2014 IEEE International Conference on Robotics & Automation (ICRA)
Hong Kong Convention and Exhibition Center
May 31 - June 7, 2014. Hong Kong, China

Towards a Functional Evaluation of Manipulation Performance in Dexterous Robotic Hand Design

Maximo A. Roa[1], Zhaopeng Chen[1], Irene C. Staal[2], Jared N. Muirhead[3],
Annika Maier[1], Benedikt Pleintinger[1], Christoph Borst[1], Neal Y. Lii[1]

***Abstract*— Dexterous multifingered hands are the most complex and versatile variants of robotic end effectors. Compared to simpler grippers and underactuated hands, they should be more capable of grasping and, especially, manipulating different objects. This paper explores the relationship between kinematic design and manipulation performance of robotic hands. Some evaluation criteria frequently used by hand designers to verify kinematic configurations are revisited. The results from these criteria are scrutinized and compared with the evaluation of the manipulation workspace and the ranges of motion of in-hand manipulation for a set of predefined objects. Simulations and actual manipulation experiments are carried out with different kinematic configurations on a modular dexterous hand. The results show some disconnection between perceived good designs through common evaluation criteria and their actual, realizable manipulation performance. This work finally gives some insight toward a more holistic approach to design hands that better address grasp and manipulation for the intended tasks and applications.**

***Index Terms*— hand evaluation; precision grasp; in-hand manipulation; dexterous end effector.**

I. Introduction

The human hand is often regarded as the best end effector in existence; as a result, it is frequently viewed as the ultimate performance goal by some roboticists. However, its multiple capabilities, including gesturing, grasping, manipulation and exploration of objects, are still difficult to replicate in a single and compact tool for use in common robotic systems. In highly structured industrial environments most of the grasping and manipulation tasks can be efficiently solved using two or three-jaw grippers, or task oriented tools such as suction cups or electromagnetic grippers [1]. Multifingered hands are better suited for less structured environments, where a broader set of capabilities is required for handling multiple objects with different mass, shape and material, which would involve an assortment of grasping and manipulation tasks. Different configurations and actuation mechanisms have been developed over several decades of research, such as the Barrett Hand [2], Robonaut Hand [3], Gifu Hand III [4], DLR/HIT Hand II [5], Shadow Dexterous Hand [6], and Awiwi Hand [7]. Replicating the same kinematics and anatomical structure of the human, as in the ACT Hand [8], is a first step towards a better understanding of the human functionality, but still requires appropriate control and sensor systems to mimic human dexterous capabilities.

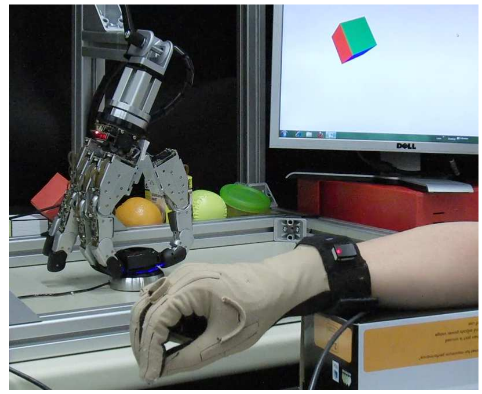

Fig. 1. A five-finger modular robotic hand commanded by a teleoperator with a data glove during a telemanipulation experiment [16]. The dexterous end-effector shows both grasping and in-hand manipulation capabilities.

In terms of flexibility for grasping different types of objects, developments in underactuated hands have shown that a low number of actuators driving coupled degrees of freedom (DoF) can also lead to successful grasps [9], [10]. This type of hands tends to have limited to no manipulation capabilities. However, with additional mechanisms, some basic manipulation functions can be achieved [11], [12]. The same phenomenon occurs in the related field of hand prosthesis, where weight restrictions and the need of a compact solution make underactuated designs more feasible. Currently, the most advanced prosthetic hands such as the i-Limb [13], Michelangelo [14] and Bebionic [15] have only six DoF, flexion/extension of each finger plus a passive abduction/adduction of the thumb, which makes them sufficient for simple grasping of objects, but unable to tackle tasks requiring higher dexterity such as using scissors or buttoning a shirt.

Comparison of the features and abilities of these hands has been carried out based on physical characteristics (size, weight, number of fingers, number of DoF, number and type of actuators), kinematic properties (range of motion per joint, closing speed) or basic dynamic information (maximum force at the fingertips) [17], [18]. The evaluation of the ability to grasp objects has been performed by computing an index of dexterity that considers the kinematic configuration of the hand, its available sensors and control system [19]; however, it does not consider the evaluation of grasping in actual hardware implementation. The comparison of hand

[1] *Institute of Robotics and Mechatronics, German Aerospace Center (DLR), Wessling, Germany.* Email: {firstname.lastname}@dlr.de
[2] *Department of Mechanical Engineering, Delft University of Technology, The Netherlands.*
[3] *Department of Mechanical Engineering, Stanford University, CA, USA.*

performance can also be carried out for specific objects using the graspability maps [20]. These maps show for one object and one given hand the potential locations for the hand that lead to a force closure grasp on the object. Functional comparisons are possible when the types of grasps are considered, i.e. when a qualitative evaluation of the number of different achievable grasp types is performed. For example, the Awiwi hand of the DLR Hand-Arm System [21] is able to reproduce the complete sets of grasps presented in taxonomies of human prehension proposed by Cutkosky [22] and Feix [23].

