A Method for Hand Kinematics Designers
7 Billion Perfect Hands

Markus Grebenstein, Maxime Chalon; Gerd Hirzinger & Roland Siegwart

Abstract—**In the past decade the design of kinematic models for hands has been addressed using several different approaches such as numerical optimization or direct measurement of human hands.**
However, once the mechanical and structural design constraints are included, no existing kinematic model of the hand fits the needs of the DLR Hand Arm System. The diversity of human hands reveals that the functional aspects are more important than the kinematics itself. In order to develop a suitable model for the hand arm system a more empirical method was developed. Based on an basic hand skeleton, that incorporates the structural constraints, incremental variations are performed to improve the parameters to fit the functional needs of the hand. The tests are derived from a set of common grasps as well as some tests performed by surgeons. To be able to rapidly appreciate the results simple cardboard prototypes are constructed. The resulting kinematics revealed to be a promising and suitable hand kinematics for the DLR Hand Arm System. The design is realized in hardware.

Index Terms—**kinematics, anthropomorphic hand, bionic, robot hand, DLR Hand Arm System**

I. Introduction

DLR currently built an antagonistically driven hand for the anthropomorphic DLR Hand Arm System (Fig. 1) [1]. The system is meant to have the properties of the human archetype, in terms of weight, size, dynamics and force.

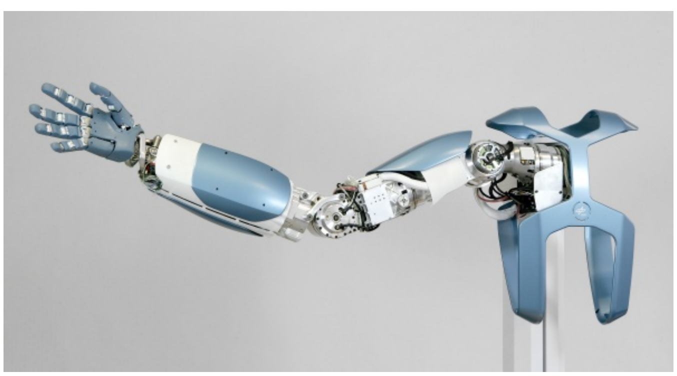


Fig. 1. The DLR hand arm system

Empirical Kinematics: A large number of kinematics mainly based on empirical results can be found. They are designed to fit the special needs of existing robot hands [2], [3], [4], data glove calibration or animation purpose. For example, Griffin [5] designed a kinematics to develop a calibration scheme for data gloves. He added longitudinal axis of rotation to implement the rotation of the thumbs during flexion.

Kinematics analysis: Giurintano and Hollister [6] developed a five link kinematics for the thumb based on cadaver analysis [7], [8] to reproduce the motion of the human thumb as close as possible. Stillfried [9] measured the kinematics of a human hand using MRI data and segmentation algorithms to extract the bones motions and therefore the hand kinematics. The "Lehrstuhl für Ergonomie" of the Technical University of Munich synthesized a kinematic model of the whole human body to realize the RAMSIS system[1] [10], [11].

Kinematics Optimization: Santos [12] and Valero Cuevas modeled the kinematics of Giurintano and Hollister using DH-parameters and optimized these using cadaver test data from [7], [8] and Monte Carlo Simulation. They optimized the found kinematics using Markov Chain Monte Carlo Simulation within a 50D parameter space [13].

Evaluation Criteria: To evaluate the kinematics several approaches are used. Examples of such methods are:

- mathematical criteria
  - manipulability ellipsoids [14], [15]
  - dexterous workspace [16]
  - grasp stability [17]
- evaluation tools

Miller [4] developed a complete environment GraspIt! to simulate hands in contact situations for evaluation purpose which could be used as an alternative (or in addition) to the cardboard prototypes to execute the tests proposed in III.

The design space of hand is extremely large and unfortunately the optimization methods are based on a very limited set of data. Santos[13], uses seven experiments from Hollister [7], [8] to optimize a non-anatomically correct model. The model is composed of hinge joints that are not representing correctly the actual joint motion. Indeed, their axis of rotation are configuration dependent. Therefore, the optimization outcome are strongly depending on the initial kinematic model. The use of cadaveric measurements also increases the errors in bone position measurement since the fast tissue deterioration allows for non natural motions as well as only passive ranges of motion can be measured[2].

