# Evaluation of Dexterous Manipulation “In the Wild”

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I will talk about not only grasping, but also manipulation
“In the Wild” has to do with everyday performance of real-world tasks

I first heard Matt Mason use the expression “in the wild” for watching what people are actually doing with their hands .. made him think of observing gorillas and cataloging their behavior

# Underactuated and soft hands?


Many of my observations will relate to how we use our own hands

Relating this to the theme of the workshop, I want to point out that although the human hand is not especially underactuated, it is soft due to a variety of effects

- What **grasp quality metrics** should be used for benchmarking robot hands?
- What **taxonomies** should be used for benchmarking robot hands?
- A very toy example of optimizing to a manipulation benchmark

With that as context, I'll give my thoughts on two main topics of the workshop, and conclude with a short, very toy example of optimizing to a benchmark that focuses on manipulation

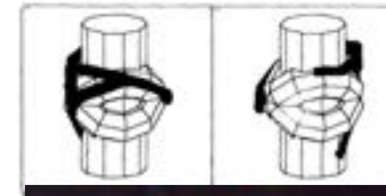
- What **grasp quality metrics** should be used for benchmarking robot hands?
- What **taxonomies** should be used for benchmarking robot hands?
- A very toy example of optimizing to a manipulation benchmark

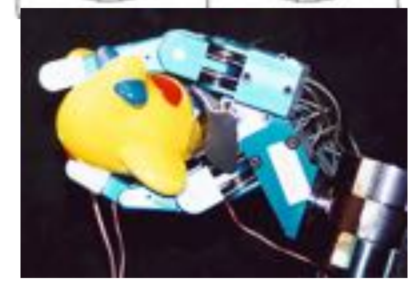
Grasp Quality Point of View #1:

Kinematic and force capabilities are necessary conditions for a good grasp

The first point of view we can look at is that the ability to apply forces to accomplish the grasp, or whatever task we need to do with the object is a necessary condition.

- (A) Measure grasp quality based on what the hand **must do**.
    - Does there exist a grasp of this object with this hand that can accomplish the task?





max wrench that can be applied to object in direction of task wrench $i$

$$Q = \min_i \frac{\|w_{i,max}\|}{\|t_i\|}, i = 1, ..., t$$

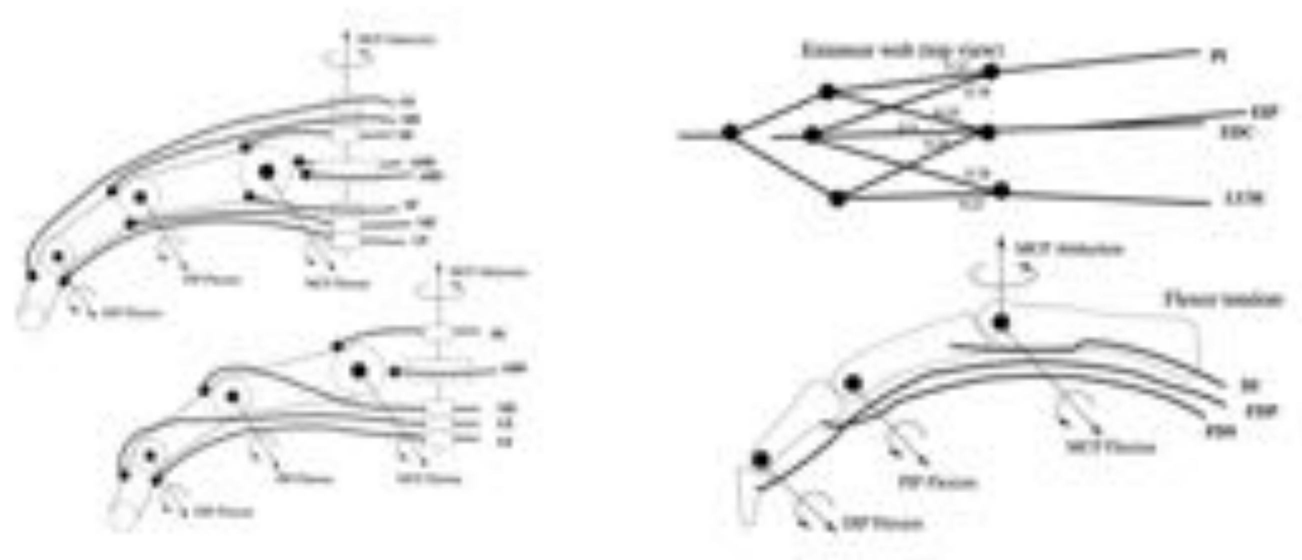
task wrench $i$


N. S. Pollard, 1994. Parallel Methods for Synthesizing Whole-Hand Grasps from Generalized Prototypes, MIT Artificial Intelligence Laboratory Technical Report AI-TR 1464.

Y. Li, J. L. Fu, and N. S. Pollard, 2007. Data Driven Grasp Synthesis using Shape Matching and Task-Based Pruning, IEEE Transactions on Visualization and Computer Graphics, 13(4), 732--747, July/August 2007.


This is where I started many years ago
We have to get the hand around the object and apply force to it, so let's start with that ..
Define the task and give a quality metric related to that task
Here is one force and torque based metric
By the way, I agree with Domenico that a stiffness based analysis is really the way to go for these types of grasps.   If you begin to add compliant elements to the hand, it is really the only thing that makes sense.

- (B) Compare designs based on what the hands **can do**.
    - Which hand / finger has greater force capabilities?



N. S. Pollard and R. C. Gilbert, 2002. Tendon Arrangement and Muscle Force Requirements for Humanlike Force Capabilities in a Robotic Finger, Proceedings of the IEEE International Conference on Robotics and Automation, Washington, D.C., May 2002.

Besides measuring ability to accomplish a task, we can simply measure and compare what the hands can do, e.g., in terms of applying forces

We have used this idea, for example, to compare tendon arrangements of human vs. different robot finger designs

## Grasp Quality Point of View #1:

## Kinematic and force capabilities are necessary conditions for a good grasp

- (A) Measure grasp quality based on what the hand **must do**.
- (B) Compare designs based on what the hands **can do**.

So .. we can measure quality based on what the hand must do and compare based on what it can do

Of course force is not the whole story .. depending on the task we may care about force, motion, stiffness, …

Grasp Quality POV #2:
Quality depends on the grasping process

The second point of view is that grasp quality is not just about forces and task needs, but depends on the entire process of acquiring the object

