A Taxonomy of Everyday Grasps in Action*

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***Abstract*— Grasping has been well studied in the robotics and human subjects literature, and numerous taxonomies have been developed to capture the range of grasps employed in work settings or everyday life. But how completely do these taxonomies capture grasping actions that we see every day? We asked two subjects to monitor every action that they performed with their hands during a typical day, as well as to role-play actions important for self-care, rehabilitation, and various careers and then to classify all grasping actions using existing taxonomies. While our subjects were able to classify many grasps, they also found a collection of grasps that could not be classified. In addition, our subjects observed that single entries in the taxonomy captured not one grasp, but many. When we investigated, we found that these grasps were distinguished by features related to the grasping action, such as intended motion, force, and stiffness – properties also needed for robot control. We suggest a format for augmenting grasp taxonomies that includes features of motion, force, and stiffness using a language that can be understood and expressed by subjects with light training, as would be needed, for example, for annotating examples or coaching a robot. This paper describes our study, the results, and documents our annotated database.**

I. INTRODUCTION

Grasping is an essential part of people's daily lives and is critical for creating robots that can interact with and make changes to their environment. Grasping has been the focus of numerous human studies (e.g. [1]), and a large body of robotics research has worked within a grasp-move-ungrasp paradigm. Within these studies, one area of focus has been hand shape and the contacts between hand and object, which constrain how the hand and object can interact.

A number of taxonomies with hand shape and object contact as central elements have been developed to classify grasps e.g. [2][3][4][5]. These taxonomies have been widely used in robotics, for applications including grasp recognition [6][7], robot hand design and evaluation [8], programming by demonstration [9], and even to support more sophisticated interaction with grasp sensitive objects [10]. They also allow researchers to communicate grasp differences in research and discussion, distinguishing power from precision grasps, tripod vs. pinch, spherical vs. cylindrical, for example.

However, the actual act of grasping can be complex. We may slide, rotate, tumble, or bend an object in order to grasp it e.g. [11][12]. In fact, pushing, rotating, tumbling, and other manipulations have been studied independently (e.g., [13][11][14]) and can be considered essential aspects of any dexterous robot's repertoire.

In this paper, we ask to what extent our existing grasp taxonomies capture the actions we do in everyday life. Our goal is to build a taxonomy / database that captures most of everyday grasping and manipulation actions.

Towards this goal, two subjects attempted to capture all actions accomplished during a typical day, with a focus on critical humanoid robot capabilities such as home care and manipulation in unstructured environments such as a home or workplace. For each observed grasp or manipulation action, our subjects attempted to classify it using the Comprehensive Grasp Taxonomy of Feix and colleagues [5]. In all, 179 distinct grasping actions were captured and classified.

We found that although many grasping actions could be classified in the existing taxonomies, there were important differences between grasps that the taxonomy did not consider. To capture these differences, we propose an extended set of annotations capturing force, motion, and stiffness information. Table XII shows an example. Our goal in devising this classification was to communicate these grasping action characteristics as precisely as possible while still making it possible for individuals with light training to understand and classify examples of manipulation actions or communicate differences between those actions to a robot, for example.

Furthermore, we found 40 grasp types which could not be well captured by existing taxonomies, including actions of pushing, grasping while pressing a button or lever, and grasping with extension (inside-out) forces. We believe our database is an improvement on our prior work, because we characterize human grasps by taking into account forces and motion exerted after a grasp is achieved. These added properties may tie into existing impedance [15] and operational space controllers [16] used in robotics.

We report our complete process and findings below. The database of classified and annotated grasps from our study can be viewed at [17].

II. RELATED WORK

A. Grasp taxonomies

Perhaps the earliest often cited grasp taxonomy is that of Schlesinger [18]. Napier [19] also contributes a basic taxonomy and an interesting discussion of hand evolution and use. Grasp taxonomies have been developed that are targeted at tasks of everyday living, including those of Kapandji [20], Edwards et al. [4] and Kamakura et al. [2]. Kamakura and colleagues, for example, classified static prehensile patterns of normal hands into 14 patterns under 4 categories (power grip, intermediate grip, precision grip and grip involving no thumb). They illustrated detailed contact areas on the hand for each grasp and analyzed for which objects the grasp may be used.