Multifingered dexterous hands, considered as versatile end effectors, are meant not only for pick and place tasks, but should also be able to perform sufficient amount of fine grasp and manipulation, as for instance carried to some success in [16] (Fig. 1). Existing robot hand designs are nonetheless far from being able to perform a "universal" set of grasp and manipulation tasks. This paper presents a first step towards a systematic approach to improve end effector mechanical design through simulation and experimental validation/verification. We revisit several design criteria commonly used in the design of anthropomorphic robotic hands, and explore fine grasp and manipulation performance for different kinematic configurations of hands. For this purpose, we take advantage of the modularity and rapid reconfigurability of the DLR/HIT Hand II. Through manipulation experiments and simulation, we confirm the limited manipulation capability of the standard configuration, which can be greatly enhanced with the redesign of the thumb position and orientation with respect to the other fingers. This leads to different functional relationships between the fingers, which translates into variations in the behavior of the hand in manipulation tasks.

This paper begins by summarizing common design criteria used in the mechanical design of multifingered hands, and explores possibilities to evaluate in-hand manipulation capabilities (Section II). The rationale behind the different kinematic configurations tested in this work is then explained (Section III), and the experimental results for the evaluation of fine grasp and manipulation capabilities are presented afterwards (Section IV). To conclude, a discussion of the findings and potential extensions of the work is presented (Section V).

II. Evaluation of Manipulation Capabilities

The variety of grasp behaviors in the human hand has been classified using different taxonomies, as the ones proposed by Cutkosky [22] or Feix [23]. Traditional qualitative evaluation of robotic hand capabilities focuses on reproducing as many grasp types as possible using a given taxonomy as a reference [7]. As for manipulation, a hand-centric taxonomy has been recently proposed that describes the variety of manipulation tasks achievable by a human/robot hand [24]. Performance-oriented tests have been developed for the assessment of human hand dexterity, although their application to robotic systems is not evident [25], [26]. This work, in turn, conducts quantitative tests for measuring manipulation abilities, as the mere observation of whether a hand can reproduce certain grasp or manipulation types is not enough to give roboticists a concise comparison of suitability of different robot hands for the intended applications.

A. Precision grasp

The opposition movement of the thumb is the key factor for achieving a precision grasp with the hand [27]. In medicine, the Kapandji test [28] has been proposed to indirectly measure the grasp ability of the human hand. In this test, the range of motion of the thumb is estimated by moving it to a predefined list of positions (fingertips and some joints/links) on the other fingers. The successful completion of the test implies that the hand is able to successfully grasp objects from a kinematic point of view. The concepts from this test were previously proposed as an indicator of the grasping ability of robotic hands [7], [29], [30], and are used here in the same sense. A first performance index P_1 is considered as the total number of predefined target positions that the thumb can reach. Note that the test considers intrinsically, but not actively, the role of parallel fingers' motion in the opposition movement and in grasping tasks, considering as parallel fingers all but the thumb.

Another option to evaluate the influence of the thumb in grasping tasks is computing the volume v_i of intersection between the thumb workspace and the workspace of each finger i, which in the analysis of human grasps is referred to as the functional workspace for precision manipulation of the i-th finger [31]. A second performance index P_2 is obtained as the sum of the intersection volumes, i.e. $P_2 = \sum_{i=1}^{4} w_i v_i$, with w_i a suitable weighting factor that can be used to stress the importance of the opposition to certain fingers. Intuitively, the larger P_2 the better the hand for grasping different objects. This criterion has been used, for instance, for defining the thumb position in the Gifu Hand III [4].

B. Fine manipulation

The ability for manipulation can be evaluated by computing the manipulation workspace, i.e. the set of possible object locations that allow some degree of manipulation on a given object. A multifingered hand can be seen as a collection of small manipulators (fingers) with a common base (palm), and the hand workspace can be seen as the union of the workspaces of each finger. However, the manipulation workspace is object-dependent, as handling the real object implies that the object must be grasped at all times during the manipulation, i.e. there must exist feasible contact locations on the object, and there must not be finger to finger/palm collisions. These factors are not considered in the computation of the hand workspace. Furthermore, the definition of manipulability depends on a particular grasp on the predefined object that is manipulated. The study of the workspace for 3D manipulation of polygonal/polyhedral objects has been previously carried out using optimization techniques and considering the object geometry, hand joint limits, force constraints, and collision avoidance [32]. As a result, given an initial grasp on the object, the workspace that

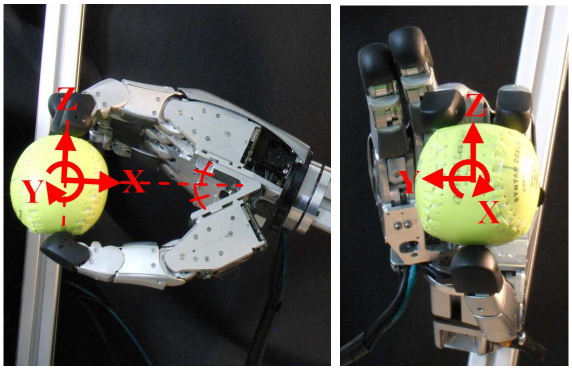

Fig. 2. The modular five-finger hand, based on components from the DLR/HIT Hand II, and its manipulation coordinate system. In this implementation, the coordinate system's orientation is fixed to the robot hand, with the X-axis being the bisector of the angle between the thumb and the opposing finger during the initial grasp of the object. The origin of the coordinate system is set to the centroid of the initial grasp [16].

contains the possible rotations and translations of the object while guaranteeing the grasp is obtained.