Approaches that model the exact kinematics of human hands are not suitable for the design of the DLR hand. Indeed, the

M. Grebenstein, M Chalon and G. Hirzinger are with Institute of Robotics and Mechatronics, German Aerospace Center (DLR e.V.), D-82234 Wessling, Germany
Corresp. Author: M. Grebenstein, markus.grebenstein@dlr.de
R. Siegwart is with Autonomous Systems Lab, ETH Zurich, CH-8092 Zurich, Switzerland

[1] The RAMSIS model is used mainly to realize ergonomic interfaces, e.g. in automobile industry.

[2] For grasping only the active range of motion can be used.

robotic system has to use technologies that are not equivalent to biological solutions (tissue regeneration, drive speed/power density) as well as a reduced number of actuators and therefore DOF has to be used.

The main focus of the aimed hand is a service robotics system. That is, it should exhibit grasping and manipulation performances as a *whole hand*. Therefore, optimality of a kinematics of a single finger is of low relevance. The design has to focus on the synergies among the five serial robots that are the five fingers and therefore the underlying functionalities. To find a functional optimal kinematics using optimization algorithms, optimizations have to be done over the complete hand. Therefore, functional parameter sets have to be defined [3]. A fundamental understanding of the entire grasping and fine manipulation process, as well as a transcription of this understanding into a set of mathematical properties, would be required to apply the methods described earlier. Poor performance in unconsidered tasks due to incomplete subsets of parameters, comparable to the over fitting in neural network learning, is very likely.

The definition of *"a good hand"* regarding grasping and manipulation using objective functions remains a work to be done and has never been practically applied apart from some simple examples.

The methodology used for the design of the DLR Hand Arm System consists in understanding the human archetype on a functional basis and transferring the functions to a technical system. Indeed, merely copying the biological system is too complex using the available technologies and an exact duplicate is not required in the field of service robotics.

This paper presents a practical approach used to design the hand of the DLR Hand Arm System. The approach consist in building a rough kinematic skeleton based on functional understanding and improving the kinematics design step by step using intuitive tests and fast prototyping. The tests are based on medical evaluation tests as well as daily grasping tasks. These tests are simple and fast; it allows very short iteration cycle, hence creating a real synergy between the hand design and the hand applications.

In the first part, the methodology is presented in details. The tests used to evaluate the performance are described. The second part explains the method through an example. First an initial model, with a set of free parameters is described. Then, the model is used on different tests. Depending on the results the parameters are modified and the tests are performed again until satisfaction.

The presented method must be adapted to the needs of each project. The relevance of the parameters obtained in the results section is limited to the specific case of the DLR hand.

[3]The well known criteria to evaluate serial robots like dexterous workspace and manipulability and even grasp stability criteria haven't been shown suitable for hand kinematics optimization and even functional evaluation

II. METHODOLOGY

There is no optimal kinematics but a variety of almost 7 billions well working ones.

Having a short look at the surrounding human hands highlights one often neglected fact: The hands of human individuals cover a very wide range of segment length, joint locations, length to width relationships (Fig. 2) and joint limits (Fig. 3) without major impacts on the persons grasping abilities.

Fig. 2. Hands of 2 team members proving that human beings have clearly different hands. The exact geometrical properties are not of prime importance but rather the functions they create.

In consequence, regarding the design of the hand of the DLR Hand Arm System the optimality is a vague notion. The focus for the design is to *fulfill all functional needs* of a hand and be aesthetically pleasant. Therefore, a suitable set of medical tests, derived from decades of hand surgery, and daily life object grasping tests is more effective than a set of mathematical calculations. Indeed, expressing the quality of a grasp is easily done under human supervision but very difficult under automated software. Therefore, the hand kinematics is designed by an empirical iterative process using a set of tests selected for the DLR hand needs. It guarantees that the final design will fulfill all the functional needs (human supervision prevents the risk of overfitting to the training data).