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Perhaps the most widely cited taxonomy in robotics is that of Cutkosky [3], which includes 16 grasp types observed in skilled machining tasks. The Cutkosky taxonomy consists of a hierarchical tree of grasps, with categories classified under power and precision. Moving from left to right in the tree, the grasps become less powerful and the grasped objects become smaller. Zheng and his colleagues [21] used this taxonomy to capture the daily activities of a skilled machinist and a house maid, giving for the first time a count of how frequently different grasps are used. The intent of our study is similar. However, we consider a broader variety of actions beyond static grasps and make special note of differences observed in grasps that have the same entries within the grasp taxonomy.

Feix et al. [5] recently developed a comprehensive taxonomy of grasps that brings together previous research with their own observations. They propose a definition of a grasp as follows: "A grasp is every static hand posture with which an object can be held securely with one hand." This definition excludes intrinsic movements, bimanual tasks, gravity dependent grasps, and flat hand grasps, for a total of 33 classified grasp types. Because it was developed with the goal of being inclusive, we selected this taxonomy as a starting place in our experiments. However, our taxonomy is not limited to grasps, and reincorporates non-prehensile manipulation tasks that people do everyday.

B. Manipulation Taxonomies

A number of taxonomies have been developed to express manipulation actions. Chang and Pollard [22] classify manipulations prior to grasping, with a focus on how the object is adjusted, considering both rigid transformation and non-rigid reconfigurations. Worgotter and colleagues [23] discuss how manipulation actions are structured in space and time. Focusing on actions of bringing together and breaking apart, they identify 30 fundamental manipulations that allow sequences of activities to be encoded. Elliott and Connolly [24] classify coordinated motions of the hand that are used to manipulate objects, identifying three classes of intrinsic movements: simple synergies such as squeeze, reciprocal synergies such as roll, and sequential patterns such as a rotary stepping motion of the fingers to change contact positions on the object. Bullock et al. [25] encode manipulation instances at a more abstract level, focusing on motion of the hand and relative motion of the hand and object at contact, with the goal of creating a classification scheme that does not assume a specific hand design. We adopt a structure similar to theirs for expressing intended motion of grasped object, but incorporate it as extra information within the context of a more conventional grasp taxonomy.

Torigoe [26] investigated manipulation in 74 species of great apes, identifying over 500 different body part manipulation acts, 300 of which are related to hand manipulation, including drape, flip, pick up, pull, push or press, roll, rotate, throw, untwist and so on. We find that a similar approach is useful for distinguishing between different grasps that have the same grasp taxonomy label and use this approach to capture the types of force applied in human manipulation.

III. METHODS

We compiled a task list from various sources for our study. First, we studied previous literature that measured self-care and mobility skills for patient rehabilitation [27][28][29][30]. The measured skills listed in these papers such as dressing, eating, and grooming cover typical and important tasks humans need to do, even for those who are disabled. Our initial list of actions was a union of the tasks mentioned in those papers. In work such as Choi et al. [31], tasks were ranked by importance, and tasks like buttoning, putting on socks, and personal hygiene were discarded because they received a low ranking and are difficult for a robot to accomplish. However, we also included these less important tasks in our list, with the goal of having a more inclusive study.

We next observed two college students' life from the time they woke up until the time they went to bed. We categorized all the hand gestures and motions that the person would use into hundreds of tasks. However, we felt this was insufficient since there are many skilled gestures (e.g. of tradespeople) that are not found in everyday life, and that the task list so far was biased toward the office settings of the subjects. Therefore, we expanded our task list to include specific tasks that people from various careers would accomplish in their workplace.

Next, we further separated the compound tasks into small task-components and movement elements, such as in Kopp et al. [27]. For example, wearing a T-shirt was broken down into three basic tasks: (1) arms in T-shirt sleeves, (2) grab the neck hole and move head through neck hole, (3) pull down and straighten shirt. We collapsed similar gestures together and classified these movements into the existing 33-grasp database of [5]. When we encountered daily-use hand gestures that were not in the basic database, we added them to the database.

Our final database contains 50 different grasp types, 4 press types, 10 grasp and press type, 2 extend types and 7 other hand types. We also illustrate where each movement may be used in daily life with corresponding pictures.

IV. DATABASE ANNOTATIONS

Fig. 1 shows the classification we have developed in order to distinguish the different manipulation actions we have observed. The focus of previous grasp taxonomies has often been on hand shape (highlighted in purple).

With our observations, however, we annotated grasps with four features: (1) hand shape, (2) force type, (3) direction, and (4) flow. The object related property is another factor that influences the hand shape and motion, but these relationships are not made explicit in our database. In contrast to traditional grasp taxonomy research, our research focuses on grasps within the context of the action that is intended. The rationale behind this focus came about when we mapped the grasping actions we encountered onto the existing grasp taxonomy of [5] and realized that a wide variety of these grasping actions belonged to one grasp type within the taxonomy, but involved very different motion, force, or flow.

