Annotating 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? In a study to classify all actions during a typical day, we found that single entries in an existing grasp taxonomy were insufficient, apparently capturing not one grasp, but many. When we investigated, we found that these seemingly different grasps could be distinguished by features related to the grasp in action, such as the intended motion, force, and stiffness. In collaboration with our subjects, we developed an annotation scheme for untrained annotators to use, which captured the differences we observed between grasping actions. This chapter describes our annotation scheme. We discuss parallels to and differences from Laban Movement Analysis, which has been long developed to capture motion and action, but does not focus on grasping. We also discuss parallels to impedance or operational space control, with the goal of moving from annotations to actionable robot control.

1 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,[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 locations of contact between hand and object, which determine how the hand and object can interact.[2]

A number of taxonomies with hand shape and object contact as central elements have been developed to classify grasps.[2–5] 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 interaction with grasp sensitive objects.[10] These taxonomies also allow researchers to communicate grasp differences, distinguishing power from precision grasps, tripod vs. pinch, spherical vs. cylindrical, etc.

With the goal of moving toward robots that can more dexterously manipulate everyday objects in human environments, we ask to what extent our existing grasp taxonomies capture the actions we do in everyday life. 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 aspects of force, motion, and stiffness. Table 12 shows an example. Our goal was to communicate motion, force, and stiffness information as precisely as possible while still allowing individuals with light training to understand and classify grasps or communicate differences to a robot.

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 have intriguing similarities to aspects of dance notation such as Laban Movement Analysis.[11] They also may tie into existing impedance[12] and operational space controllers[13] used in robotics.

We report our complete process and findings below. The complete classification can be viewed in our online database.[14] A short version of this paper has previously appeared elsewhere.[15]

2 RELATED WORK

Perhaps the earliest well known grasp taxonomies are those of Schlesinger[16] and Napier,[17] which led the way in discriminating major hand shapes and grasp functions. Grasp taxonomies have been developed for tasks of everyday living, including those of Kapandji,[18] 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.

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[19] 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," and identify 33 grasp types that are distinct from one another and fit this definition. Because it was developed with the goal of being inclusive, we selected this taxonomy as a starting place in our experiments. However, the grasp definition of Feix et al.[5] does exclude a variety of movements, bimanual tasks, gravity dependent grasps, and flat hand grasps that we found important, and we include these additional types in our own taxonomy.

A number of taxonomies have been developed to express manipulation actions as well. Chang and Pollard[20] 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[21] 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[22] 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.[23] 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[24] 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 of classifying manipulation actions using action verbs is useful for distinguishing between different force intentions for grasps having the same grasp taxonomy label and adopt it as extra information in our taxonomy.

3 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.[25–28] 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.,[29] 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 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.[25] 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 an existing 33-grasp database.[5] When we encountered hand gestures that were not in the basic database, we added them to the database.

Our final database contains 73 database categories, of which 50 are grasp types, 4 are press types, 10 are grasp and press type, 2 are extend types and 7 are other hand types. We also illustrate where each movement may be used in daily life with corresponding pictures.[14]

4 DATABASE ANNOTATIONS

Fig. 1 shows the classification we have developed in order to distinguish the different 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 an existing grasp taxonomy[5] and realized that actions belonging to one grasp type within the taxonomy often involved very different motion, force, or flow.