Taking this into account appropriate kinematics using a given number of DOF for robot hands can be found by:

- understanding the basic functionalities of the human hand and transferring them to an initial kinematic skeleton
- prototyping the kinematics in reality or simulation
- analyzing the resulting kinematics using a set of tests
- iterative redesign of the kinematics
- repeating the process until satisfaction

A. Hand Skeleton

To derive important basic functionalities three major regions of interest can be defined:

- palm

Fig. 3. Passive motion limit of authors and coauthors thumb

- fingers
- thumb

The palm includes the Hamatocarpal joint (HMC) located at the lower end of the fifth finger metacarpal bone (located in the palm) which enables motion of the metacarpal bone and palm flexion. This motion toward the thumb improves the opposition and enables more inward orientation of the 5th finger.

The palm of the human hand is spanned by the metacarpal bones of the fingers. The fingers, consisting of the proximal, medial and distal phalanges (bones), are connected to the metacarpals by the metacarpal joints (MC). The joints of the fingers, so called interphalangeal joints, starting from the proximal phalanx are the PIP (proximal interphalangeal joint[4]) and the DIP join. The thumbs PIP (MP) number of DOF is not completely consistent within literature [18], [19] (Fig. 4).

Since the thumb is crucial for the grasping performance[5] it should be payed extra attention during the functional analysis as well as during the design process.

B. Joint types

The human hand uses hinge-, condyloid- and saddle joints. For the kinematics design the condyloid joints, which are not practically feasible in a technical system, can be represented by cardan joints if the first axis of the joint is roughly orthonormal to the palm [20].

C. Twist and inclination

Since a serial column of orthogonal axis joints does not change orientation of the fingertip out of the sagital plane[6] this can be done introducing axis inclination ϵ (angle of the joint axis[7] within the frontal plane Fig. 6a, Fig. 4) and twist ζ (rotation of the axis around the longitudinal axis of the phalanx Fig. 6b, Fig. 4).

As shown in [21] the fingers of the human hand also have inclination within the PIP and DIP joint. The inclination angle is increasing starting form the index toward the 5th finger. The inclination of the joint axis enables the fingers to be parallel in straight position whereas it turns the fingertips toward the inside of the palm when flexing. This inward orientation plays a central role with fine manipulation of small objects like balls. Furthermore, it dramatically increases the opposition quality of the thumb with the 4th and 5th finger [20].