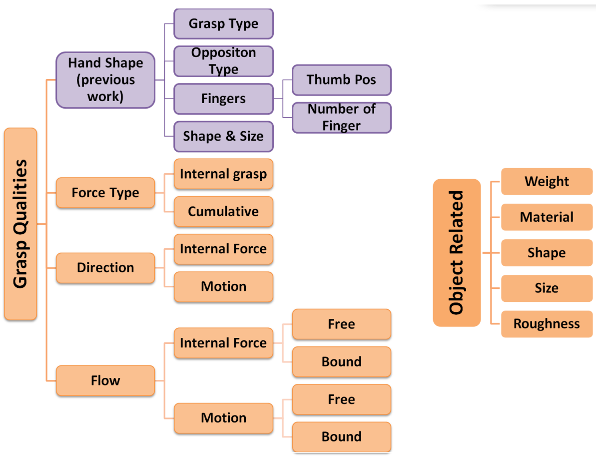


Fig. 1: Simple Classification of the Database

A. *Hand shape*

Our classification of hand shape comes directly from Feix et al. [5], combined with ideas from Napier [32]. For hand shape, we consider: grasp type, opposition type, thumb position, involvement of specific fingers, shape and size of the hand.

Grasp type can be power grip, precision grip, or intermediate. A power grip is usually applied by partly flexed fingers with the palm providing countering pressure, while a precision grip is more of a pinching of the object between fingers.

Opposition type refers to which part of the hand is mostly used, including palm (red in Fig. 2), pad (green), side (blue), and back (Fig. 3).

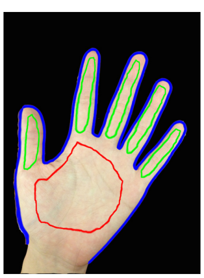


Fig. 2: Palm, pad, side

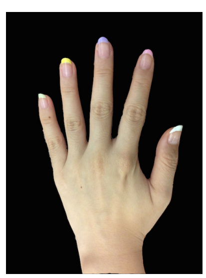


Fig. 3: Back

Thumb position is classified as ABD, ADD, EXT, or FLX (Fig. 4). It is also important to indicate specific fingers (2: index finger, 3: middle finger, 4: fourth finger, 5: little finger) involved in each gesture.

Finally, we express shape (spherical, cylindrical, disk-like, etc.) and size (large, medium, small) of the object being held [32].

B. *Force Type*

There are many different ways in which forces can be distinguished or described: axis direction, magnitude of the force, location of force exertion, and so on. However, we found that describing forces using verbs from the English language made it easier for our subjects to annotate grasping actions and provided a clearer description to other people than the alternatives we investigated. We use 20 verbs to describe these forces (Table I).

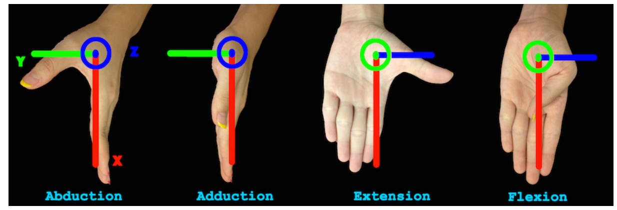


Fig. 4: Local coordinates and thumb positions of the left hand

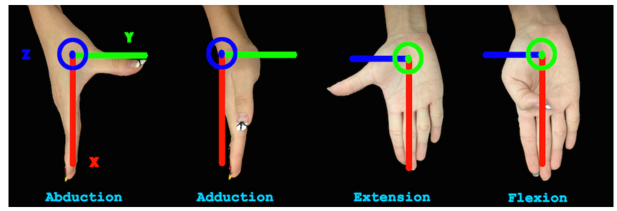


Fig. 5: Local coordinates and thumb positions of the right hand

TABLE I: Force Type Definitions and Frequency

Force Type	Definition	Freq-uency
Break off	Remove a part of an object	3
Extend	Apply outward forces from within the object	3
Grab	Hold or secure without opposing gravity	32
Hold	Grasp object in a way that resists gravity	41
Lever	Pivot one end of an object around a fixed end	4
Lift	Apply upward force greater than gravity	7
Place	Put something in a specified position	1
Press	Exert force in a direction away from the shoulder	31
Pull	Exert force in a direction towards the shoulder	18
Punch	Press or push with a short, quick movement	1
Put in	Insert one object into another	4
Roll	Cause rotation without prehension	3
Rub/Stroke	Move back and forth while pressing	9
Scratch	Rub with something sharp or rough (with the hand directly or a tool)	2
Squeeze	Apply compressive force around object greater than needed to hold object	4
Take out	Remove one object from another	2
Throw	Propel an object through the air	3
Turn	Flip or rifle through pages	1
Twist	Cause rotation with prehension	13
Swing	Move with a smooth, curving motion like hand waving or arm swinging	6