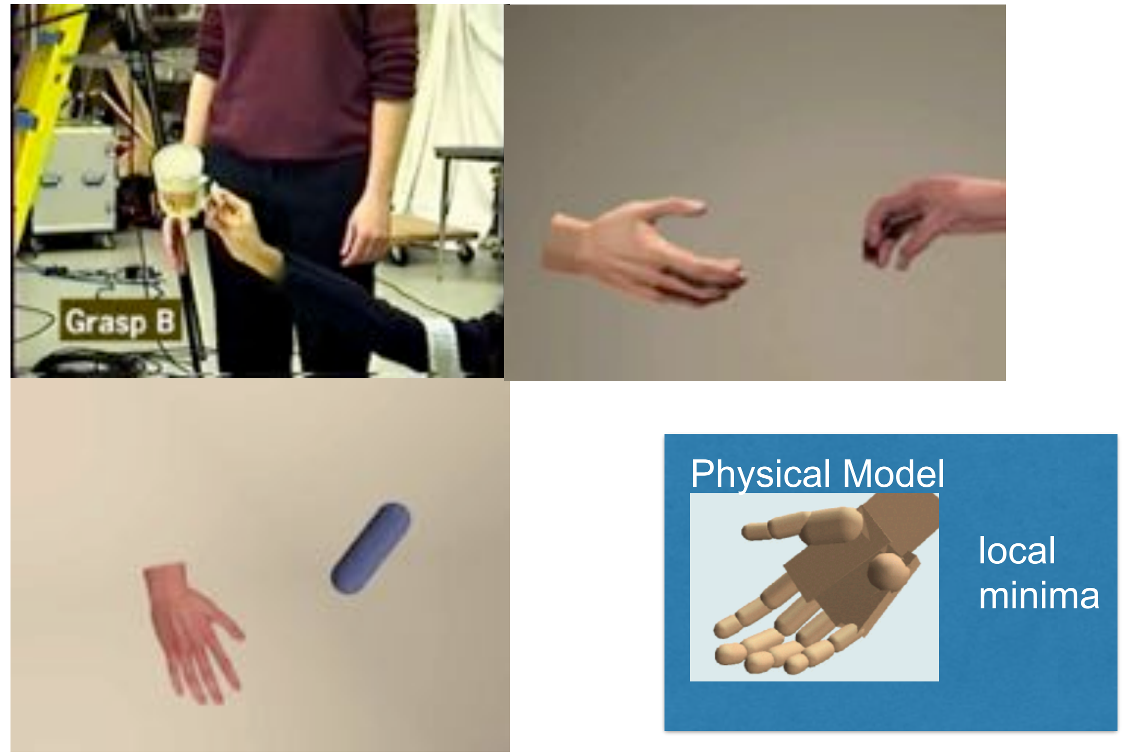
# Grasp Quality POV #2:
# Quality depends on the grasping process


N. S. Pollard and Victor B. Zordan, 2005. Physically Based Grasping Control from Example, ACM SIGGRAPH / Eurographics Symposium on Computer Animation, Los Angeles, CA, pp 311-318, 2005.

As an example of what I mean, 10 or 12 years ago, we were acquiring and simulating grasps for computer graphics purposes.

From a motion capture sequence, we would build a controller with one parameter (roughly how hard the hand would “squeeze” the object) and test that controller in simulation with multiple objects

We did not get good results until we added the thenar and hypothenar eminences to our physical model




N. S. Pollard and Victor B. Zordan, 2005. Physically Based Grasping Control from Example, ACM SIGGRAPH / Eurographics Symposium on Computer Animation, Los Angeles, CA, pp 311-318, 2005.

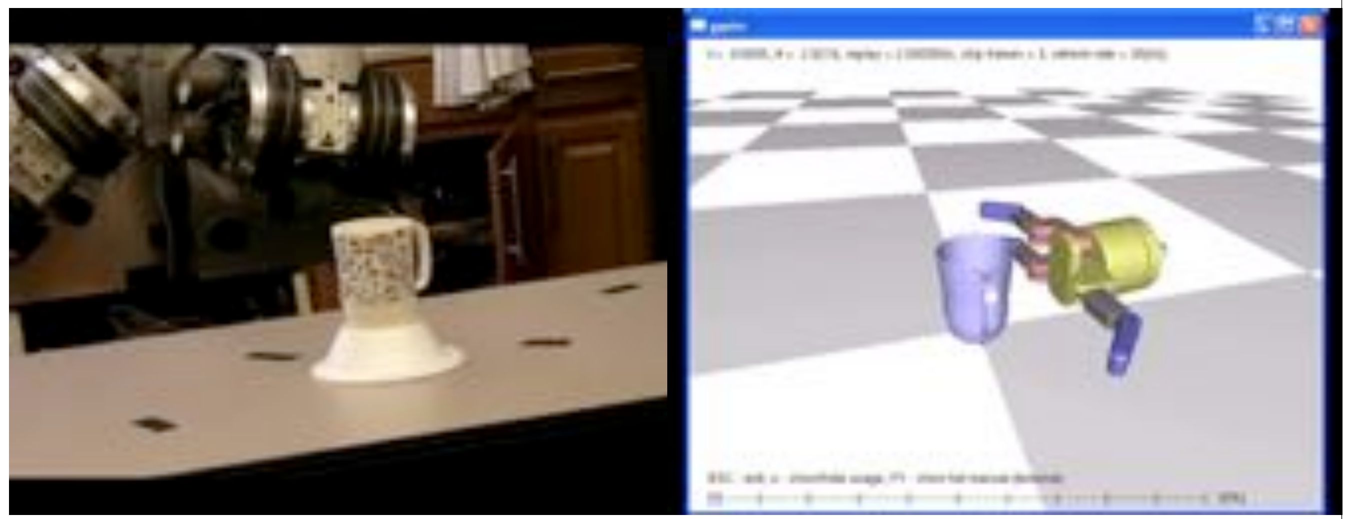
While our original simulated physical hand model could apply relevant forces, the object was frequently slipping from the grasp.

New physical model -> improved results

Splitting the palm and adding thenar and hypothenar eminances resulted in a better hand

Maybe this is obvious, but this kind of palm shape is not a universal feature in hands today .. a benchmarking setup that rewards robustness to grasp failures could perhaps encourage something like this

# Grasp Quality POV #2:
# Quality depends on the grasping process



J. Kim, K. Iwamoto, J. J. Kuffner, Y. Ota, and N. S. Pollard, 2013. Physically-based Grasp Quality Evaluation under Pose Uncertainty, IEEE Transactions on Robotics, 29(6), 1424--1439, December 2013.

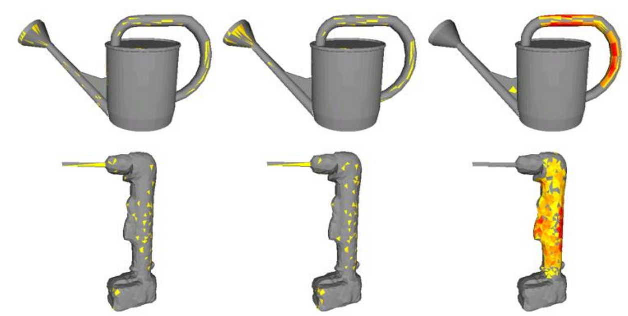


Here is a second example with a robotics application in mind

Here, we were testing grasps defined as a preshape and closing strategy vs. their likelihood of success in the presence of uncertainty

- Top 30 grasps


- Top 30 grasps (accumulated finger/hand prints)




Top grasps considering dynamics and uncertainty were more successful in realistic situations

J. Kim, K. Iwamoto, J. J. Kuffner, Y. Ota, and N. S. Pollard, 2013. Physically-based Grasp Quality Evaluation under Pose Uncertainty, IEEE Transactions on Robotics, 29(6), 1424--1439, December 2013.



Using this setup, we were able to show that our simulation environment was adequate for evaluating potential grasps

When we include uncertainty and dynamics in our simulations, the “good” grasp choices appear much better than when we do not

By the way, I think Ravi’s notion of low skew in human grasps could potentially be explained by the need to handle dynamics and uncertainty robustly.   It’s worth checking out

# Experiments
## (for measuring actual grasp success rates)

- Five objects used
- 10 grasps tested for each object
- Actual grasp success rates measured from experiments
  - 10 trials for each grasp
  - Grasp quality scores measured manually
    - (0, 0.5, 1) using visual inspection
    - (0, 0.25, 0.5, 0.75, 1) using interactive inspection

scoring

J. Kim, K. Iwamoto, J. J. Kuffner, Y. Ota, and N. S. Pollard, 2013. Physically-based Grasp Quality Evaluation under Pose Uncertainty, IEEE Transactions on Robotics, 29(6), 1424--1439, December 2013.

