On the Dexterity of Robotic Manipulation: Are Robotic Hands Ill Designed?

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One of the key skills that granted humans the ability to shape the world is grasping. If humans would not be able to grasp and to manipulate objects and tools, it would be very difficult to assemble and craft complex objects and to use tools. The next step is the translation of these skills to a machine that can automate such manufacturing tasks. The development of a hand as dextrous as the human is a challenge for robotic community for a long time (Cutkosky 1985). Some of the best prototypes of robotic hands, like the Shadow hand, either invest in complex kinematics or in novel and foldable design (Wei, Dai et al. 2011) to achieve in-hand manipulation, but results are still far from the human dexterity. Our intuition is that a more complex kinematics is not necessarily improving the grasping skills, whereas an optimal placement of the thumb actuation can achieve similar or better results without the impact on the complexity. We validate this idea by exploring the grasping capabilities of the iCub robot (Italian Institute of Technology), and correlating them with human based experiments on grasping.

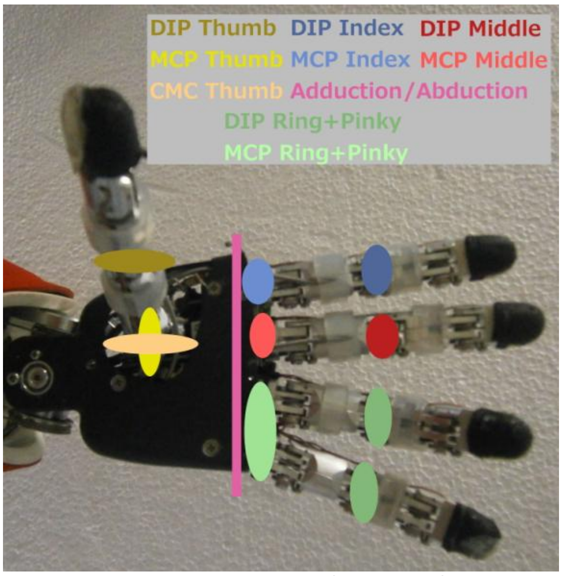

Figure 1 - Kinematic structure of the hand of the iCub

Object Name	No. of Synergies	Median removal force (N)	Standard Deviation (N)	Duration [sec]	Preshaping time [sec]	Enveloping time [sec]
 Cuboid	3	92.35	7.23	78	35	43
	2	51.59	5.88	92	37	55
 Cylinder	3	92.35	7.23	133	30	103
	2	92.35	7.23	89	26	63
	1	51.59	5.88	111	30	81
	Envl. Only	15.81	1.48	119	-	119
 Receiver	3	92.35	7.23	109	73	36
	2	92.35	7.23	109	74	35
	1	15.81	1.48	109	74	35
	Envl. Only	15.81	1.48	56	-	56
 CD Case	3	4.9	1.86	124	74	50
	2	4.9	1.86	120	74	46
	1	4.9	1.86	127	72	55
	Envl. Only	4.9	1.86	48	-	48
 Markers	3	92.35	7.23	119	73	46
	2	51.59	5.88	119	74	45
 Mouse	3	15.81	1.48	116	77	39
	2	15.81	1.48	109	74	35
	1	4.9	1.86	109	74	35
	Envl. Only	No Grip	No Grip	4	-	4
 Glass	3	No Grip	No Grip	111	73	38
 Handle	3	51.59	5.88	122	77	45
	Envl. Only	51.59	5.88	59	-	59

Table 1 - Results of synergy based grasping algorithm

Robotic design of a multi-fingered hand is based upon kinematic modelling of the human one. Our hand is a very complex organ featuring 27 bones, 36 muscles and a complex web of tendons, and its physiological properties are very well understood (Gray 1918). However, given such complexity, it is not trivial to define the number of Degrees of Freedom (DoF) that are needed to control the phalanxes. Some of the existing models feature 15 DoFs (Bianchi, Salaris et al. 2013), while others consider 25 DoFs (Peña Pitarch 2008). The choice depends on the cost and mechanical complexity. The hand of the iCub robot features a simpler kinematics with 9 DoF in total (Figure 1): three joints for the thumb, two joints for the other fingers and one joint for the adduction or abduction of all the fingers except of the thumb. The joints are tendon driven and actuated using a Falhaber 1016M012G motor.