We are interested in the general performance of a hand manipulating objects (using a precision grasp), therefore we aim to find not only the manipulation workspace, but also the range of manipulation achievable in each DoF of the object. For each object we consider the three translational and rotational degrees of freedom, according to the coordinate system of the hand presented in Fig. 2. To obtain the manipulation workspace and the range of manipulation, we discretize the workspace of the hand, then locate the object in one of the possible positions inside the workspace, and find a suitable initial force closure (FC) grasp. Given the object pose with respect to the hand, the reachable points on the object surface are computed using the workspace of each finger, and the points closest to the fingertips that guarantee a FC grasp are chosen as the initial contact points [33]. Once this initial grasp is obtained, the object can be moved a small step in the desired direction of manipulation, and the new object position should still allow a reachable FC grasp. The procedure is repeated until a non-feasible position is reached, i.e. a position that is not reachable for the fingers, leads to self-collisions, or does not allow a FC grasp on the object. The contacts between fingertips and object are considered to be rolling contacts, and the fingertips are represented as pointclouds that describe the possible points of contact, as shown in Fig. 3. The size of the manipulation workspace of an object should decrease with the number of contacts. Therefore, for the performance evaluation we used 3 fingers to grasp different objects, both in simulation and in experiments; results are discussed in Section IV.

III. Modular testbed

Finger positioning is integral to a robot hand's performance. As addressed earlier, the thumb is the single most important finger in an anthopomorphic end effector [27]. As a result, we believe that thumb placement serves as a good starting point to examining the effects of finger positioning on the hand on grasp and manipulation performance.

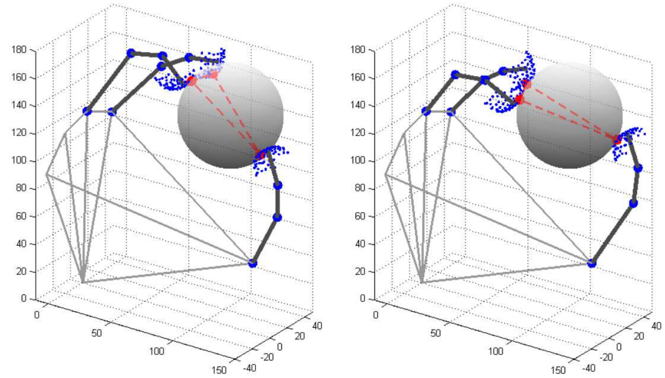

Fig. 3. Simulation of manipulation of a ball, in this case rotation in the X-direction.

TABLE I

Specifications for different thumb locations

Thumb base module	Opposing finger	Orientation from opposing finger	Orientation from palm
Original	Middle	30°	40°
I-50°	Index	50°	90°
I-60°	Index	60°	90°
I-70°	Index	70°	90°
M-50°	Middle	50°	90°
M-60°	Middle	60°	90°
M-70°	Middle	70°	90°

Due to the lack of a roll joint of the thumb in our base robot hand module, its placement becomes even more critical to the effectiveness of the hand [34]. This is a problem that occurs also in prostheses design, in the cases where the thumb has a fixed position [14]. To define some relevant thumb configurations for the experiments, we carried out a series of simulations to search for suitable thumb placements. The aperture angle of the thumb with respect to the palm influences the manipulability of objects with different sizes; smaller thumb placement angles optimize toward grasping smaller (e.g. paper-thin) objects, whereas larger angles are more suited for larger objects. To simplify the analysis of different configurations, the thumb is located in direct opposition to the index or middle fingers, and in a 90° angle with respect to the palm. With these considerations, we include in the present study six configurations in addition to the original one, as summarized in Table I. Based on Yoshikawa's work on manipulability [35], we set for each finger the configuration with the highest manipulability index, and, given an aperture angle, we located the thumb in a cartesian position that guarantees that a pinch grasp is always possible, as illustrated in Fig. 4. Fig. 5 shows two examples of the real implementation of different thumb locations on the modular hand.

IV. Results and Discussion

A. Precision grasp

The Kapandji test was performed on all seven thumb placements of the modular robotic hand. The thumb was moved to try to reach with the fingertip all the links of the

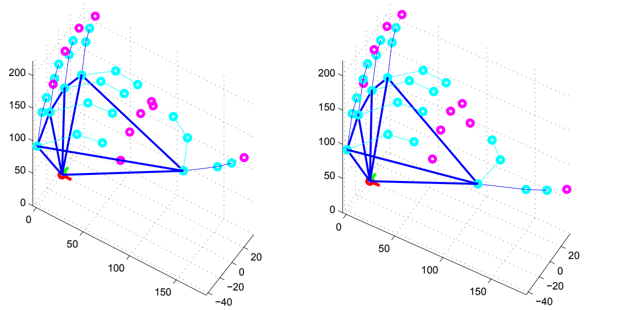

Fig. 4. Examples of simulated hand kinematics. The magenta circles mark the center point of each fingertip in two configurations, relaxed and pinch grasp. The joint configuration for the pinch grasp is the one that provides the highest manipulability according to Yoshikawa [35]. In the left, the thumb is placed opposing the index finger at an angle of 50°, whereas the right figure illustrates the thumb opposing the middle finger at an angle of 70°.

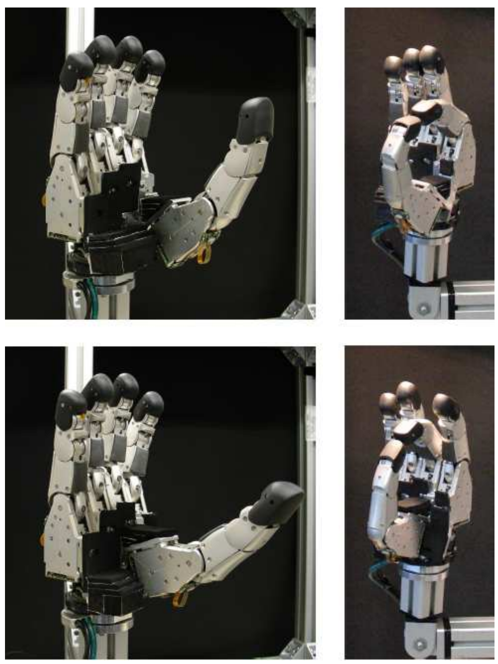

Fig. 5. Implementations of different thumb configurations with the modular hand. On top, the relaxed and pinch grasp configurations are shown for the thumb placed directly opposing the index finger at 50°. The same configurations are shown at the bottom when the thumb opposes the middle finger at 70°.

parallel fingers. Each finger is indicated by its first letter (Index, Middle, Ring and Little finger), and links are indicated with P (proximal phalange), I (intermediate phalange), and D (distal phalange). Results of the test are presented in Table II. Note that the original thumb configuration can reach all the 12 points of contact in the Kapandji test, as the hand was specifically designed for fulfilling the requirements of this test. The performance index P_1 allows a direct comparison of the results for different thumb configurations.