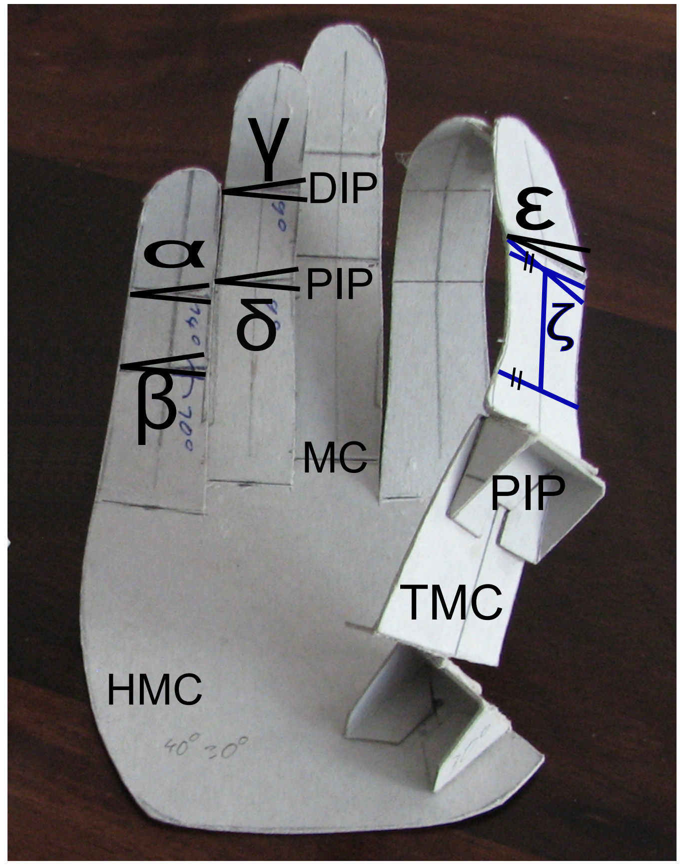


Fig. 4. Joints of the hand and varied parameters

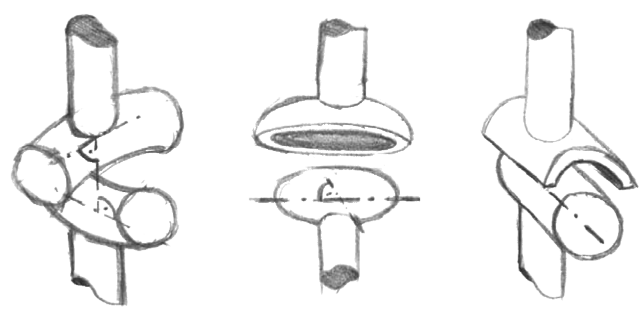


Fig. 5. Saddle-, condyloid- and hinge- joint

III. Evaluation Tests

To improve the kinematics within the iteration process the qualities of the realized kinematics are evaluated by human supervised tests. These can be grouped into:

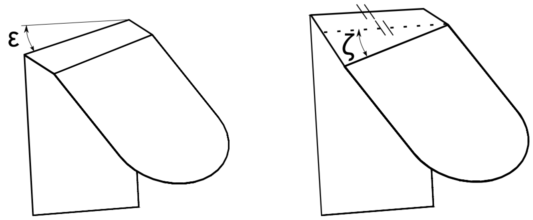
- tests derived from hand surgery

[4]anatomically correct the PIP of the thumb is named MP joint

[5]The importance of the thumb can be seen by insurance rates for the loss of a thumb which is twice the sum payed for the loss of an index finger.

[6]middle- plane of the finger

[7]Inclination of the joints is defined as the angle of deviation of the axes from the perpendicular position



(a) Inclination (b) Twist

Fig. 6. Joint angle variation and its effects

- grasping tests
- aesthetic tests

1) Medical tests: The loss of a finger or even hand is a dramatic limitation of the humans ability to work and live, impairing the individuals life quality. Therefore, there have been tremendous achievements in hand surgery in the past decades. For example, the loss of a thumb can be partially compensated by replacing the missing thumb by the middle or the index finger. The hands capabilities can be restored almost completely by these surgeries called policization [22].

Hand surgeons developed a set of fast and reliable tests to evaluate the success of the surgery and therefore grasping ability. These tests can be applied to robot hands as well since they evaluate the grasping and manipulation capabilities of the hands regardless whether they are human or robot hands. A well known example of such test is the Kapandji Test (Fig. 8). It is a testing routine to evaluate the reachability of several partially combined finger positions. The positions used for the design of the DLR- Hand Arm Systems are:

- Contact of thumb fingertip with metacarpal (MC) (Fig. 4, 8c, 8d) base of all fingers
- Contact of the fingertip pulp of the thumb to the tip of index and 5th finger without reconfiguration of PIP and DIP (Fig. 4, 8a, 8b) joint positions (5th Finger Test)

For more accurate investigation of the grasping abilities and in order to account for natural grasp distribution a more advanced scoring scheme can be applied to the Kapandji Test [23].

2) Grasping: The variety of grasps existing is tremendous and would go beyond the scope of this paper but a subset of them are commonly used to evaluate the capabilities of hands. Only few examples are listed which are representatives of the most important grasping functions:

- key grasp
- pinch grasp
- grasping of cylindrical objects in different sizes
- grasping of spherical objects in different sizes

An overview of grasping tasks can be found in [24], [21], [25], [18].

3) Aesthetics: The overall appearance of the hand is important when performing human interactions. The hand should look balanced and should be easily accepted (similar to the prosthesis design philosophy). It is recommended to perform everyday grasping tasks using the prototypes within the natural surroundings (desk, home etc.) since it provides a good scaling reference and supports intuition.

Joint:	thumb	index	middle	ring	5th
(T)MC	2DOF	2DOF	2DOF	2DOF	2DOF
PIP	1DOF	1DOF	1DOF	1DOF	1DOF
DIP	1DOF	1DOF	1DOF	1DOF*	1DOF*
$\sum$	4	4	4	3+1*	3+1*+1 HMC

TABLE I
DOF OF THE FINGERS (*COUPLED DOF).

IV. CASE STUDY

In the following we exemplify the proposed design method showing the design process of the hand of the DLR Hand Arm System.