Although we don't make a distinction in our database, it's interesting to note that these force words imply (1) an internal grasp force (exerted by the hand), or (2) a cumulative / external force (exerted by the wrist or whole arm), or (3) both. Table II demonstrates two examples of internal forces (squeezing a tube of toothpaste and grabbing the handle of a pan). Table III shows two examples of cumulative forces: throwing a basketball and pushing down on a door handle. Both tasks involve the internal force of *grabbing* and the cumulative force of *throw* or *press*.

TABLE II: Internal Force Examples

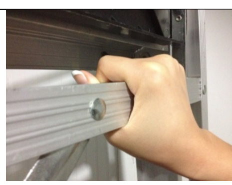
Example		
Force Type	Squeeze	Hold
Annotation	Squeeze toothpaste	Hold a pan

TABLE III: Cumulative Force Examples

Example		
Force Type	Throw	Grab&Press
Annotation	Shoot a basket ball	Press down a door handle

In our database, both force and motion are important. For this reason, *grab* and *hold* are not the same, even though they feature the same motion (i.e. no motion). We define *grab* as touching or securing an object that is resting on a surface. We define *hold* with a gravitational factor, where the hand/arm is applying an upward force to counteract gravity (Table IV).

TABLE IV: Hold & Grab Examples

Example		
Force Type	Grab	Hold
Annotation	Grab the ladder	Hold a laundry detergent

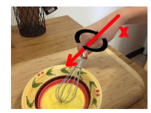
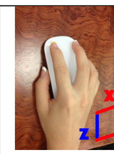
C. Direction

In order to specify the direction of a force or motion, we need to specify the direction subspace and the coordinate frame as shown in Table V. The direction subspace describes a subset of the six-dimensional space within which the motion is occurring. Examples of direction subspaces that we use include: (1) along a linear axis, (2) rotation around an axis, (3) movement within a plane, or (4) inwards/outwards (towards or away from the center of an object). We note that the motion direction can be very different from the force direction. For example, when we zip a zipper, the internal force direction of the hand is *inwards* for the zipper (i.e. grab the zipper tightly), but the direction of motion is *along* the zipper. Similarly, the internal force direction is *inwards* to hold the egg beater but the direction of motion is around the x-axis (Table VI). We use the notation x(45)y to describe movements along an axis that is halfway between the x- and y-axes (e.g., Table XII, second row). Directions that are less constrained or more difficult to describe are captured in freeform text (e.g., ”a cone about the x-axis” or ”various”).

TABLE V: Direction Examples

Property	**Possible Values**	**Example**
Direction Subspace	along x/y/z axis or combination	Table VI 1
	rotate around x/y/z axis	Table VI 2
	plane xy/xz/yz	Table VI 3
Coordinate Frame	hand	Table VII 1
	global	Table VII 2
	object	Table VII 3

TABLE VI: Axes Examples

Example			
Motion Axes	along x/-x (object)	around x axis (hand)	along xz plane (hand)
Force Axes	inward, hold zipper	inward, hold egg beater	against the surface
Annotation	Zip a zipper	Beat with egg beater	Move a mouse

Most of the time, we use the local coordinates of the hand to describe the direction of movement. However, we also sometimes use global coordinates of the world or local coordinates of the object, depending on its degree of usefulness.

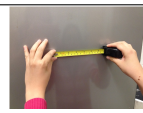
Hand coordinates: The local coordinates of the hand are defined as follows: The direction of four fingers are defined as the x-axis. The y-axis is defined as coming out of the palm in the ventral/palmar direction. The z-axis is defined as the thumb pointing away from the little finger for both hands (Figures 4 and 5). This results in using either the left hand rule for left hand or right hand rule for right hand to compute the z-axis. This unorthodox use of coordinate frames results in symmetrical descriptions of movements and grasps using the two hands. Local coordinates of the hand are mostly used when the motion is along one of the hand coordinate axes. For example, Table VII, first column, shows rubbing the hands along the local x-axis.

Global coordinates: Global coordinates of the world are used when the motion is along the direction of gravity or within a coordinate system that could be fixed to our local environment. For example, when we dribble a basketball, we maneuver the ball within a coordinate frame fixed to the world, not the hand or the ball (Table VII, second column). The direction of gravity is defined as the global z-axis.