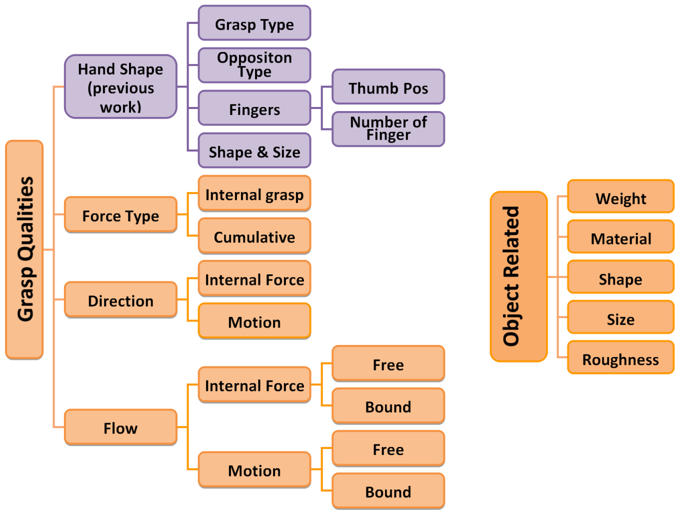


Fig. 1 Simple Classification of the Database

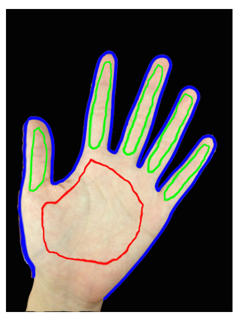


Fig. 2 Palm, pad, side

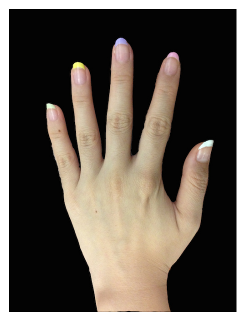


Fig. 3 Back

4.1 Hand shape

Our classification of hand shape comes directly from Feix et al.,[5] combined with ideas from Napier.[30] For hand shape, we consider: grasp type, opposition type, thumb position, involvement of specific fingers, and prototypical object shape and size.

Grasp type can be power grip, precision grip, or intermediate. A power grip is typically 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, which allows freedom to sense or create internal motions of the object within the hand.

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).

Thumb position is classified as abduction (ABD), adduction (ADD), extension (EXT), or flexion (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.

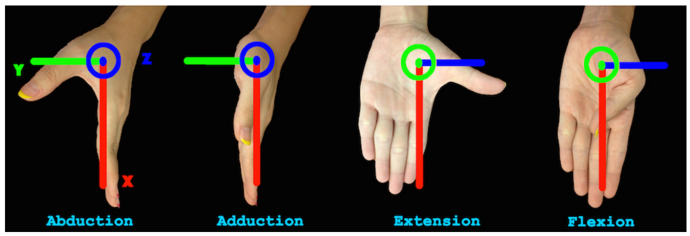


Fig. 4 Local coordinates and thumb positions of the left hand

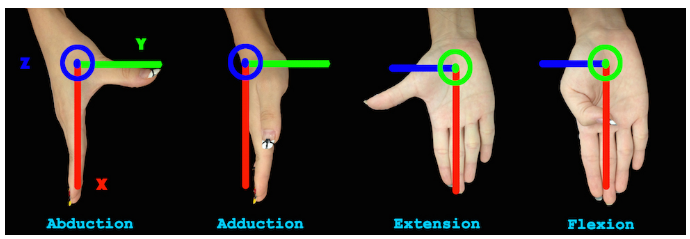


Fig. 5 Local coordinates and thumb positions of the right hand

Finally, we express shape (spherical, cylindrical, disk-like, etc.) and size (large, medium, small) of the object being held.[30]

4.2 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 the forces observed in our study (Table 1).

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 (e.g. *squeeze*, Table 2), or (2) a cumulative / external force exerted by the wrist or whole arm (e.g. *throw*, Table 3), or (3) both (e.g., *grab* a door handle and *press* to open, Table 3).

Table 1 Force Type Definitions and Frequency

Force Type	Definition	Frequency
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
Swing	Move with a smooth, curving motion like hand waving or arm swinging	6
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

Table 2 Internal Force Examples

Example		
Force Type	Squeeze	Hold
Annotation	Squeeze toothpaste	Hold a pan

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 4).

Table 3 Cumulative Force Examples

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

Table 4 Hold & Grab Examples

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

4.3 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 5. 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 6). 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 12, 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").

