fixed hook and palmar).

In some of those cases, the thumb is adducted in order to "get out of the way," as is the case in the palmar grasp. Overall, this adds a parameter to describe and classify grasps and, therefore, is a valuable addition to existing grasp properties.

Even though there has been considerable effort in creating statistics of human hand use [54], [56], [59]–[63], much is still unclear. Comparing those publications is difficult, as most of them use a different set of grasp types. Even though certain grasps or groups of grasps can be compared, it is still impossible to fully compare the results due to the different grasp classifications. This highlights the need for a common grasp classification, as this allows for direct comparison between publications.

A second observation from those publications is that the grasp frequencies shift considerably depending on the environment. Each environment contains different objects and affords different tasks; therefore, the grasp frequencies shift accordingly. The frequency data give important estimates of human hand use; however, there is still considerable uncertainty regarding human grasp frequencies. Additional studies with more subjects in different environments should be done. Those differences between environments are also important to consider in human–computer interaction. For example, when training a system that is supposed to interpret the human hand actions, it is important to train the system in similar environments to the ones where it will be deployed. Such a trained system might not extrapolate well to different environments as grasp-type frequencies can shift and decrease the classification accuracy.

As shown in the grasp property table (see Fig. 5), each grasp type is performed on objects with specific size, weight, rigidity, and force requirement. However, there is also considerable overlap, and it appears that many grasps could be interchanged. Bullock *et al.* exploit this fact in [64], where an optimal minimal set of grasps is sought. This overlap is significant, as it highlights that the human can chose from a set of potential suitable grasps to complete a task. However, subtle details including the orientation of the object, other task demands, friction, and personal factors (preferences, chance [27]) could ultimately define the grasp. The influence of many of those parameters is still speculative and requires more research.

As highlighted in Fig. 5, there is no trend showing that grasps referenced often in the literature are also used more often in real life. There are a couple of potential reasons for the discrepancy. First, the grasp frequency is dependent on the environment. The housekeeper and machinist environment, on which the grasp frequency is based, could be very different to the environment the authors had in mind while creating their taxonomies. Other publications [39], [55], [59], [60] that estimate grasp frequencies use different grasp definitions, therefore making the comparison difficult. Ultimately, the environment dependence of the grasps might change the prevalence accordingly. Second, each taxonomy in the literature uses a different classification with a different number of grasps. Some authors try to list the most common grasps, whereas others provide an elaborate list of grasps. Consequently, summing up the number of occurrences could have introduced a bias. For example, full hand wrap grasps are divided into three grasps (grasps # 1, 2, and 3), and most authors do not list all three. Therefore, summing those up can result in an artificial low number for each grasp, even if most authors list at least one of the three. The other extreme is the lateral grasp(#16) as it is very distinct and not divided into "subgrasps." It is listed by all but three authors. Finally, the discrepancy between the literature and real life-grasp frequencies could actually be real. The result is significant for all domains in human–computer interaction where it should be considered that the human intuition is not necessarily in line with reality. It highlights the importance for systematic analyses of human performance.

As the GRASP taxonomy helps to better understand human grasping, we also anticipate that it will be useful for the robotic grasping community. A common approach to reduce the control complexity of hands with many degrees of freedom is to define a set of grasp types that the hand executes. In that respect, the GRASP taxonomy can be a guideline for selecting the most useful and appropriate grasp types. In cases of learning by demonstration, it can be helpful to use grasp types as intermediate step when going from human motion to robotic execution. The GRASP taxonomy will be very useful for this approach, as it contains a large set of grasps; thus, using this set alone might be sufficient for this purpose.

Since the taxonomy was created as a superset of previous ones, it covers by definition more hand postures than the grasp taxonomies presented in the literature so far. Our current data do not allow to directly infer whether the set of grasps is complete. A study, which based their classification on the GRASP taxonomy, tried to classify all hand usage in everyday-life sit uations [65]. They found that most grasps were covered and the missing grasps appear to be mainly highly specialized grasps. Our experience with the taxonomy confirms this view, as we never encountered significant missing grasps. Therefore, the authors think that the current list of grasps is sufficient for most applications.

VI. Conclusion and Future Work

The goal of this paper was to generate a more comprehensive human grasp taxonomy to serve as basis for human grasp analysis than what currently exists in the literature. From a comprehensive literature review, 211 grasp examples were found, and based on those, 33 unique prehensile grasp types were extracted. The grasp types were then arranged in a novel taxonomy, arranged according to the number of fingers in contact with the object and the position of the thumb.

While the taxonomy has proven useful in the examination of human grasping behavior, a few directions of future inquiry are open. While the classification was found to be valid for a large human grasping video dataset, the completeness of the taxonomy in a larger diversity of environments could be examined. Data-driven approaches have the potential to simplify this, otherwise, very labor intensive process [63], [65], [66]. Furthermore, the taxonomy could be extended to include nonprehensile "grasps," or for dynamic within-hand manipulation movements, both of which are currently excluded by the grasp definition we utilize. However, although these are important aspects of hand function, incorporating them into a single taxonomy may be prohibitively complex and may be best left as separate classifications.

We hope that the GRASP taxonomy will be useful and will help to establish a common definition of human grasp types.

The taxonomy and documents can be downloaded at grasp.xief.net.

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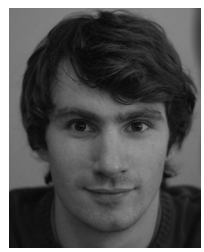

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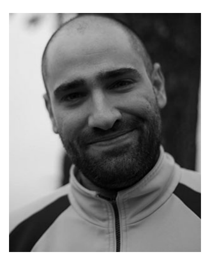

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