A. Initial Kinematics

In the DLR hand, due to the design constraints, the maximum number of active DOF is 19. The hand should have anthropomorphic grasping and manipulation abilities but should limit in its DOF to fit the restricted design space of the forearm [20], [1]. In consequence, the thumb has 4 DOF (instead of 5), but this does not impair the abilities of the hand. The impressing results of policization (see III) in hand surgery prove that a 4 DOF thumb is sufficient for a majority of grasping tasks [22]. Following [18], [26] the TMC geometry of the thumb in addition to the 2nd degree of freedom in the PIP results in an inward orientation of the pulp during TMC and PIP flexion. This change of orientation is crucial for proper opposition of the thumb to the fingers while grasping e.g. a cylindrical object [20], [22]. Therefore, the lack of the 5th degree of freedom has to be compensated.
The experiences with DLR Hand II [27] have shown that coupling PIP and DIP of the 5th and ring finger is not problematic but also reduces the number of active DOF[8]. The starting configuration can be seen in table I.

As starting point we built several prototypes based roughly on [18],[11] and direct measurements of a human hand. Given that the thumb is by far the most important finger within the hand, the location and the orientation of the axes of the TMC joint as well as the PIP and DIP joint angles (of the thumb) have been set up in varying configurations:

- Thumb base joint located within the palm
- Thumb base in front of the palm
- Thumb axes of TMC orthogonal
- Thumb axes of TMC nonorthogonal
- Thumb PIP without twist and inclination
- Thumb PIP with twist
- Thumb PIP with inclination
- Thumb PIP with twist and inclination

The inclination and twist values of the PIP and DIP axis are used as parameters during the the second phase of the kinematics design. It has to be noted that to start it is important to realize a wide range of different prototypes. It prevents

[8]The coupling was not taken into account for the kinematics prototypes.

local extremum, as a randomized process does in numerical optimization.

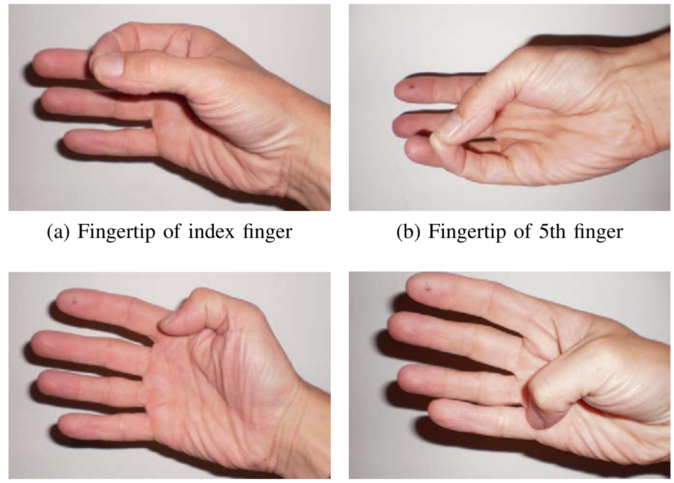
B. Prototyping

Inspired by [18] cardboard prototypes are used (Fig. 7). Fast prototyping methods (STL or equivalent) can also be used. Software prototyping [4], [28], is another alternative but lacks the physical interaction needed to “feel” the design. The card board prototypes have the advantage of being very fast, easy to modify and cheap, however their flexibility and limited accuracy limit their use to the first development steps. Using physical prototypes grasping common objects can be performed without any additional modelization effort. ”Gambling around” with the prototypes is important and helps because the human being, even having limited or no grasping/kinematics knowledge, has a pretty good intuition about good or bad kinematics. A final refinement is done using simulation for the thumb joints and is also recommended to make final adjustment of kinematics. Certainly, interference problems are best detected using a 3D model.

Fig. 7. Four samples on the left have been built for the evaluation of the thumbs parameters. The 4 hands on the right are used to investigate the inclination of the 4th and 5th finger. These hands lack a movable thumb for handling reasons. This is not advised since this test is contradictory to thumb opposition (see IV).