Table III summarizes the results for the computation of the functional workspace for each finger, and presents the performance index P_2 that allows the comparison between

TABLE II

KAPANDJI TEST RESULTS WITH SEVEN DIFFERENT THUMB CONFIGURATIONS

	M-50°	M-60°	M-70°	I-50°	I-60°	I-70°	Orig.
I-D	✓	✓	✓	✓	✓	✓	✓
I-I	✓	✓	✓	✓	✓	✓	✓
I-P	x	x	x	x	x	x	✓
M-D	✓	✓	✓	✓	✓	✓	✓
M-I	✓	✓	✓	✓	✓	✓	✓
M-P	x	x	x	x	x	x	✓
R-D	✓	✓	✓	✓	✓	✓	✓
R-I	✓	✓	✓	✓	✓	x	✓
R-P	x	x	x	x	x	x	✓
L-D	x	✓	✓	x	x	x	✓
L-I	x	✓	x	x	x	x	✓
L-P	x	x	x	x	x	x	✓
P_1	6	8	7	6	6	5	12
Rank	4 (tied)	2	3	4 (tied)	4 (tied)	7	1

TABLE III

FUNCTIONAL WORKSPACE OF THE FINGERS (IN cm^3)

	M-50°	M-60°	M-70°	I-50°	I-60°	I-70°	Orig.
Index	11.51	3.60	0.47	47.58	30.52	18.58	35.59
Middle	55.76	40.26	27.29	3.89	0.72	0.42	33.79
Ring	10.91	3.20	0.46	0	0	0	5.80
Little	0	0	0	0	0	0	0.003
P_2	78.17	47.07	28.23	51.46	31.24	19.01	75.18
Rank	1	4	6	3	5	7	2

different thumb configurations. Note that in configurations where the thumb opposes the middle finger, the corresponding functional workspace of the middle finger is the largest among all the parallel fingers; for the thumb configurations opposing the index finger, the largest functional workspace corresponds to the index finger.

As a final qualitative verification, basic geometric shapes (boxes, cylinders and spheres) were grasped with the different hands, and no significant difference in behavior was detected, other than the initial relative pose between hand and object had to be adjusted according to the hand geometry.

B. Fine manipulation

To compare different thumb configurations, the technique described in Section II-B is employed to obtain the workspace and possible ranges of motion for three different balls of radius 20, 35 and 42.5mm. The simulation is cross checked with experiments using the same objects. For the experiment, the balls are placed in a predefined position with respect to the hand, fingers are closed and then the object is manipulated in the desired DoF until the object is dropped or until the fingers cannot provide additional motion in the desired direction. The control of the internal forces to guarantee the FC grasp is performed using a spatial impedance controller [36].

Fig. 6 presents the simulated and experimental results of this manipulation. Note that the simulations guarantee that

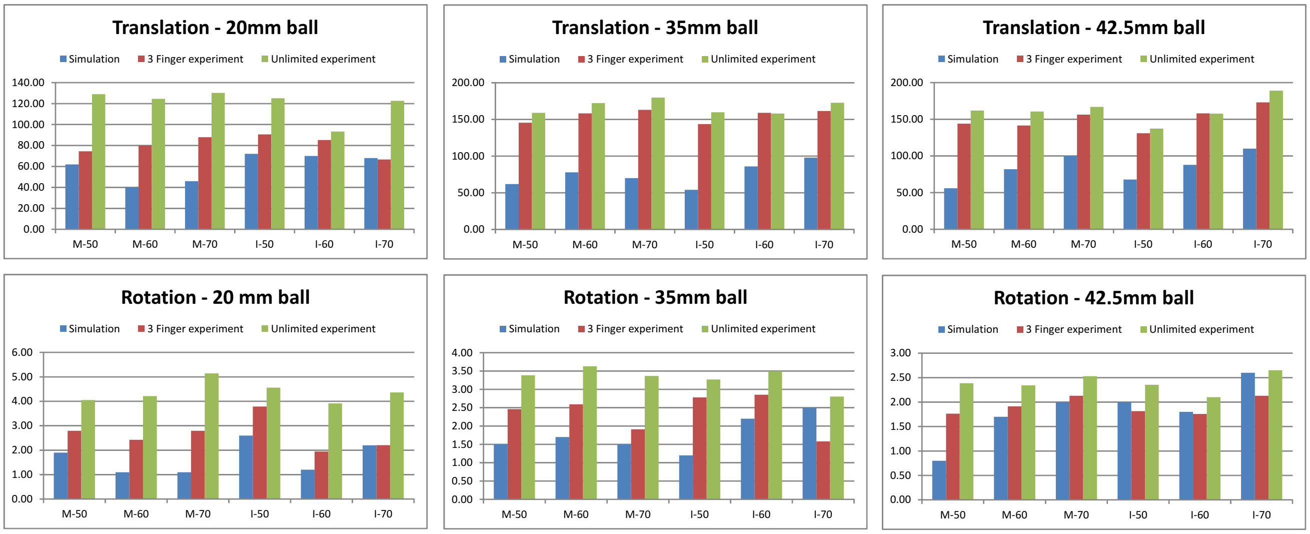

Fig. 6. Results of simulation and experiments manipulating three balls of different sizes. Translations are measured in mm, and rotations are measured in rad.