Object coordinates: Finally, occasionally the local coordinates of the object must be used since, in some motions, the object shape decides the direction of motion. If the object is a long stick or string type, we define the direction along the stick to be the x-axis. If the object is rectangular in shape, we define the direction along the long side to be the x-axis and the direction along the short side as the z-axis. For example, when we pull out measuring tape, the motion direction is along the tape's long dimension: the x-axis (Table VII, third column).

Many motions or forces can be described naturally in multiple coordinate frames. For example, plugging in a charger could be expressed in the coordinate frame of the charger, the wall, or the hand. We asked our subjects to make the annotations that were most intuitive for them. The important point is that all three coordinate frames are useful, as different actions may have their focus on different frames.

TABLE VII: Coordinate Frame Examples

Example			
Coordinate Frame	Hand	Global	Object
Motion Axes	along x/-x	along z/-z	along x/-x
Annotation	Rub hands	Dribble basketball	Measure with a tape measure

D. Flow

The effort factor we use here is flow. Flow comes from the Laban Effort / Shape notation [33]. It refers to "attitude toward bodily tension and control" and can be *free*, *bound* and *half-bound*. Free refers to the moving direction of the gesture being very casual, while bound refers to the action being very stiff or tightly controlled. The half bound annotation is used when the action is bound along one or more axes and free along the rest. For example, in Table XIII, the flow of motion in dragging toilet paper is half-bound because in the plane that is perpendicular to the axis of the toilet paper, the motion is still free. Our informal observation is that most of the time we specify an action as being free or bound depending on whether the action includes a goal location. For example, if we try to plug in a charger into a wall or stick a key into a key hole, the motion is bound, but if we just throw the key for fun, the action is entirely free (Table VIII).

E. Object related factors

Most grasps depend on the object our hands manipulate, thus object related factors is another important feature in describing hand gestures.

From our observations, weight is an important factor since it affects both internal and cumulative force applied on the object. A simple example is when we hold an empty box or a full box. If the box is empty, we tend to grab the top piece of the box, but if the box is heavy, we would hold from the bottom and lift it up (Table IX).

TABLE VIII: Flow Factor Examples

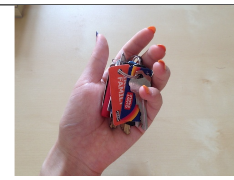
Example		
Flow	Bound Motion/ Bound Force	Free Motion/ Half Bound Force
Annotation	Stick key into key hole	Hold keys

TABLE IX: Weight of Object Examples

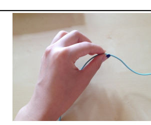
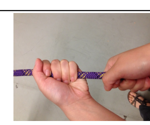
Example		
Object weight	Light	Heavy
Annotation	Grab an empty box	Hold a heavy box

The material of the object also strongly affects grasping strategy. For example, grabbing highly deformable material requires continuous adjustment of grasp shape as the object changes shape. Another example of the effect of material is that people will grab raw meat differently than paper.

The shape and size of the object affects hand shape. We usually pinch a thin wire but grab a thick string, see Table X.

Finally, the friction coefficient of an object determines how hard we grab the object. The thick string in Table X is rougher then the exercise bar, so we would grab the bar harder to prevent our hand from sliding.

TABLE X: Shape & Size & Roughness of Object Examples

Example			
Size	Thin	Thick	Thick
Roughness	Slippery	Rough	Slippery
Annotation	Grab a wire	Grab a rope	Grab exercise bar

V. RESULTS

Our main result can be found on our website [17]. Of all the force types, as shown in Table I (frequency column), *hold* (41), *grab* (32), *press* (31) and *pull* (18) make up the majority of tasks that we observed in our study.

We show two examples from our database here, including all entries for the Large Diameter Grasp and all entries for the Lateral Grasp (Table XI).

A. *Large diameter cylinder*

In a large-diameter grasp (as shown in Table XI), the hand shape is more appropriate for a larger-diameter cylinder-shaped objects using all five fingers. The opposition type is palm, and we use all finger pads. The thumb is clearly abducted.