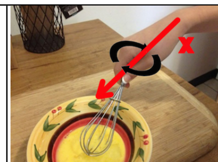
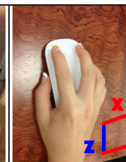
Most of the time, we use the local coordinates of the hand to describe the direction of movement. However, we also sometimes use global coordinates of the world or local coordinates of the object, depending on its degree of usefulness.

Hand coordinates: The local coordinates of the hand are defined as follows: The direction of the four fingers is 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

Table 5 Direction Examples

Property	**Possible Values**	**Example**
Direction Subspace	along x/y/z axis or combination	Table 6 1
	rotate around x/y/z axis	Table 6 2
	plane xy/xz/yz	Table 6 3
Coordinate Frame	hand	Table 7 1
	global	Table 7 2
	object	Table 7 3

Table 6 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

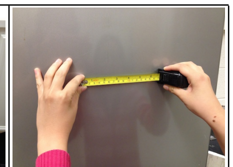
the thumb pointing away from the little finger for both hands (Figures 4 and 5). This results in using either the left hand rule for left hand or right hand rule for right hand to compute the z-axis. This unorthodox use of coordinate frames results in symmetrical descriptions of movements and grasps 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 7, 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 7, 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 7, 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 focus on different frames of reference.

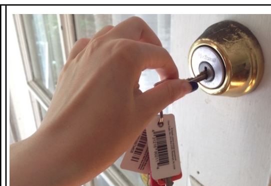
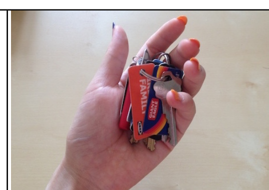
Table 7 Coordinate Frame Examples

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

4.4 Flow

The effort factor we use here is flow. Flow comes from the Laban Effort / Shape notation.[31] 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 14, 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 lock, the motion is bound, but if we just throw the key for fun, the action is entirely free (Table 8).

Table 8 Flow Factor Examples

Example		
Flow	Bound Motion/ Bound Force	Free Motion/ Half Bound Force
Annotation	Stick a key in the door lock	Hold keys

4.5 Object related factors

Most grasps depend on the object our hands manipulate, thus object related factors are also important features for 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 9).

Table 9 Weight of Object Examples

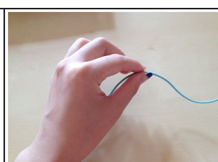
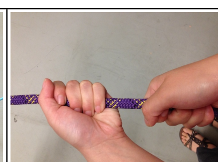
Example		
Object weight	Light	Heavy
Annotation	Grab an empty box	Hold a heavy box

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 10.

Finally, the friction coefficient of an object determines how hard we grab the object. The thick string in Table 10 is rougher then the exercise bar, which will affect the force needed to prevent slipping in both cases.

Table 10 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

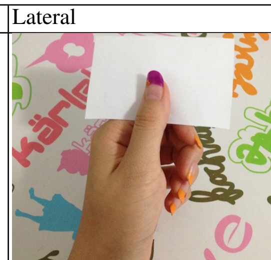
5 RESULTS

Our main result is an annotated database of grasping actions observed in our study. The database contains 73 grasp types, including the 33 types enumerated in Feix et al.,[5] along with 40 additional types. Each of these 73 types includes one or more annotated examples. Examples are annotated with force type, motion direction, force direction, and flow to more fully describe the grasp in action. Each of the 179 total examples differs from the others by at least one annotation.

One additional result listed here is a count of force types, which can be found in Table 1 (frequency column). In this table, we can see, for example, that *hold* (41), *grab* (32), *press* (31) and *pull* (18) make up the majority of tasks that we observed in our study.

The full database can be found on our website.[14] In this Chapter, we describe two of the 73 grasp type entries (Sections 5.1 and 5.2) as well as listing some of the new grasp types (Section 5.3).