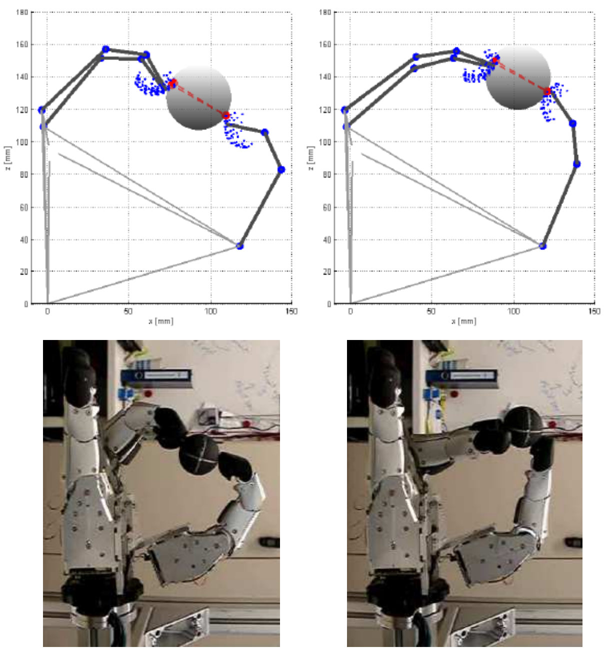

Fig. 7. Examples of comparing simulation and actual manipulation of a ball, in this case for translation in the X-direction. Although simulation can show an accurate trend of manipulation capabilities, it has difficulties dealing with situations where the manipulation range can be extended with the loss of contact by a finger. In this case, the middle finger lost contact with the object, but the object was still securely grasped with the remaining two fingers, and the X-translation motion continued for an extended range. The photos of the actual in-hand manipulation have been rotated 90° for easier comparison with the simulation results.

the three fingers are always in contact with the ball, but this condition is not necessarily satisfied in the experiments, as illustrated in Fig. 7. Therefore, the experimental results are presented with two different bars, one showing the total range of motion including the restriction of all the fingertips being in contact with the object ("3-finger" experiment), and another one showing the total motion obtained even though one finger had been detached from the object ("unlimited" experiment). The "unlimited" experimental results generally show an extension of manipulation range, which has not been simulated. The original thumb configuration is not shown, as in the experiments with that configuration the objects were grasped but the motion in most of the directions was either impossible or negligible. Note that the simulation results are conservative; in general, they underestimate the motion of the ball with respect to the motion obtained during the experiments. Simulations do not capture behaviors such as the rotation of the ball over one of the links, i.e. outside the area considered as fingertip in the simulations, or cases where one finger loses contact but the remaining fingers still guarantee a FC grasp and the object is still manipulable. Note also that during the experiments there is an important source of error in the location of the ball with respect to the hand. The combination of the previous factors is more critical for smaller objects, which show the larger difference between the limited ("3-finger") and "unlimited" experiment.

Fig. 6 compares experiments and simulations for *one* initial position of the balls with respect to the hand. However, in simulation one can afford to try all the possible locations of the object inside the hand workspace, and verify the possible ranges of motion for each one of those positions. For performing the simulations, the potential hand workspace is discretized, and each discrete point is considered as an initial position of the object; then, the simulation of manipulation is performed, as described in Section II-B. Fig. 8 shows for instance the workspace for two different thumb configurations, for the three different ball sizes. The size of the manipulation workspace is related to the number of spheres in each figure. The diameter of each sphere represents the translational capabilities, and the color indicates the rotational capabilities for manipulating the object initially located in the center of such sphere. For visualization, we used the addition of the ranges of motion along the three axis of movement (L_1 norm)