TABLE XI: Large Diameter and Lateral Grasp

Name	Large Diameter	Lateral
Picture		
Type	Power	Intermediate
Opp.Type	Palm	Side
Thumb Pos	Abd	Add
VF2	2-5	2
Shape	Cylinder/Cuboid	Card piece
Size	Large Diameter	Thin

Our database entries for this grasp are shown in Table XII, and we see that this single entry in the grasp taxonomy contains a variety of different examples. Force types are varied, including *hold*, *grab*, *squeeze*, *press*, and *twist*. Even with the same force type, other annotations can differ. For example, as shown in Table XII (top), the action of *drink water* involves motion around the y-axis, while holding a bottle does not involve any motion. The flow can vary even within the same task. As shown in Table XII (bottom), the motion of squeezing a towel is free, but the internal force of grabbing the towel is bound.

B. *Lateral*

In a lateral grasp (as shown in Table XI), the hand shape is more suitable for a thin card-shaped object by using only the thumb and index finger. The opposition type is side, and the pad of the thumb is used, too. The thumb is clearly adducted.

For some very similar tasks, the direction and flow can be different. As shown in Table XIII first row, the flow of motion in putting on gloves and dragging toilet paper are different. Putting on gloves is bound since the direction of motion is set along the arm. But dragging toilet paper is half-bound.

The two tasks in Table XIII second row appear almost identical, but the direction of motion is different in terms of hand coordinates. Twisting the key happens around y-axis, and twisting the knob happens around z-axis.

Some motions are in the same direction but with different force types as shown in Table XIII third row. They are both in the xy-plane but since the force types are different, the flow is different.

C. *New Types*

From our observations, the cumulative taxonomy in [5] has covered most types of grasps. However, there exist some hand shapes which are not represented by their taxonomy. As mentioned in the object related section, some grasps involving deformable objects are captured in our database. And some very specific gestures such as opening a soda can and tying shoes are also listed in our database. Overall, there are 40 new types. We illustrate 8 of them in Table XIV. All classifications and annotations can be found in our database [17].

TABLE XII: Large Diameter Cylinder Grasp Examples

Example		
Force Type	Hold	Hold
Motion Dir	around y axis (hand)	-
Force Dir	-	-z (global)
Flow	Free Motion/ Bound Force	Bound Force
Annotation	Drink water	Hold a bottle
Example		
Force Type	Hold	Grab&Press
Motion Dir	x(45)y (hand)	-
Force Dir	-	z (global)
Flow	Free Motion/ Half Bound Force	Bound Force
Annotation	Throw paper	Grab cabbage
Example		
Force Type	Squeeze	Twist
Motion Dir	-	around z axis (hand)
Force Dir	inwards (hand)	inwards (hand)
Flow	Bound Force	Free Motion/ Bound Force
Annotation	Squeeze an empty soda bottle	Squeeze towel to dry

TABLE XIII: Lateral Grasp Examples

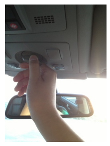
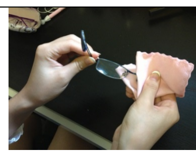
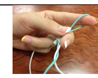
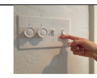
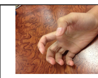
Example		
Force Type	Pull	Pull
Motion Dir	-x (hand)	xz plane (hand)
Force Dir	-	-
Flow	Bound Motion/ Bound Force	Half Bound Motion/ Bound Force
Annotation	Put on gloves(along the arm)	Drag toilet paper
Example		
Force Type	Twist	Twist
Motion Dir	around y axis (hand)	around x axis (hand)
Force Dir	-	-
Flow	Bound Motion	Bound Motion
Annotation	Twist the key to start up the car	Twist the knob in car
Example		
Force Type	Hold	Rub/Stroke
Motion Dir	xy plane (hand)	xy plane (hand)
Force Dir	-	inwards (hand)
Flow	Free Motion/ Half Bound Force	Half Bound Motion/ Bound Force
Annotation	Give card to someone	Wipe classes
Example		
Force Type	Hold	Hold
Motion Dir	z (global)/ -z (global)/ around x axis (hand)	around x axis (hand)
Force Dir	-	-
Flow	Free Motion/ Bound Force	Half Bound Motion/ Bound Force
Annotation	Eat with scoop	Pour washing powder

TABLE XIV: New Type Examples

Example				
Annotation	Tie	Shuffle cards	Lift up the switch	Scratch
Example				
Annotation	Press perfume bottle	Open soda bottle	Use screwdriver	Use pliers

Some, but not all of the new grasp types can be found in other taxonomies, such as [20] and [4].

VI. DISCUSSION

Effective grasp taxonomies capture not only hand shape, but also the nature of contact between the hand and object. The best in this regard is perhaps the Kamakura taxonomy [2], which illustrates in great detail regions on the hand that come in contact with the object. The patterns and extent of these regions reveals much, especially when considering grasp control and robot hand design.