To evaluate the grasping capabilities of the iCub, experiments were executed on real world objects with simple shapes. The algorithm for grasping takes inspiration from grasping synergies (Santello, Flanders et al. 1998). Synergies were extracted using Singular Value Decomposition from 8 kinaesthetic demonstrations of grasping a cuboid using the iCub. A subset of the synergies was used to preshape the hand of the iCub in similar way to humans (Jakobson and Goodale 1991) before grasping. The grip was then finalized through an enveloping phase. For this stage the fingers of the iCub were linearly moved together until no motion was detected for 10 seconds. This stage grants the generalization of the grip beyond classes of objects that are very different from the cuboid used for learning. Objects taken in consideration were: a simple cuboid, a simple cylinder, a phone receiver, a set of three markers taped together, a Compact Disc (CD) keep case, a computer mouse, a fencing handle pistol grip and a plastic rigid glass. The latter was grasped only from the top as the grasp from the side would be been similar to the one required to grasp a cylinder. The algorithm performed equally well using two or three out of nine primitives. The strength of the grasp was evaluated experimentally, by measuring the pulling force required by a human to remove the object from the robotic hand. Results are summarized in table 1. It can be seen that grasping is more successful when the thumb and the other fingers of the robotic hand are replicating a human oblique arch. The markers, the phone receiver, the computer mouse, the cylinder and the cuboid fall inside this category and the final grip is tight. The grasp used for the glass does not comply with this assumption. Hence, the grasp is not successful, while the CD case is weakly grasped because of the linear movement of the fingers in the enveloping phase. The fencing handle was grasped firmly, reinforcing the principle that a grasp is tight if an oblique arch is created between the thumb and the other fingers (Figure 2). This reinforces the idea that misplacement of a thumb can impact the success and the appropriateness of a grasp.

Figure 2 - iCub grasping a fencing pistol grip. The thumb placement guaranteed a tight grip but oriented the handle upwards.

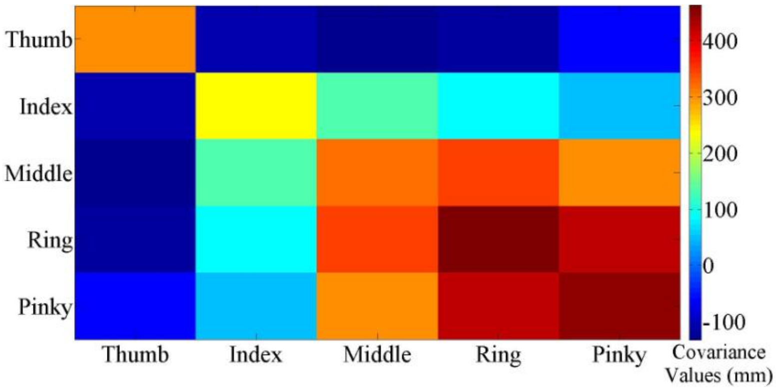

Figure 3 - Covariance (in mm) between thumb basal joint (CMC) displacement and proximal interphalangeal joint (PIP) in human hands while grasping simple shapes for stacking.

To evaluate the difference between robotic grasping and human grasping, experiments were conducted on human subjects too. The task was to build the tallest stack out of a limited amount of objects with simple shapes. By analyzing the movements of the hand, it is possible to observe that there is a strong negative covariance relationship between the thumb movements and the movements of the other digits (Figure 3). This might suggest that the position of the thumb (*dominant finger*) is deciding the right way to grasp an object, the *grasp affordance*, and the other four fingers are offering a support role to the grasp (*supportive fingers*). To conclude, we can state that robotic in-hand manipulation is still a difficult task, as robotic hands rarely implement oblique arches and foldable mechanisms in the same way humans do. Humans can shape up to four oblique arches, one per each supportive finger. The iCub hand, as many other robotic hands, has some difficulties in creating a similar structure with the middle finger and cannot shape any arch with the ring and pinky fingers.

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Acknowledgments

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