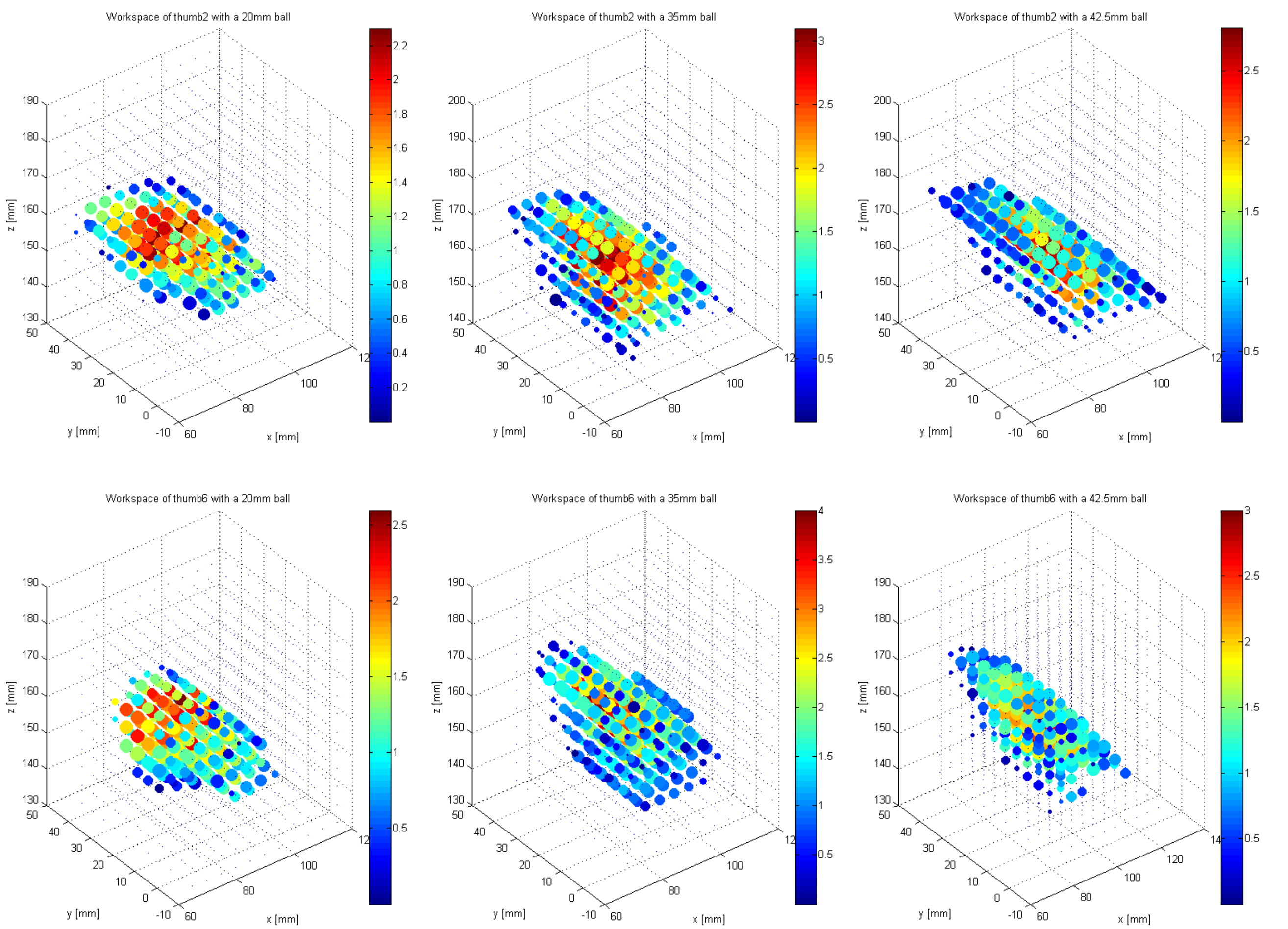

Fig. 8. Workspaces and manipulation ability for two different thumb configurations: I-50° (top), and M-60° (bottom). The sphere size is an indicator of the translational capabilities, and the color indicates the rotational capabilities for manipulating the object initially located in the center of such sphere.

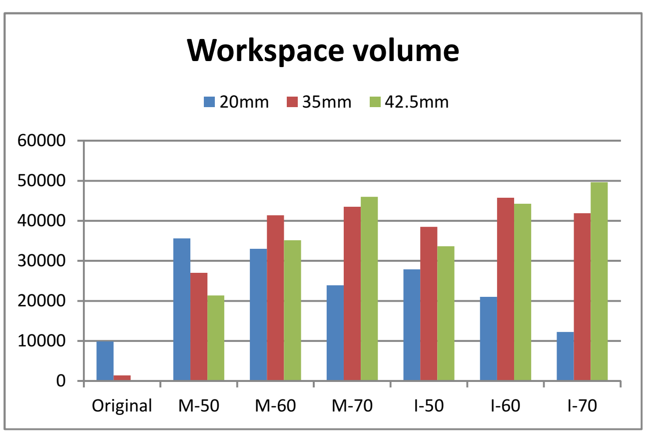

Fig. 9. Volume of the manipulation workspace (in mm^3) for three balls of different sizes.

for defining the size and color of each sphere.

Fig. 9 presents the volume of the manipulation workspace for the seven different thumb configurations. Note that the original thumb configuration provides very small manipulation capabilities, which illustrates the limitations of this thumb placement. For instance, this configuration was barely able to grasp the largest ball, and no manipulation was possible in this case. Note also that the thumb locations with an angle of 50° provide a larger workspace for the small ball, and the configurations with an angle of 70° provide larger workspaces for larger balls.

C. Discussion

On applying human-based metrics to robot hand design: Different tests were applied to assess the performance of several hand configurations in fine grasping and manipulation tasks. The Kapandji test was originally proposed for surgeons to check the grasp ability of human hands by verifying the ability of the thumb to reach predefined locations. The thumb is similarly important in dexterous humanoid robot hands [27], and should be closely examined during design. Perhaps due to the lack of a more robotic-focused test metric, the Kapandji test (or modified versions of it) is often used to determine the viability of a robotic hand design. However, the designer can sometimes (unintentionally) ignore the human specific kinematics implications and only aim for an empirical match. Furthermore, precision grasp and manipulation are tasks where physical contacts with the target object are made only with the fingertips. This is in clear contrast with the Kapandji test, in which the thumb should make contact with each joint/link of every finger. The computation of the functional workspace for the fingers has also been proposed to measure the grasp ability of a given hand kinematics, but it is also strongly oriented towards human-like configurations. For instance, the computation of such measure on a Barrett hand will result in a very low value of functional workspace for all the fingers. With these aspects in mind, we believe that such human-based tests should be applied cautiously for the design of robotic hands.

The original DLR-HIT hand II is a case of an anthropomorphic hand whose kinematics differs from the human hand, with the most glaring differences including the identical specifications for all five fingers, and the lack of a roll joint in the base of the thumb. It scored a perfect 12 out of 12 on the Kapandji test, as shown in Table II, and had also a high score in terms of functional workspace, as shown in Table III. However, as a manipulator, it is less capable than hands with our modified thumb configurations (lower volume of the manipulation workspace and lower ranges of motion for the tested objects). Inversely, the modified thumb positions examined in this work have lower scores on the Kapandji test, although all of them had significantly better manipulation performance. As a result, we are not able to draw direct correlations between the Kapandji test score or the size of the functional workspace, which have been used as traditional criteria in the design of robotic hands, with actual robotic hand manipulation performance. Our findings point to the need for test metrics which are tailored to the characteristics of robot hand design and target tasks. The test metrics should be holistically designed to cover both functionalities, grasping and manipulation, while taking into account the kinematic configuration of the end effector.