However, we find annotating only shape and contact to be insufficient to convey important differences between everyday actions; in part because this set of actions is more broad than grasping, but also because many grasps that may look similar from a snapshot involve very different uses of the hand to accomplish a task.

We find that to communicate these differences, we need to express the type of force, directional information, and stiffness information for the action.

It is interesting to note the similarities between our annotations and the parameters required for impedance control [15] or operational space control [16], where one expresses a task in terms of the desired impedance or motion/force/stiffness properties of the manipulator. It is possible that alternative annotation schemes could be developed that fall even more closely in line with these control approaches. However, through extensive trial and error, we found that the annotation scheme we suggest supports clear communication between people as well as ease of labeling examples. It certainly seems possible that these annotations can be used to inform robot control approaches or be incorporated into a demonstration and coaching framework. Demonstrating these connections is left as future research.

One limitation of this database is that we need a more accurate system for describing the direction of motion and force that takes into account that the direction might not be perfectly aligned onto a single axis.

We can also ask whether all entries in our database are relevant for humanoid robots. We believe that as robot become more pervasive, especially in the home and in health care and rehabilitation scenarios, a large majority of the grasps depicted here will become of interest. However, we did not attempt to make this distinction in order to have a more inclusive and comprehensive database.

It may be possible to organize this database from a different point of view, such as making the force types or motion types the central classification rather than grasp type. We chose grasp type as the first level of organization in order to be consistent with existing taxonomies. However, it is interesting to consider whether a different organization may lead to a simpler or more intuitive way of describing these results.

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REFERENCES

[1] C. L. MacKenzie and T. Iberall, *The grasping hand*. Elsevier, 1994, vol. 104.

[2] N. Kamakura, M. Matsuo, H. Ishii, F. Mitsuboshi, and Y. Miura, "Patterns of static prehension in normal hands," *The American Journal of Occupational Therapy: Official Publication of the American Occupational Therapy Association*, vol. 34, no. 7, pp. 437–445, 1980.

[3] M. R. Cutkosky, "On grasp choice, grasp models, and the design of hands for manufacturing tasks," *IEEE International Conference on Robotics and Automation (ICRA), 1989*, vol. 5, no. 3, pp. 269–279, 1989.

[4] D. J. B. S. J. Edwards and J. D. McCoy-Powlen, "Developmental and functional hand grasps," Oct 2002.

[5] T. Feix, R. Pawlik, H. Schmiedmayer, J. Romero, and D. Kragic, "A comprehensive grasp taxonomy," in *Robotics, Science and Systems: Workshop on Understanding the Human Hand for Advancing Robotic Manipulation*, June 2009. [Online]. Available: http://grasp.xief.net

[6] S. Ekvall and D. Kragic, "Grasp recognition for programming by demonstration," in *IEEE International Conference on Robotics and Automation (ICRA), 2005*. IEEE, 2005, pp. 748–753.

[7] G. Heumer, H. Ben Amor, M. Weber, and B. Jung, "Grasp recognition with uncalibrated data gloves-a comparison of classification methods," in *Virtual Reality Conference, 2007. VR'07. IEEE*. IEEE, 2007, pp. 19–26.

[8] A. M. Dollar and R. D. Howe, "The highly adaptive SDM hand: Design and performance evaluation," *The International Journal of Robotics Research*, vol. 29, no. 5, pp. 585–597, 2010.

[9] S. B. Kang and K. Ikeuchi, "Toward automatic robot instruction from perception-mapping human grasps to manipulator grasps," *IEEE International Conference on Robotics and Automation (ICRA), 1997*, vol. 13, no. 1, pp. 81–95, 1997.

[10] R. Wimmer, "Grasp sensing for human-computer interaction," in *Proceedings of the Fifth International Conference on Tangible, Embedded, and Embodied Interaction*. ACM, 2011, pp. 221–228.

[11] K. M. Lynch, "Toppling manipulation," in *IEEE International Conference on Robotics and Automation (ICRA), 1999*, 1999, pp. 2551–2557.

[12] K. Hauser, V. Ng-Thow-Hing, and H. Gonzalez-Baños, "Multi-modal motion planning for a humanoid robot manipulation task," in *Robotics Research*. Springer, 2011, pp. 307–317.

[13] M. T. Mason, "Mechanics and planning of manipulator pushing operations," *The International Journal of Robotics Research*, vol. 5, no. 3, pp. 53–71, 1986.