Here is our experimental setup ..

Our success test was very simple, involving two people poking and prodding the object to see how secure the grasp was and rating it from 0 to 1.

Simulation results were very well correlated with our experiments for this type of grasping situation.

# Grasp Quality POV #2:
# Quality depends on the grasping process

- Hand surface geometry matters
- We must consider the dynamics of the grasping process
- We must consider uncertainty

So .. hand surface geometry matters, dynamics matter, uncertainty matters, and we can take these things into consideration by evaluating success of the entire grasping process

Grasp Quality POV #3:
Quality depends on the use of sensors

Third, let me talk a little bit about sensors, because all of the previous examples I have shown, even though they involve grasping processes, those processes are essentially open loop.    They require no sensing, other than to find the object well enough to initiate the grasp.

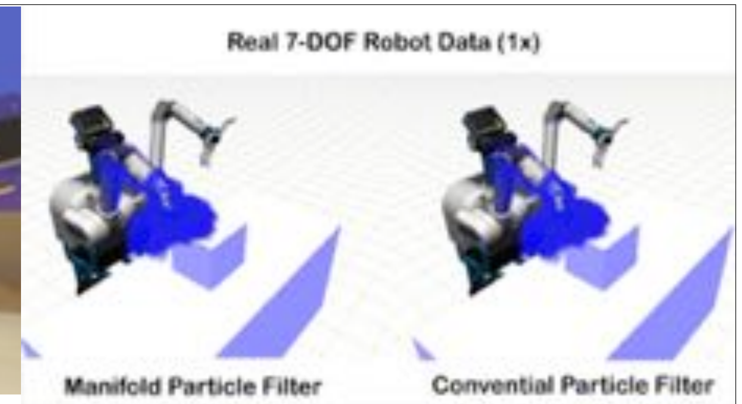
What I've shown you so far is very much like trying to snatching things out of the air

# Grasp Quality POV #3:
# Quality depends on the use of sensors


But people don’t just snatch things out of the air
We seem to make frequent use of touches and adjust our grasping process based on information gained from those touches

We may make a touch with our hands and then adjust our grasp ..  or otherwise make changes to the task that is underway

This video is 1/4 speed




J. A. Bagnell, F. Cavalcanti, L. Cui, T. Galluzzo, M. Hebert, M. Kazemi, M. Klingensmith, J. Libby, T. Liu, N. S. Pollard, M. Pivtoraiko, J.-S. Valois, and R. Zhu, 2012. An Integrated System for Autonomous Robotics Manipulation, IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2955-2962, October, 2012

M. Klingensmith, M.C Koval, S.S. Srinivasa, N.S. Pollard, and M. Kaess. "State estimation on high-dimensional implicit contact manifolds." arXiv: 1604.07224, 2016.

M.C. Koval, D. Hsu, N.S. Pollard, and S.S. Srinivasa. "Configuration lattices for planar contact manipulation under uncertainty." WAFR 2016.

Here are some examples of work we have done to gather information using touch.

So, we have to consider how a hand design is "better" if it can increase success rate by clever use of sensors and information gathering.

- Points of View regarding Grasp Quality:
  - Kinematic and force capabilities are necessary conditions for a good grasp (but not sufficient)
  - Quality depends on the grasping process
  - Quality depends on the use of sensors

For “grasping in the wild,” we want real-world tasks that include uncertainty

We should be designing hands and control algorithms together.

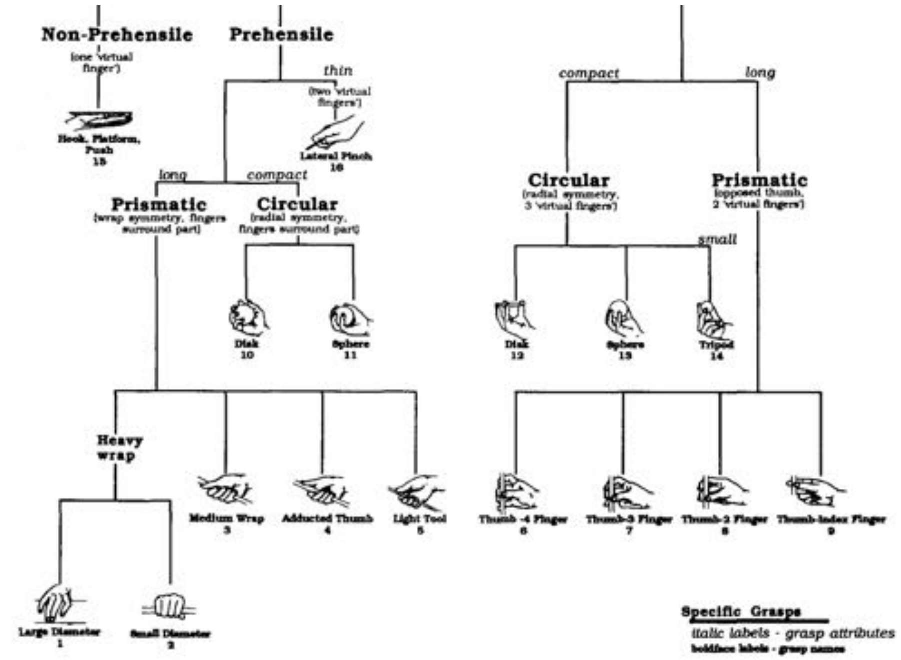
A bit of a summary so far …

kinematic and force capabilities necessary but not sufficient
the grasping process matters, dynamics matter, uncertainty matters

we should be designing hands and control algorithms together and evaluating hands and control algorithms together .. once we get past the basic tests, i think it’s hard to separate these things

- What **grasp quality metrics** should be used for benchmarking robot hands?
- What **taxonomies** should be used for benchmarking robot hands?
- A very toy example of optimizing to a manipulation benchmark

# Cutkosky Taxonomy




Cutkosky, Mark R. "On grasp choice, grasp models, and the design of hands for manufacturing tasks." Robotics and Automation, IEEE Transactions on 5.3 (1989): 269-279.

The Cutkosky taxonomy may still be the most widely cited one in robotics

# Kamakura Taxonomy


Kamakura, Noriko, et al. "Patterns of static prehension in normal hands." American Journal of Occupational Therapy 34.7 (1980): 437-445.