Table 11 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

5.1 Large diameter cylinder

The first grasp type we examine is the large diameter cylinder grasp. In a large-diameter grasp (Table 11, Left), the hand shape is appropriate for a larger-diameter cylinder-shaped object, and all five fingers are used. The opposition type is palm. The thumb is abducted.

Our entire database entry for this grasp is shown in Table 12, 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 12 (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 12 (bottom), the motion of squeezing a towel is free, but the force is bound.

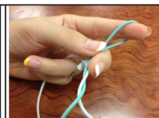
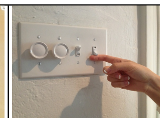
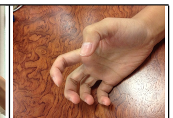
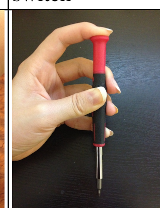
Table 12 Large Diameter Cylinder Grasp Examples

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

5.2 Lateral

The second grasp type we review is the lateral grasp. As shown in Table 11, Right, in the lateral grasp, the hand shape is more suitable for a thin card-shaped object, which is pinched between the thumb and index finger. The opposition type is side, and the pad of the thumb is used. The thumb is adducted.

Table 13 New Type Examples

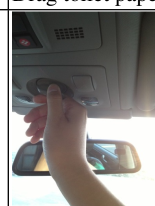
Example				
Annotation	Tie	Shuffle cards	Lift up the switch	Scratch
Example				
Annotation	Press perfume bottle	Open soda bottle	Use screwdriver	Use pliers

For some very similar tasks, the direction and flow can be different. As shown in Table 14 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 14 second row appear almost identical, but the direction of motion is different in terms of hand coordinates. Twisting the key happens around y-axis of the hand (the axis out of the palm), and twisting the knob happens around the x-axis of the hand (the direction aligning with the forearm).

Some motions are in the same direction but with different force types and flow as shown in Table 14 third row. In this case, the force based interactions are both in the xy-plane of the hand (or equivalently the object), but one example has free motion while gently holding the grasped object and the other has motion relative to the object that is constrained to maintain forceful contact for cleaning. These differences are reflected in the differing annotations.

Table 14 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 glasses
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 spoon	Pour washing powder

5.3 New Types

From our observations, the existing taxonomy that served as our starting point[5] has covered many types of grasps. However, there exist some actions which are not represented by their taxonomy, for which we have created new categories in the database. Some of the new entries involve deformable objects. Some are very specific gestures such as opening a soda can and tying shoes. Overall, we have added 40 new categories. We illustrate 8 of them in Table 13. All classifications and annotations can be found in our database.[14] Some, but not all of the new grasp types can be found in other taxonomies, such as those of Kapandji[18] and Buckland et al.[4]

6 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 intentions – 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[12] or operational space control,[13] where one expresses a task in terms of the desired impedance or motion/force/stiffness properties of the manipulator. Annotations such as those we propose here could form the starting point for a learning-from-demonstration or coaching system where the user indicates to the robot coordinate frames and directions best suited for position control and force control, along with indications of the level of force or stiffness required for the task. In particular, we found the use of English language verbs very promising for conveying the type of force desired in a way that was intuitive for our subjects, and the use of multiple coordinate frames (hand, object, and world) make it easier to specify axes along which motion and force should be emphasized or constrained. It is of great interest to us to explore mechanisms for translating such annotations into robot controllers and allowing users to provide feedback to adjust those controllers in a language that is natural to them.