[14] E. Yoshida, M. Poirier, J.-P. Laumond, O. Kanoun, F. Lamiraux, R. Alami, and K. Yokoi, "Pivoting based manipulation by a humanoid robot," *Autonomous Robots*, vol. 28, no. 1, pp. 77–88, 2010.

[15] N. Hogan, "Impedance control: An approach to manipulation: Part iiimplementation," *Journal of Dynamic Systems, Measurement, and Control*, vol. 107, no. 1, pp. 8–16, 1985.

[16] O. Khatib, "A unified approach for motion and force control of robot manipulators: The operational space formulation," *IEEE International Conference on Robotics and Automation (ICRA), 1987*, vol. 3, no. 1, pp. 43–53, 1987.

[17] J. Liu, F. Feng, Y. Nakamura, and N. Pollard, "A taxonomy of everyday grasps in action," June 2014. [Online]. Available: http://www.cs.cmu.edu/~jialiu1/database.html

[18] I. G. Schlesinger, "Der mechanische aufbau der künstlichen glieder," in *Ersatzglieder und Arbeitshilfen*. Springer, 1919, pp. 321–661.

[19] J. R. Napier and R. Tuttle, *Hands*. Princeton University Press, 1993.

[20] I. A. Kapandji and L. H. Honoré, *The physiology of the joints: annotated diagrams of the mechanics of the human joints*. E. & S. Livingstone London, 1970, vol. 1, no. 2.

[21] J. Z. Zheng, S. De La Rosa, and A. M. Dollar, "An investigation of grasp type and frequency in daily household and machine shop tasks," in *IEEE International Conference on Robotics and Automation (ICRA), 2011*. IEEE, 2011, pp. 4169–4175.

[22] L. Y. Chang and N. S. Pollard, "Video survey of pre-grasp interactions in natural hand activities," June 2009.

[23] F. Worgotter, E. E. Aksoy, N. Kruger, J. Piater, A. Ude, and M. Tamosiunaite, "A simple ontology of manipulation actions based on hand-object relations," *Autonomous Mental Development, IEEE Transactions on*, vol. 5, no. 2, pp. 117–134, 2013.

[24] J. M. Elliott and K. Connolly, "A classification of manipulative hand movements," *Developmental Medicine & Child Neurology*, vol. 26, no. 3, pp. 283–296, 1984.

[25] I. M. Bullock, R. R. Ma, and A. M. Dollar, "A hand-centric classification of human and robot dexterous manipulation," *Haptics, IEEE Transactions on*, vol. 6, no. 2, pp. 129–144, 2013.

[26] T. Torigoe, "Comparison of object manipulation among 74 species of non-human primates," *Primates*, vol. 26, no. 2, pp. 182–194, 1985.

[27] B. Kopp, A. Kunkel, H. Flor, T. Platz, U. Rose, K.-H. Mauritz, K. Gresser, K. L. McCulloch, and E. Taub, "The Arm Motor Ability Test: reliability, validity, and sensitivity to change of an instrument for assessing disabilities in activities of daily living," *Archives of Physical Medicine and Rehabilitation*, vol. 78, no. 6, pp. 615–620, 1997.

[28] C. Collin, D. Wade, S. Davies, and V. Horne, "The Barthel ADL Index: a reliability study," *Disability & Rehabilitation*, vol. 10, no. 2, pp. 61–63, 1988.

[29] J. M. Linacre, A. W. Heinemann, B. D. Wright, C. V. Granger, and B. B. Hamilton, "The structure and stability of the functional independence measure," *Archives of Physical Medicine and Rehabilitation*, vol. 75, no. 2, pp. 127–132, 1994.

[30] N. Pollock, M. McColl, A. Carswell, and T. Sumsion, "The Canadian occupational performance measure," *Client-centred Practice in Occupational Therapy: A Guide to Implementation*, pp. 103–114, 2006.

[31] Y. S. Choi, T. Deyle, T. Chen, J. D. Glass, and C. C. Kemp, "A list of household objects for robotic retrieval prioritized by people with ALS," in *Rehabilitation Robotics, 2009. ICORR 2009. IEEE International Conference on*. IEEE, 2009, pp. 510–517.

[32] J. R. Napier, "The prehensile movements of the human hand," *Journal of Bone and Joint Surgery*, vol. 38, no. 4, pp. 902–913, 1956.

[33] A.-A. Samadani, S. Burton, R. Gorbet, and D. Kulic, "Laban effort and shape analysis of affective hand and arm movements," in *Affective Computing and Intelligent Interaction (ACII), 2013 Humaine Association Conference on*. IEEE, 2013, pp. 343–348.