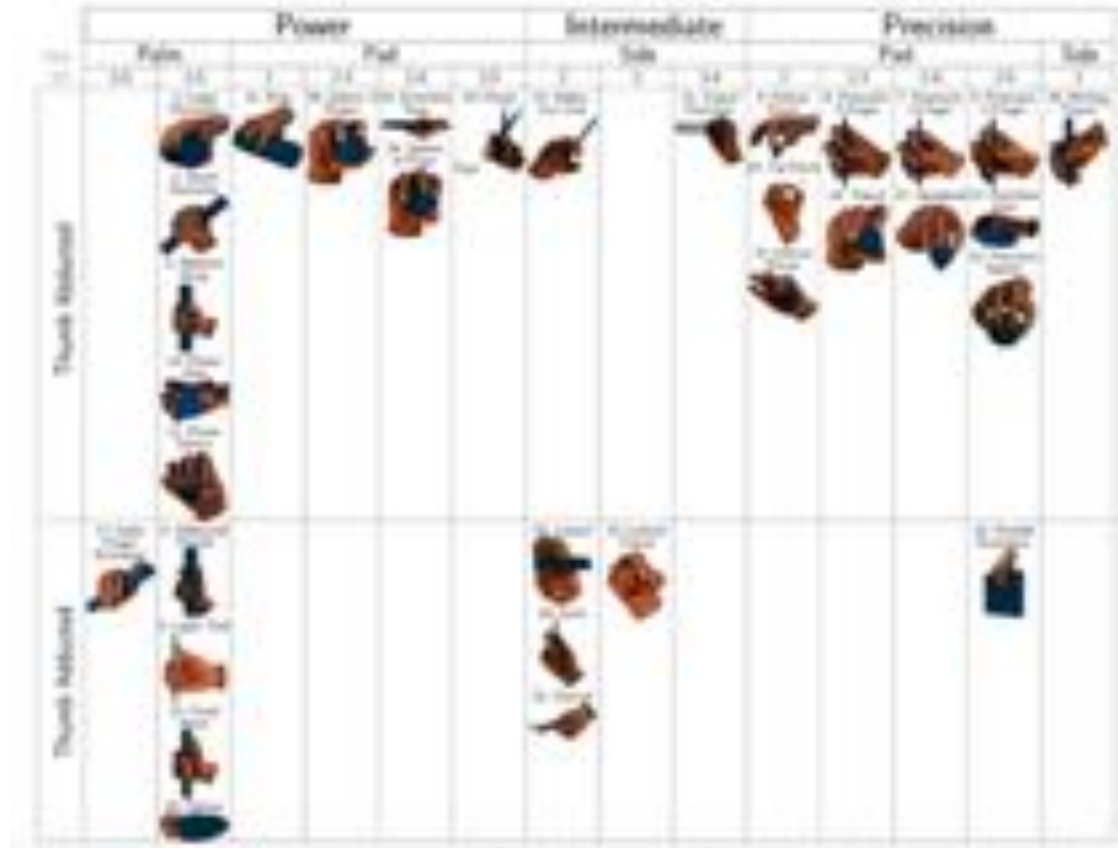
I like this one, because of its portrayal of contact regions

# Feix et al. Cumulative Taxonomy

Feix, Thomas, et al. "A comprehensive grasp taxonomy." Robotics, Science and Systems: Workshop on Understanding the Human Hand for Advancing Robotic Manipulation. 2009.

The Feix et al. cumulative taxonomy does the nice service of bringing many references together and has gained a lot of attention

# Feix et al. Cumulative Taxonomy




And the 33 grasps in this taxonomy seem like a nice starting point for thinking about grasp type

# 1 Day, Two Subjects, Grasps from Feix et al.

J. Liu, F. Feng, Y. Nakamura, and N. S. Pollard, 2014. A Taxonomy of Everyday Grasps in Action, IEEE International Conference on Humanoid Robots (Humanoids 2014), Madrid, Spain, November 2014.

http://www.cs.cmu.edu/~jialiu1/database.html

With the goal in mind of testing this taxonomy "in the wild" we did a study where two subjects attempted to document all of their grasps in a day

They found all 33 grasps from Feix et al.

# 1 Day, Two Subjects, “Grasps” NOT in Feix et al.

J. Liu, F. Feng, Y. Nakamura, and N. S. Pollard, 2014. A Taxonomy of Everyday Grasps in Action, IEEE International Conference on Humanoid Robots (Humanoids 2014), Madrid, Spain, November 2014.

http://www.cs.cmu.edu/~jialiu1/database.html

They also found many more ….

- 173 observed grasps, almost every one of which is annotated differently
- How many grasps do we need — thousands?   tens of thousands?   a million?



In fact, if you look at the details (which they did), almost every observed grasp had some difference from all the others, in observable shape, the user's intent, the needs of the task, etc..

If we were to continue this process how many grasps might we need?

# All these grasps .. can we organize them better?

So … maybe we can organize these grasps in a better way

Taxonomy POV #1:
There are six basic types of grasp based on hand shape

I think .. if we look at hand shape, I see six different grasp types in the Feix et al. taxonomy

# Considering hand shape: Six types of human grasps


Here they are.
Differences within each group come from object geometry and adjustments to better perform the intended task

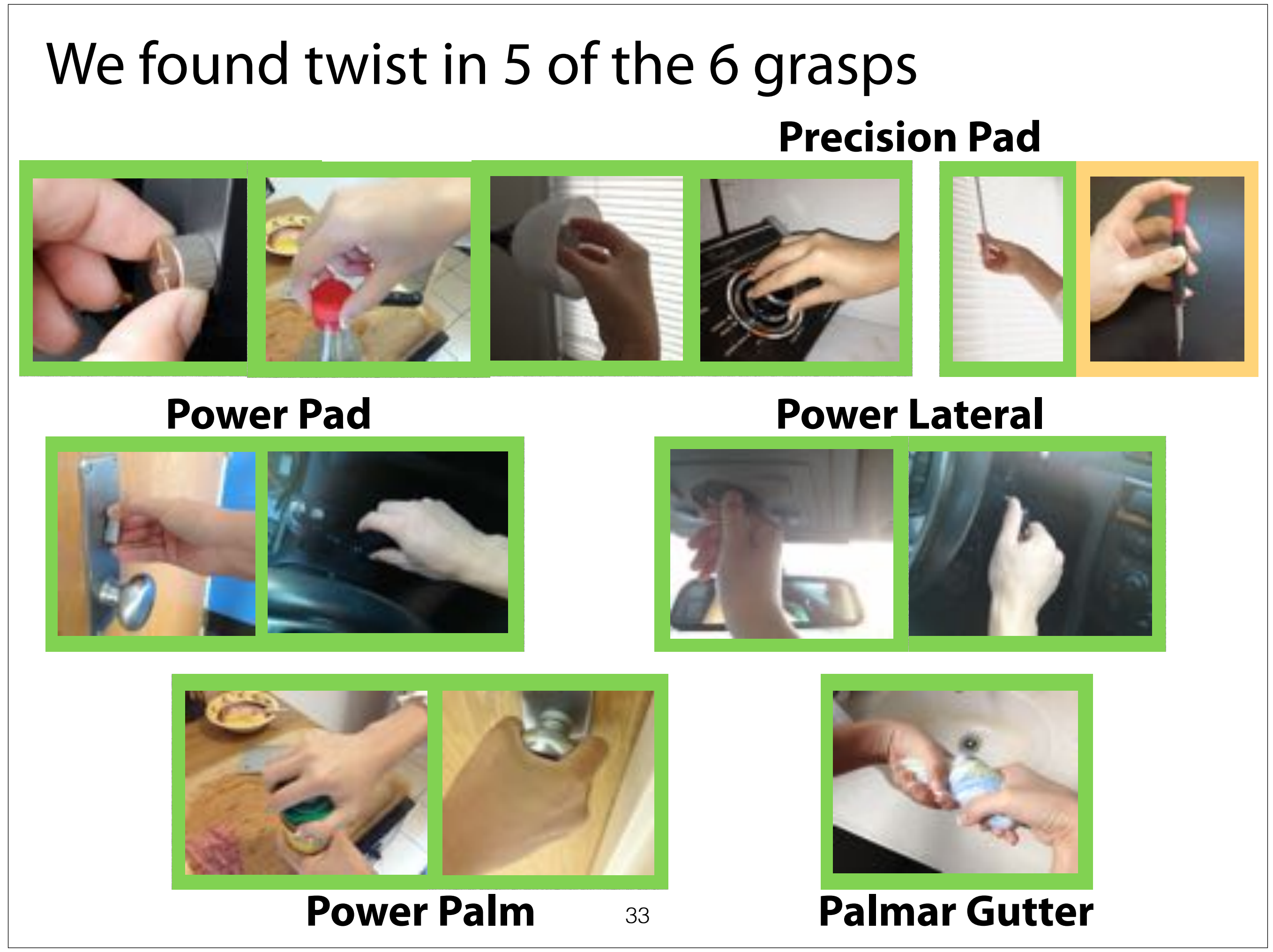
Taxonomy POV #2:
A two-level taxonomy may have a
second tier consisting of verb/task/action

But hand shape is not really enough. If I were to add a second tier to this taxonomy, I would base it on the intended action

## People prefer expressing intentions as verbs
## 20 Verbs for 173 Observed Grasps

| 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 |
| Take out | Remove one object from another | 2 |
| Throw | Propel an object through the air | 3 |
| Turn | Flip or riffle through pages | 1 |
| Twist | Cause rotation with prehension | 13 |
| Swing | Move with a smooth, curving motion like hand waving or arm swinging | 6 |

We found that people preferred to express intended action as verbs .. here are the ones we needed for our 173 grasps




Here is an example of one of the verbs, “twist.”