The similarities between our classification scheme and Laban Movement Analysis (LMA)[11] are also intriguing and invite further exploration. Perhaps we may consider the static grasps of the conventional taxonomies as Shape Forms – static shapes that the hand may take while grasping an object. Annotation mechanisms within the category of Space may capture our intent when annotating motion and force directions, where we consider natural coordinate frames and landmarks that serve to orient the action. Annotation mechanisms within the category of Effort were motivating to us when considering how to discriminate between grasps. Although we did not make direct use of the Action Effort verbs (Float, Punch, Glide, Slash, Dab, Wring, Flick, and Press), many of them are represented in our force list of Table 1. In addition, we attempted to directly adopt the Effort category of Flow to allow users to discriminate between stiff and tightly controlled vs. free or flowing intent. We are interested to explore further how theory and practical experience from LMA may allow us to create more precise and comprehensive annotations.

Although there are similarities between our annotation scheme and LMA categories, there are also differences. For example, although our verb list is similar to the Action Effort verbs, there are verbs in our list that may fit one or more Action Effort verbs depending on how the action is performed. For example, in our database subjects used “Press” for forcefully supporting a cabbage for cutting and also for lightly pressing a small button, which may correspond to different Action Effort verbs such as “Press” and “Dab.” In addition, there are items in our verb list that do not correspond well to the Action Effort verbs, such as “Put In” and “Take Out.” The largest conceptual difference seems to be that our subjects considered verbs in our list to express *what* the hand was doing, as opposed to *how* the action was performed. Given this conceptual difference, it is interesting to see the level of similarity we do see in the two sets of verbs.

We also found that we needed to give our lightly trained users a great variety of verbs as options to specify force intent. We have listed 20 such verbs in Table 1 and have no doubt that a more extensive survey of everyday actions will require adding others. Intent of an action as it affects function and appearance of grasping appears to be challenging to capture and communicate in a manner that can discriminate between actions that are evidently different to both the performer and the observer.

One limitation of this database is that we need a more accurate system for describing the direction of motion and force that accommodates directions that do not perfectly align with an easily identifiable single axis. However, interestingly, this situation appears to be uncommon.

We can also ask whether all entries in our database are relevant for humanoid robots. We believe that as robots become more pervasive, especially in home, 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.

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. Christine L MacKenzie and Thea Iberall. *The grasping hand*, volume 104 of *Advances in Psychology*. Elsevier, 1994.
2. Noriko Kamakura, Michiko Matsuo, Harumi Ishii, Fumiko Mitsuboshi, and Yoriko Miura. Patterns of static prehension in normal hands. *The American Journal of Occupational Therapy: Official Publication of the American Occupational Therapy Association*, 34(7):437–445, 1980.
3. Mark R Cutkosky. On grasp choice, grasp models, and the design of hands for manufacturing tasks. *IEEE International Conference on Robotics and Automation (ICRA), 1989*, 5(3):269–279, 1989.
4. D. J. Buckland S. J. Edwards and J. D. McCoy-Powlen. *Developmental and Functional Hand Grasps*. Slack Incorporated, first edition, 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.
6. Staffan Ekvall and Danica Kragic. Grasp recognition for programming by demonstration. In *IEEE International Conference on Robotics and Automation (ICRA), 2005*, pages 748–753. IEEE, 2005.
7. Guido Heumer, H Ben Amor, Matthias Weber, and Bernhard Jung. Grasp recognition with uncalibrated data gloves-a comparison of classification methods. In *Virtual Reality Conference, 2007. VR'07. IEEE*, pages 19–26. IEEE, 2007.
8. Aaron M Dollar and Robert D Howe. The highly adaptive SDM hand: Design and performance evaluation. *The International Journal of Robotics Research*, 29(5):585–597, 2010.
9. Sing Bing Kang and Katsushi Ikeuchi. Toward automatic robot instruction from perception-mapping human grasps to manipulator grasps. *IEEE International Conference on Robotics and Automation (ICRA), 1997*, 13(1):81–95, 1997.
10. Raphael Wimmer. Grasp sensing for human-computer interaction. In *Proceedings of the Fifth International Conference on Tangible, Embedded, and Embodied Interaction*, pages 221–228. ACM, 2011.
11. Jean Newlove and John Dalby. *Laban for all*. Routledge, 2003.
12. Neville Hogan. Impedance control: An approach to manipulation: Part III: Implementation. *Journal of Dynamic Systems, Measurement, and Control*, 107(1):8–16, 1985.
13. Oussama 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*, 3(1):43–53, 1987.
14. Jia Liu, Fangxiaoyu Feng, Yuzuko Nakamura, and Nancy Pollard. Grasp taxonomy in action online database: http://graphics.cs.cmu.edu/nsp/projects/graspDatabase/database.html, 2014.
15. Jia Liu, Fangxiaoyu Feng, Yuzuko Nakamura, and Nancy Pollard. A taxonomy of everyday grasps in action. In *IEEE International Conference on Humanoid Robots (Humanoids 2014)*, November 2014.
16. Ing G Schlesinger. Der mechanische aufbau der künstlichen glieder. In *Ersatzglieder und Arbeitshilfen*, pages 321–661. Springer, 1919.
17. John Russell Napier and Russell Tuttle. *Hands*. Princeton University Press, 1993.
18. Ibrahim Adalbert Kapandji and Louis Henri Honoré. *The physiology of the joints: annotated diagrams of the mechanics of the human joints*, volume 1. E. & S. Livingstone London, 1970.
19. Joshua Z Zheng, Sara De La Rosa, and Aaron 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*, pages 4169–4175. IEEE, 2011.
20. Lillian Y Chang and Nancy S Pollard. Video survey of pre-grasp interactions in natural hand activities. In *Robotics: Science and Systems (RSS) 2009 Workshop on Understanding the Human Hand for Advancing Robotic Manipulation*, June 2009.
21. Florentin Worgotter, Eren Erdal Aksoy, Norbert Kruger, Justus Piater, Ales Ude, and Minija Tamosiunaite. A simple ontology of manipulation actions based on hand-object relations. *Autonomous Mental Development, IEEE Transactions on*, 5(2):117–134, 2013.