On the simulation of manipulability: Simulations have shown to be an effective tool to complement experimental evaluation, particularly for providing an initial assessment of the hand performance, and for identification of trends in the hand behavior. However, simulations have limitations; for example, the current implementation is purely based on kinematics, and does not include information on forces and torques. Also, for the computation of the ranges of manipulation in predefined directions, the fingertip is assumed to have a finite geometry, and once the object loses contact with such geometry the simulation is stopped. However, reality shows that fine manipulation is still achievable even when the object is rolling on the link surface and not on the fingertip, or when one of the fingers loses contact but the object is still grasped within the hand. Mainly these phenomena explain the differences obtained between the simulated manipulation workspace and the real one obtained via experimentation. Nevertheless, the general trend in the behavior of different hand configurations was sufficiently captured by the simulations to make them a valuable design aid.

The right hand for the right job: All hands, including the human hand, have limitations. Imagine using a human hand to pick up a strand of hair, from a table top, or to grasp a basketball: these examples demonstrate the object size limitations on both ends of the scale. We observed a similar phenomenon in the different thumb placements, where the narrower thumb angles (M-50° and I-50°) can better manipulate smaller objects (e.g. 20mm ball), whereas the larger thumb placement angles (M-70° and I-70°) perform better with larger objects. This implies that every hand configuration has a range of object size that it is suited to manipulate, with both a minimum and a maximum size limit. With this understanding, we can better select a configuration for a set of tasks based on the sizes of the target objects.

V. Final remarks

Different end effectors have been created to provide grasp and manipulation functionalities for robotic applications. Although specific grippers or tools can be designed for particular tasks in structured environments, a more versatile end effector is required for normal environments that for instance require human-robot interaction. Multifingered hands can provide this versatility; however, most of them have been designed based on qualitative behaviors or on metrics focused on the grasping ability and inspired by the human hand, which do not always fit robot designs with widely different kinematics. Nevertheless, current dexterous robotic hands are already capable of more difficult in-hand manipulation tasks, as shown in in this paper.

A first study of the performance of a multifingered robotic hand was presented in this work, and the attached video presents examples of the evaluation experiments. To understand the functionality of the hands, several tests were discussed, focused on the main applications of current robot hands: grasping and manipulation. Different hand configurations were considered by changing the location and orientation of the thumb. It was shown that traditionally accepted criteria for designing robotic hands, such as the Kapandji test and the functional workspace, do not necessarily imply larger manipulation workspaces or better manipulation performances. Also, the consideration of manipulability for the hand can greatly improve the versatility of the end effector without affecting significantly their behavior for common grasping tasks.

The results also make evident that every hand, whether human or robotic, has a range of objects that it can properly handle. This implies that there are some minimum and maximum object sizes for obtaining a desired manipulability. This insight and information can aid in the selection of a suitable hand configuration for the target tasks.

The creation of guidelines for designing new modular end effectors would be a valuable contribution for the continuation of this work. This paper chose to focus on the manipulation and the preceding fine grasp aspects of hand design, taking into account the influence of the thumb location. The influence of additional parameters like finger and link lengths is a possible extension of the analysis. Also, power grasps have not yet been considered. However, a general-purpose multifingered hand should demonstrate sufficient power grasp capabilities for the broader versatility needed to service more applications and environments. Suitable metrics for measuring such ability are yet to be properly defined and integrated with qualitative metrics as the ones presented here.

References

[1] G. Monkman, S. Hesse, R. Steinmann, and H. Schunk, *Robotic Grippers*. Wiley VCH, 2007.

[2] W. Townsend, "The Barrett hand grasper - programmably flexible part handling and assembly," *Industrial Robot*, vol. 27, no. 3, pp. 181–188, 2000.

[3] C. Lovchik and M. Diftler, "The Robonaut hand: a dexterous robot hand for space," in *Proc. IEEE Int. Conf. Robotics and Automation - ICRA*, 1999, pp. 907–912.

[4] T. Mouri, H. Kawasaki, K. Yoshikawa, J. Takai, and S. Ito, "Anthropomorphic robot hand: Gifu hand III," in *Int. Conf. Control, Automation and Systems*, 2002, pp. 1288–1293.

[5] H. Liu, K. Wu, P. Meusel, N. Seitz, G. Hirzinger, M. Jin, Y. Liu, S. Fan, T. Lan, and Z. Chen, "Multisensory five-finger dexterous hand: The DLR/HIT hand II," in *Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems - IROS*, 2008, pp. 3692–3697.

[6] Shadow Robot Company, "The Shadow dexterous hand." [Online]. Available: http://www.shadowrobot.com/products/dexterous-hand/

[7] M. Grebenstein, M. Chalon, W. Friedl, S. Haddadin, T. Wimböck, G. Hirzinger, and R. Siegwart, "The hand of the DLR hand arm system: Designed for interaction," *Int. J. Robotics Research*, vol. 31, no. 13, pp. 1531–1555, 2012.

[8] A. Deshpande, Z. Xu, M. Vande, B. brown, J. Ko, L. Chang, D. Wilkinson, S. Bidic, and Y. Matsuoka, "Mechanisms of the anatomically correct testbed (ACT) hand," *IEEE/ASME Trans. Mechatronics*, vol. 18, no. 1, pp. 238–250, 2013.

[9] L. Birglen, T. Laliberte, and C. Gosselin, *Underactuated Robotic Hands*. Springer, 2008.

[10] A. Dollar and R. Howe, "The highly adaptive SDM hand: Design and performance evaluation," *Int. J. Robotics Research*, vol. 29, no. 5, pp. 585–597, 2010.

[11] L. Odhner and A. Dollar, "Dexterous manipulation with underactuated elastic hands," in *Proc. IEEE Int. Conf. Robotics and Automation - ICRA*, 2011, pp. 5254–5260.

[12] V. Tincani, M. Catalano, E. Farnioli, M. Garabini, G. Grioli, G. Fantoni, and A. Bicchi, "Velvet fingers: A dexterous gripper with active surfaces," in *Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems - IROS*, 2012, pp. 1257–1263.