We found twist motions performed with 5 of the 6 hand shapes.

# Which grasp types are used for which actions?

| | Power Palmar | Power Other Palm | Power Lateral | Precision Lateral | Power Pad | Precision Pad |
|---|---|---|---|---|---|---|
| Hold | 10 | 3 | 4 | 2 | 5 | 6 |
| Grab | 10 | 8 | 2 | 1 | 3 | 1 |
| Pull | 6 | 4 | 2 | | 1 | 1 |
| Twist | 1 | 1 | 2 | | 2 | 6 |
| Pinch | 2 | | 2 | 1 | | 3 |
| Swing | 3 | 1 | | | | 1 |
| Lift | | 3 | | | | 1 |
| Press | 2 | 1 | | | 1 | |
| Put In | 1 | 1 | | | | 2 |
| Rub/Stroke | 2 | | 1 | | | 1 |
| Break Off | | 1 | | | 1 | 1 |
| Lever | 1 | 1 | | | | |
| Squeeze | 1 | | | | 1 | |
| Throw | | | 2 | | | |
| Extend | | | | | | 1 |
| Take Out | | | | | | 1 |
| Turn | | | | | 1 | |



Of course, hand shape X verb may not be a dense matrix.    Here is what we found.

If we have non-anthropomorphic hands, by the way, we may care less about hand shape and would just make use of the verbs and choose objects of different sizes and tasks with different force requirements

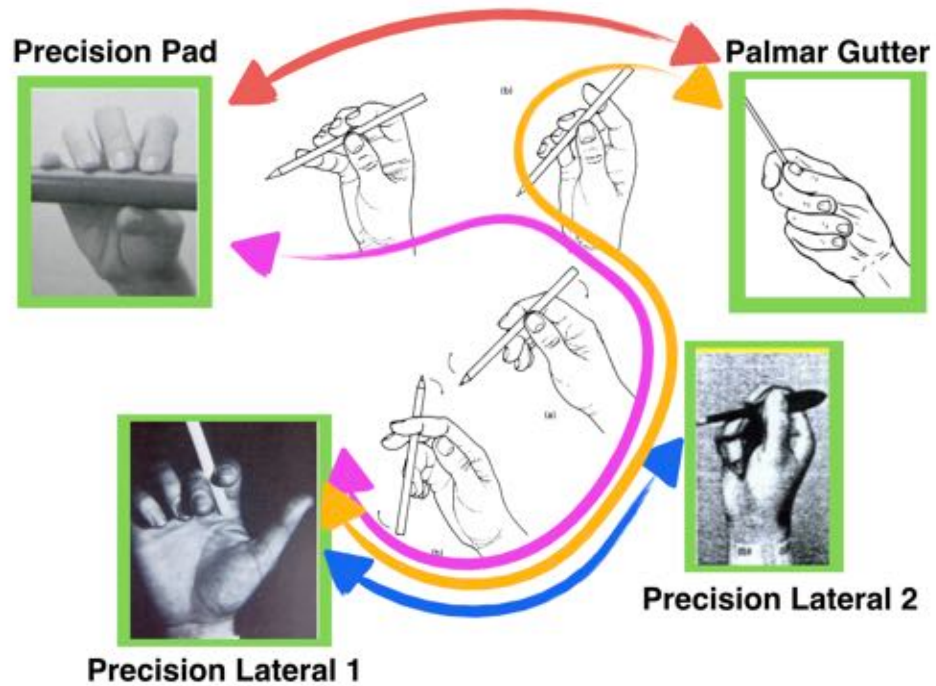
Taxonomy POV #3:
In-hand manipulations are used to acquire objects into a grasp and shift between grasps

Beyond hand shape and action, we have to consider how we are going to get the object into the hand and out of the hand and maneuver between different grasps if necessary

This video gives some great examples .. watch what he does

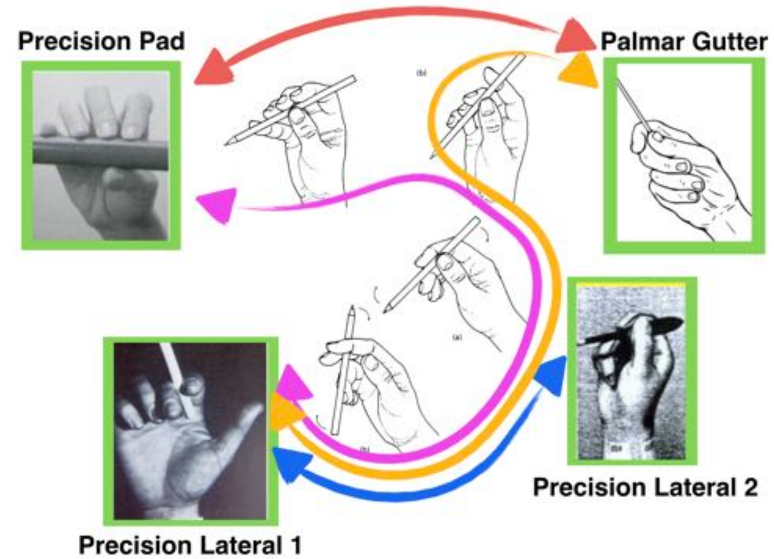
Lift wrench into the hand to use it, flip it over, flip to the other usable side, put it down, pick up another to read the label … tuck it into the hand to use the fingertips, get it out and use the wrench again …