22. John M Elliott and KJ Connolly. A classification of manipulative hand movements. *Developmental Medicine & Child Neurology*, 26(3):283–296, 1984.
23. Ian M Bullock, Raymond R Ma, and Aaron M Dollar. A hand-centric classification of human and robot dexterous manipulation. *Haptics, IEEE Transactions on*, 6(2):129–144, 2013.
24. Takashi Torigoe. Comparison of object manipulation among 74 species of non-human primates. *Primates*, 26(2):182–194, 1985.
25. Bruno Kopp, Annett Kunkel, Herta Flor, Thomas Platz, Ulrike Rose, Karl-Heinz Mauritz, Klaus Gresser, Karen L McCulloch, and Edward 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*, 78(6):615–620, 1997.
26. C Collin, DT Wade, S Davies, and V Horne. The Barthel ADL Index: a reliability study. *Disability & Rehabilitation*, 10(2):61–63, 1988.
27. John Michael Linacre, Allen W Heinemann, Benjamin D Wright, Carl V Granger, and Byron B Hamilton. The structure and stability of the functional independence measure. *Archives of Physical Medicine and Rehabilitation*, 75(2):127–132, 1994.
28. N Pollock, MA McColl, A Carswell, and T Sumsion. The Canadian occupational performance measure. *Client-centred Practice in Occupational Therapy: A Guide to Implementation*, pages 103–114, 2006.
29. Young Sang Choi, Travis Deyle, Tiffany Chen, Jonathan D Glass, and Charles 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*, pages 510–517. IEEE, 2009.
30. John R Napier. The prehensile movements of the human hand. *Journal of Bone and Joint Surgery*, 38(4):902–913, 1956.
31. Ali-Akbar Samadani, Sarahjane Burton, Rob Gorbet, and Dana Kulic. Laban effort and shape analysis of affective hand and arm movements. In *Affective Computing and Intelligent Interaction (ACII), 2013 Humaine Association Conference on*, pages 343–348. IEEE, 2013.