[13] Touchbionics, "i-Limb Ultra prosthetic hand." [Online]. Available: http://www.touchbionics.com/products/active-prostheses/i-limb-ultra/

[14] Ottobock, "Myoelectric hand prostheses." [Online]. Available: http://www.ottobock.de/cps/rde/xchg/ob_com_en/hs.xsl/5057.html

[15] RSLSteeper, "Bebionic hand." [Online]. Available: http://bebionic.com/the_hand

[16] N. Y. Lii, Z. Chen, M. A. Roa, A. Maier, B. Pleintinger, and C. H. Borst, "Toward a task space framework for gesture commanded telemanipulation," in *Proc. IEEE Int. Symp. on Robot and Human Interactive Communication - RO-MAN*, 2012, pp. 925–932.

[17] J. Bellter and A. Dollar, "Performance characteristics of anthropomorphic prosthetic hands," in *Proc. IEEE Int. Conf. on Rehabilitation Robotics*, 2011, pp. 921–927.

[18] D. Alba, M. Armada, and R. Ponticelli, "An introductory revision to humanoid robot hands," in *Proc. Int. Conf. on Climbing and Walking Robots - CLAWAR*, 2005, pp. 701–712.

[19] L. Biagiotti, F. Lotti, C. Melchiorri, and G. Vassura, "How far is the human hand? a review on anthropomorphic robotic end-effectors," Internal Report - University of Bologna, 2004.

[20] M. A. Roa, K. Hertkorn, F. Zacharias, C. Borst, and G. Hirzinger, "Graspability map: A tool for evaluating grasp capabilities," in *Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems - IROS*, 2011, pp. 1768–1774.

[21] M. Grebenstein, A. Albu-Schaffer, T. Bahls, M. Chalon, O. Eiberger, W. Friedl, R. Gruber, S. Haddadin, U. Hagn, R. Haslinger, H. Hoppner, S. Jorg, M. Nickl, A. Nothhelfer, F. Petit, J. Reill, N. Seitz, T. Wimböck, S. Wolf, T. Wusthoff, and G. Hirzinger, "The DLR hand arm system," in *Proc. IEEE Int. Conf. Robotics and Automation - ICRA*, 2011, pp. 3175–3182.

[22] M. Cutkosky, "On grasp choice, grasp models, and the design of hands for manufacturing tasks," *IEEE Trans. Robotics and Automation*, vol. 5, no. 3, pp. 269–279, 1989.

[23] T. Feix, R. Pawlik, H. B. Schmiedmayer, J. Romero, and D. Kragic, "A comprehensive grasp taxonomy," in *Robotics Science and Systems - RSS, Workshop on Understanding the Humand Hand for Advancing Robotic Manipulation*, 2009.

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

[25] K. Yancosek and D. Howell, "A narrative review of dexterity assessments," *J. Hand Therapy*, vol. 22, no. 3, pp. 258–269, 2009.

[26] C. Light, C. P.H., and P. Kyberd, "Establishing a standardized clinical assessment tool of pathologic and prosthetic hand function: Normative data, reliability, and validity," *Archives of Physical Medicine and Rehabilitation*, vol. 83, pp. 776–783, 2002.

[27] M. Chalon, M. Grebenstein, T. Wimböck, and G. Hirzinger, "The thumb: guidelines for a robotic design," in *Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems - IROS*, 2010, pp. 5886–5893.

[28] A. Kapandji, "Cotation clinique de l'opposition et de la contre-opposition du pouce," *Annales de Chirurgie de la Main*, vol. 5, no. 1, pp. 68–73, 1986.

[29] M. Chalon, A. Wedler, A. Baumann, W. Bertleff, A. Beyer, J. Butterfass, M. Grebenstein, R. Gruber, F. Hacker, E. Kraemer, F. Landzettel, M. Maier, H. Sedlmayr, N. Seitz, F. Wappler, B. Willberg, T. Wimboeck, G. Hirzinger, and F. Didot, "Dexhand: A space qualified multi-fingered robotic hand," in *Proc. IEEE Int. Conf. Robotics and Automation - ICRA*, 2011, pp. 2204 –2210.

[30] S. Shin, S. Han, K. Lee, H. Moon, H. R. Choi, and J. C. Koo, "A design framework for dexterous robotic hand," in *Intl. Conf. on Ubiquitous Robots and Ambient Intelligence*, 2011, pp. 539 –541.

[31] L.C.Kuo, H. Chiu, C. Chang, H. Hsu, and Y. Sun, "Functional workspace for precision manipulation between thumb and fingers in normal hands," *J. Electromyography and Kinesiology*, vol. 19, pp. 829–839, 2009.

[32] Y. Guan, H. Zhang, X. Zhang, and Z. Guan, "Workspace of 3-D multifingered manipulation," in *Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems - IROS*, 2008, pp. 2679–2684.

[33] M. A. Roa, K. Hertkorn, C. Borst, and G. Hirzinger, "Reachable independent contact regions for precision grasps," in *Proc. IEEE Int. Conf. Robotics and Automation - ICRA*, 2011, pp. 5337–5343.

[34] H. Wang, S. Fan, and H. Liu, "An anthropomorphic design guideline for the thumb of the dexterous hand," in *Proc. IEEE Int. Conf. Mechatronics and Automation*, 2012, pp. 777–782.

[35] T. Yoshikawa, "Manipulability of robotic mechanisms," *Int. J. Robotics Research*, vol. 4, no. 2, pp. 3–9, 1985.

[36] Z. Chen, N. Y. Lii, T. Wimboeck, S. Fan, and H. Liu, "Experimental evaluation of cartesian and joint impedance control with adaptive friction compensation for the dexterous robot hand DLR-HIT II," *Int. J. of Humanoid Robotics*, vol. 8, no. 4, p. 649, 2011.