# Here are transitions between several different grasp types




Pen twiddling sketch from Elliott and Connelly 1984

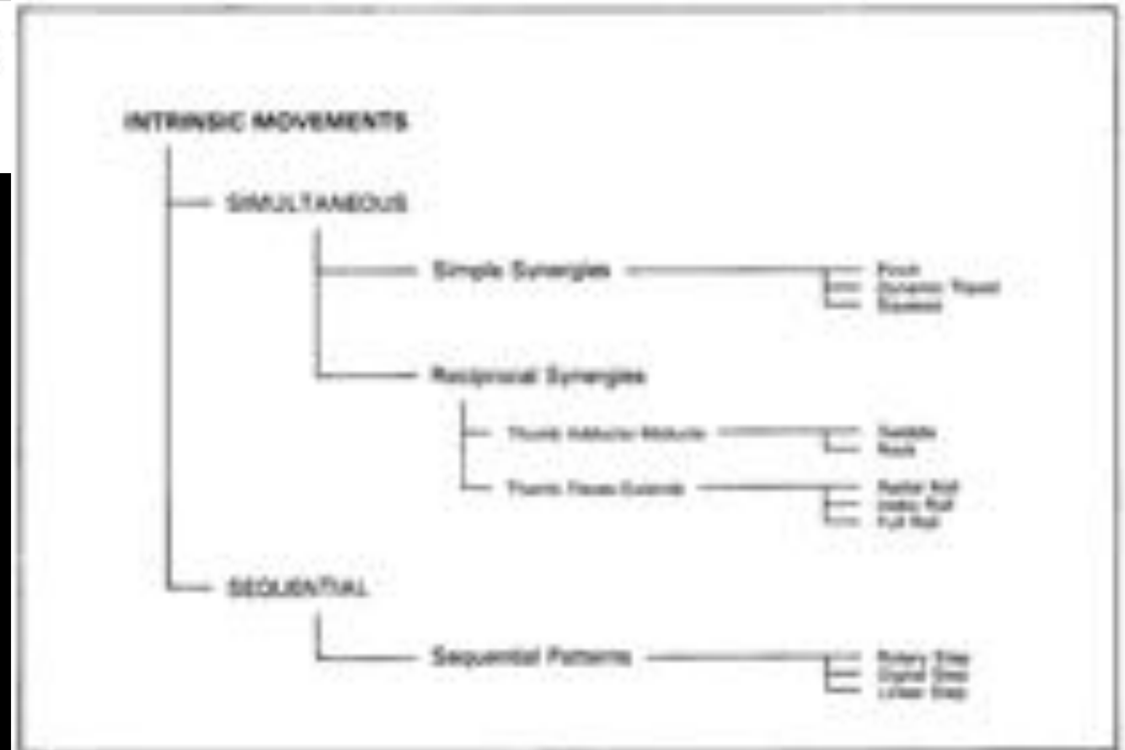
Ok, maybe we're not ready to benchmark bike repair yet, but here's a small example of moving between some different grasp types




An eight year old can do transitions like this with ease

# A CLASSIFICATION OF MANIPULATIVE HAND MOVEMENTS

*J. M. Elliott*
*K. J. Connolly*




There is one categorization of intrinsic manipulations that I especially like, and I want to bring your attention to it

# Simple Synergies

Pinch

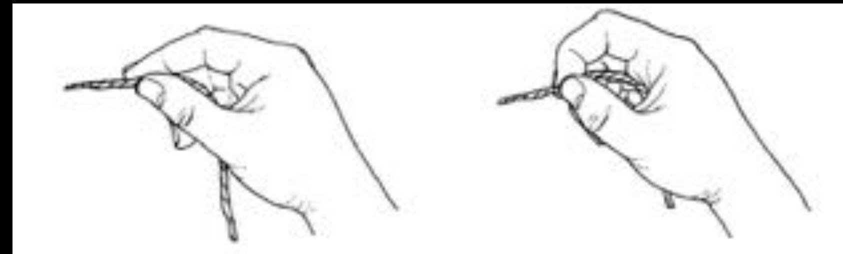


*Fig. 4.* Pinch: (a) thumb and index extended, (b) thumb and index flexed. These represent terminal positions for digits when executing this pattern of movement.

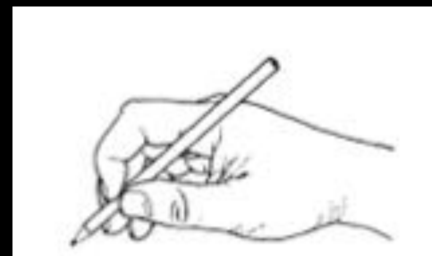


*Fig. 5.* Dynamic tripod: small, simultaneous flexion and extension movements of thumb, index and digit 3 manipulate pen.

Dynamic Tripod

*Fig. 6.* Squeeze: precise configuration of fingers is determined by shape of syringe. Simultaneous flexion of thumb, index and digit 3 will drive plunger into barrel.

Squeeze

Here are some examples of the movements they consider

# Reciprocal Synergies
# Thumb Abducts/Adducts

Fig. 7. Twiddle: (a) thumb in full abduction, (b) thumb in partial adduction, with concurrent index flexion. Extent of thumb adduction is quite variable, depending on extent of movement required in alternating between postures illustrated.

Twiddle

Rock

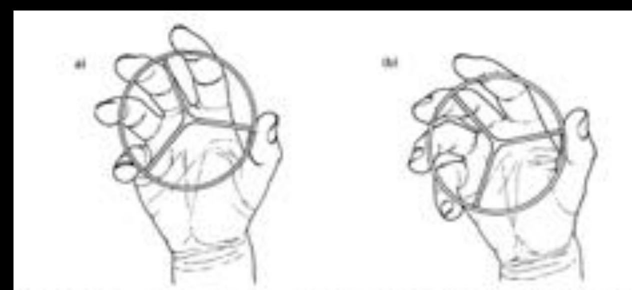


Fig. 8. Rock: illustrated in ventral view with a petri dish. (a) Thumb in partial abduction, (b) thumb in partial adduction.

Rock

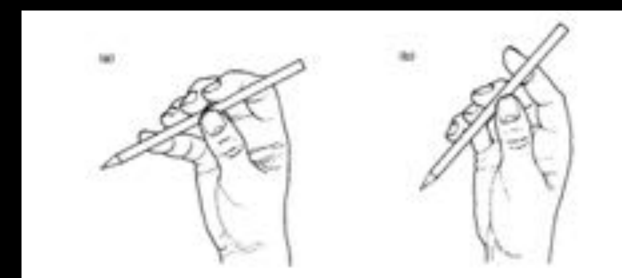


Fig. 9. Rock: illustrated with pencil held transversely, in radio-ulnar axis. Movements of thumb and digit 3 are much reduced compared with movements of other digits. (a) Ulnar digits relatively extended, (b) ulnar digits relatively flexed.

# Reciprocal Synergies
# Thumb Flexes/Extends

Radial Roll

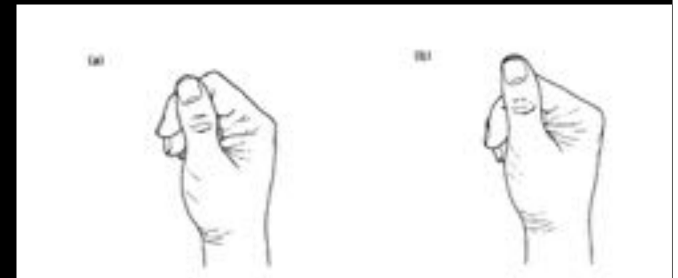
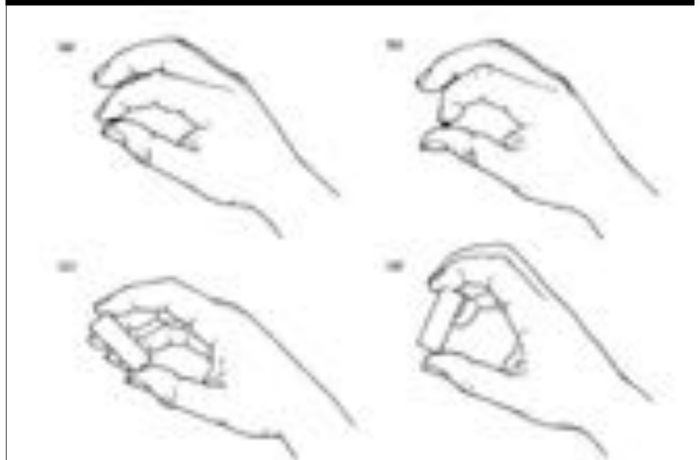


Fig. 10. Radial Roll. In this example the thumb is adducted throughout; in other instances it may be partially abducted, consequently operating radial index more distally. (a) Index less flexed. (b) index more flexed.

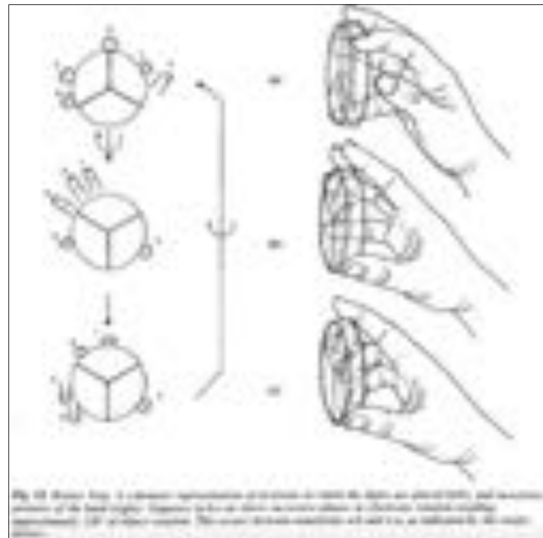
Index Roll

Full Roll

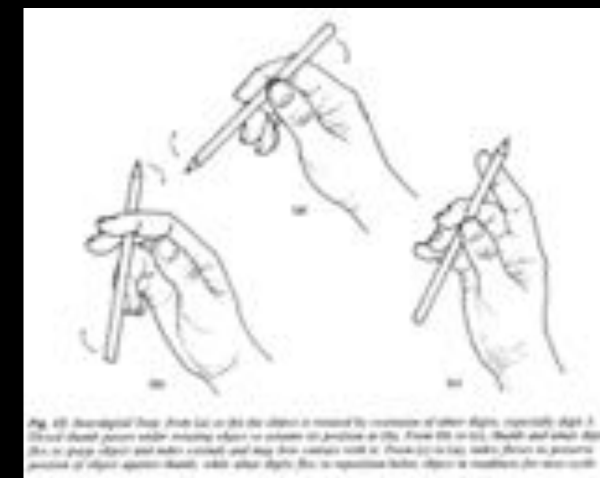


Difference between index roll and full roll is that full roll may use more of the fingers.

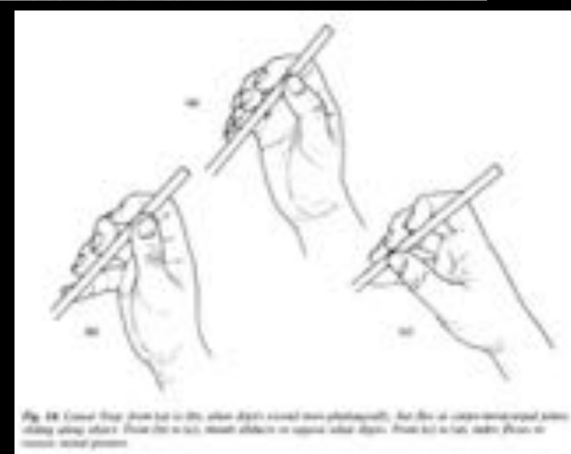
# Sequential Patterns



Rotary Step



Digital Step



Linear Step

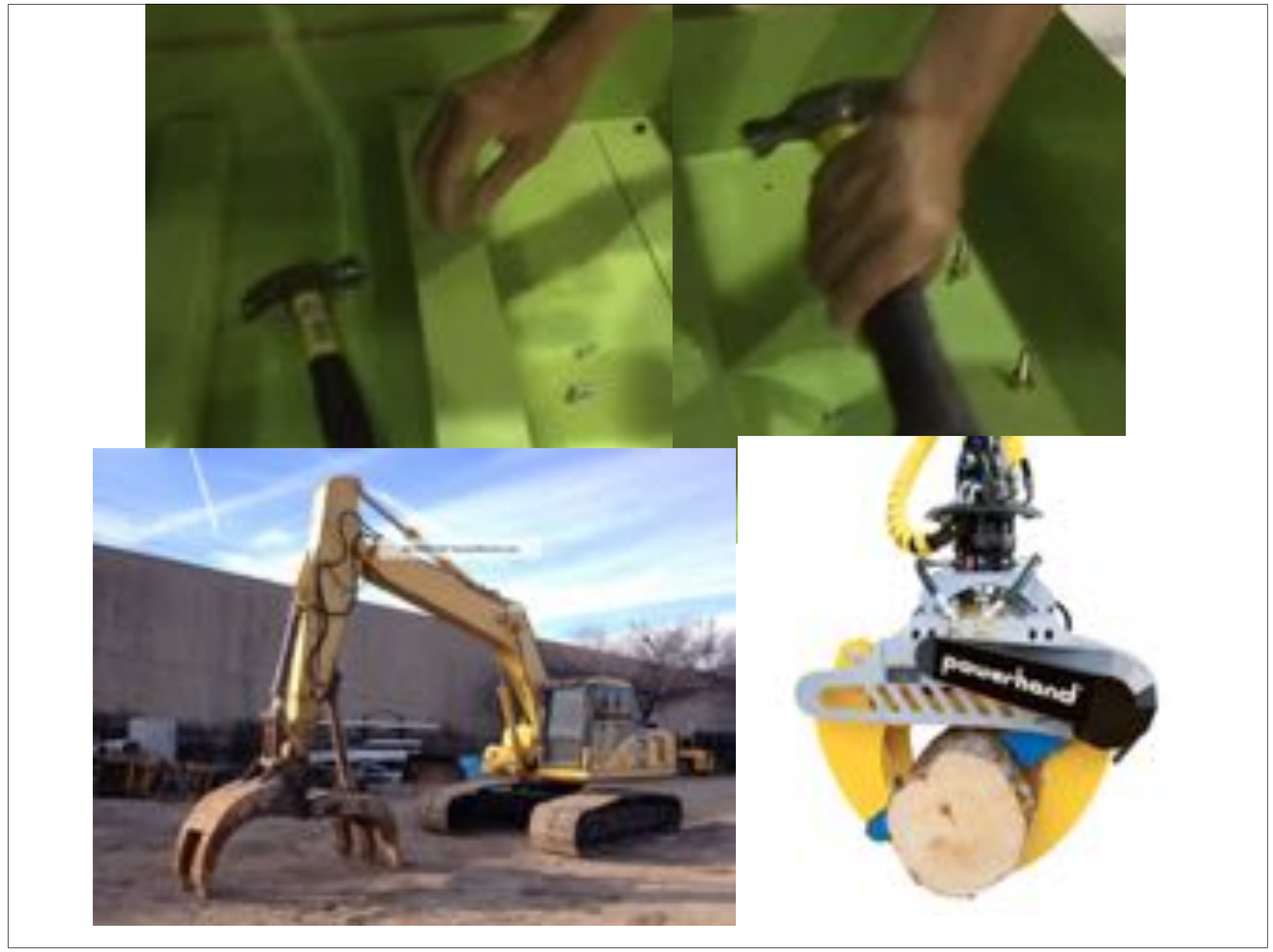
# Not Classified

Palmar Slide


*Fig. 15. Palmar Slide: the movement, illustrated in change from (a) to (b), involves extension of thumb and radial deviation of index, with some extension.*

# Humanlike vs. not

Of course we need to be careful here … if we want to make a functional hand and not necessarily one that does things exactly the way people do, then maybe the trick is to come up with a task set that *could* evoke such manipulations, but then again might not …. Here is one example




If we just want to pull the hammer out of there by getting the gripper all wrapped around the handle, we don't really need a hand ..

we can make something like this grappler, which would be much better than the gripper tool we tested .. it's just that it will only do this thing, and of course, it won't look very humanlike if we care about that

- Points of View regarding Taxonomy:
  - Six basic types of grasp based on hand shape
  - A second tier consisting of verb/task/action
  - In-hand manipulations to acquire objects into a grasp and shift between grasps

What we want to do with the object may be more important than hand shape.

For humanlike grasping, a small collection of different grasp types and strategies to move into and between them may needed.

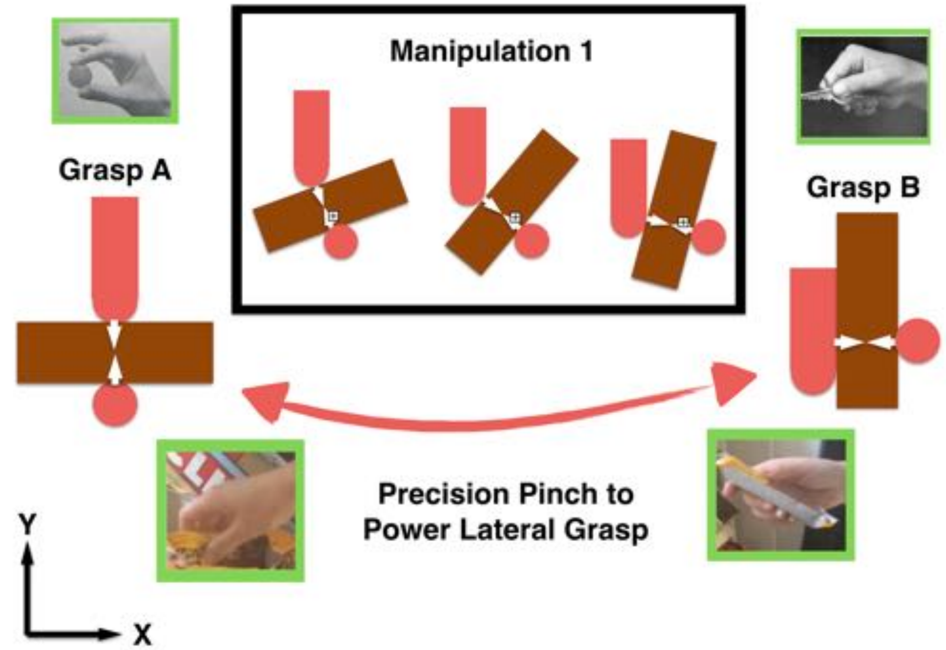
Elliott and Connelly gives one source of intrinsic hand motions

A bit of a summary about taxonomies …

- What **grasp quality metrics** should be used for benchmarking robot hands?
- What **taxonomies** should be used for benchmarking robot hands?
- A very toy example of optimizing to a manipulation benchmark

# A very toy example of optimizing to a manipulation benchmark

Here is one manipulation between two grasps

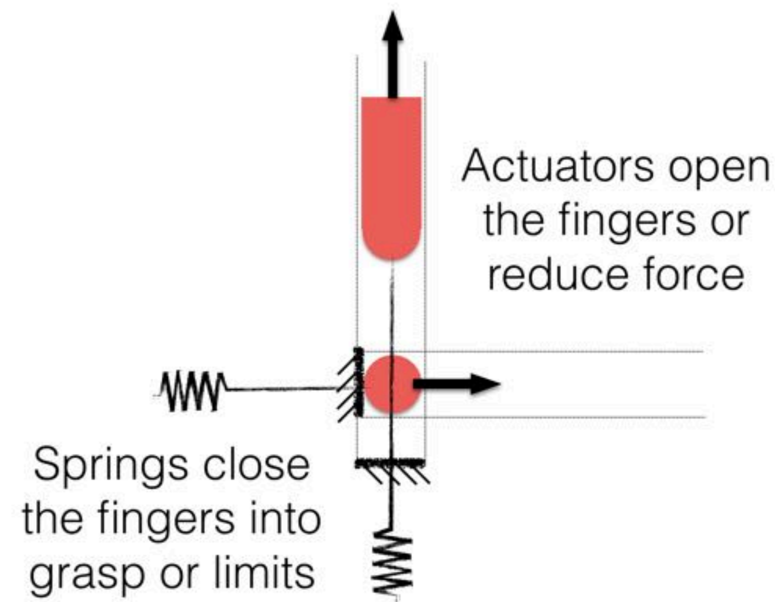



The desired motion is a manipulation from a pinch grasp to a lateral grasp, abstracted into 2D

# A very toy example of optimizing to a manipulation benchmark

We can make this manipulation trivial through optimal placement of:

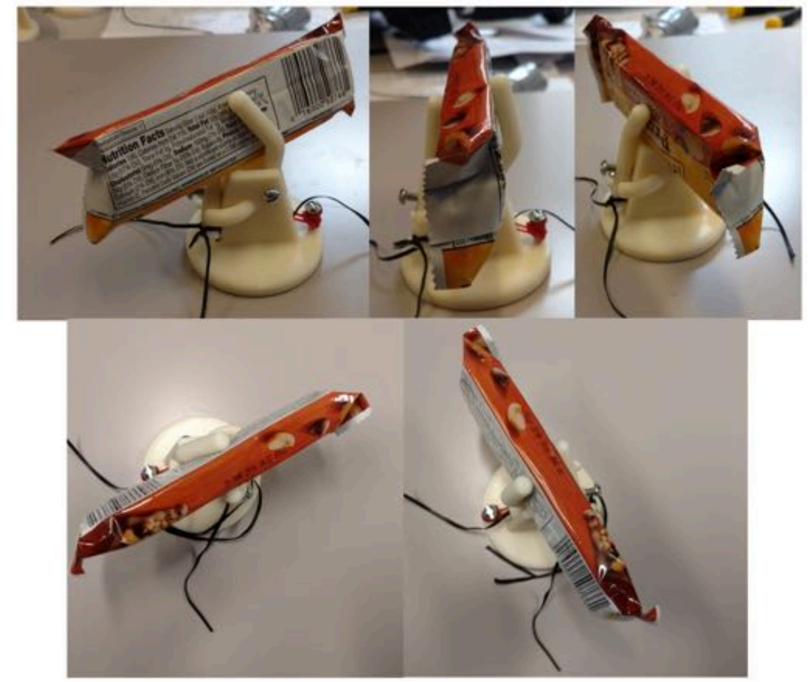
- joint locations
- joint limits
- compliant elements




Let's suppose a manipulator where the thumb moves in X and the finger moves in Y. We will specify a family of objects to manipulate.
We will add compliant elements and joint limits and optimize their parameters to reduce required actuator forces and increase robustness to errors.

# 3D printed output that accomplishes the manipulation

- Compliant elements reduce actuation torque by 90%
- Joint limits increase acceptable error by a factor of 3



Here is our result.

Compliant elements minimize amount of actuation needed by a huge amount (90%)

Joint limits make the manipulation more robust in the presence of error (errors can be 3X larger)

If we optimize designs to the right benchmark set, I think we could get some innovative and surprising designs

# Summary: Points of View

- **Grasp Quality**:
  - *Kinematic and force capabilities* are necessary conditions for a good grasp (but not sufficient)
  - We must consider the *grasping process*
  - We must consider *use of sensors* to improve success
- **Taxonomy**:
  - S*ix basic types of grasp* based on *hand shape*
  - A second tier consisting of *verb/task/action*
  - We can select tasks that evoke *in-hand manipulations* to acquire objects and shift between grasps

Overall summary

When talking about grasp quality I focused on the need to design hands and control algorithms together

My opinion is that coming up with benchmarks for anthropomorphic grasping is easier than otherwise, but in most cases I do not think it is what we want to do.