C. Application of the Tests/ Kinematics Improvement

In the following the results of the applied tests as well as exemplary measures are given. It enables the hand designers to use the method for their own purpose. Further, the incompatible sets of tests are highlighted. Tradeoffs have to be selected depending on the relative tests importance. Kinematics prototypes of an early, mid and almost final state of the kinematics are shown. The prototypes are modified or rebuilt repeatedly using the tests described in section III until a satisfying solution is found. The iterative process mostly relies on the designer’s intuition or state of the art and anatomical knowledge in the beginning. However, once the main parameters like joint location or order of axes are fixed the tuning can be done by taking appropriate measures to improve the kinematics instead of building rather arbitrary



(a) Fingertip of index finger (b) Fingertip of 5th finger

(c) Base of index finger (d) Base of 5th finger

Fig. 8. Most important positions of the Kapandji Test

prototypes. The parameters modified within the examples are shown in table II.

Finger	Parameter	Range
thumb	TMC position	$\approx$20mm distal and palmar
	TMC 1st axis orientation	
	TMC angle between axis	[60,90]
	ϵ inclination DIP	[0°,5°]
	ζ twist between PIP and DIP	[0°,9°]
ringfinger	δ inclination PIP	[5°,9°]
	γ inclination DIP	[5°,9°]
5th finger	β inclination PIP	[10°,14°]
	α inclination DIP	[10°,14°]

TABLE II
VARIED PARAMETERS WITHIN SHOWN HANDS

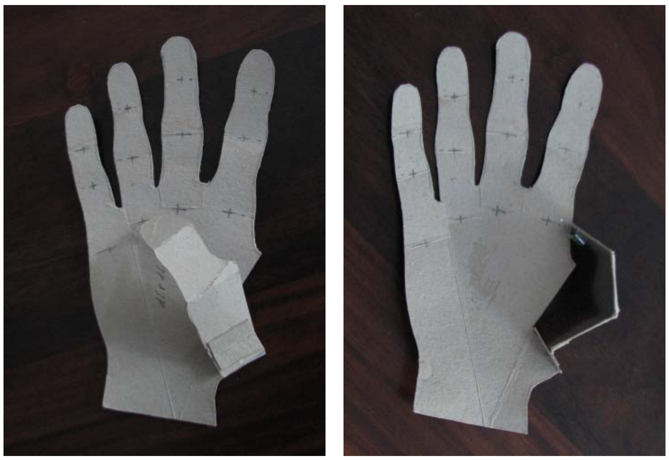
1) Kapandji Test with Different Thumb Configurations: The Kapandji Test [22], [29] developed for hand capabilities evaluation in surgery enables a really fast and reliable method to evaluate the thumbs ability to move to all necessary positions for proper grasping (see Fig. 8 and III-1). Therefore, it was the first test performed with every thumb configuration. The Kapandji Test should be performed with every prototype even in later ”fine-tuning” stages to ensure good grasping and manipulation performance.

The capability of the thumb to reach all finger bases is dominated by the point of intersection of the first axis of the thumb and the palm[9]. If the point of intersection is located at the basis of one finger the thumb is within its singularity and therefore not able to reach any other position of the palm[10](Fig. 9a). Further a thumb TMC placed to close to the palm frontplane leads to sideways collision of thumb and index finger and its ”metacarpal bone” (Fig. 9b).
Measures to improve Kapandji Test results:

[9]A first axis not pointing towards the palm leads to unnatural motion of the thumb and fails almost all test. Therefore it is not shown.

[10]if the thumbs fingertip is located within or nearby the middle (sagital) plane of the thumb

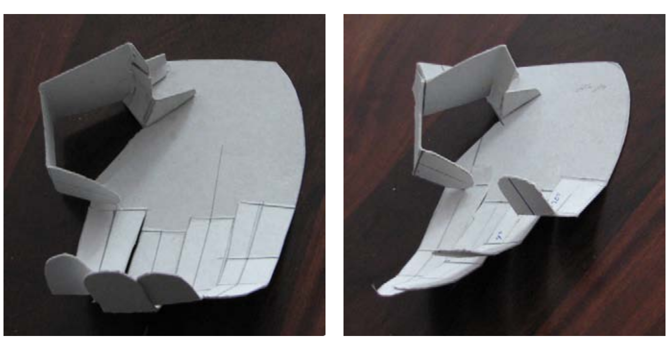
- To enlarge the range of reachable finger bases, the intersection point of first axis and palm has to be more distant from the finger bases.
- If the thumb collides with the index finger sideways the TMC base has to be placed further in front of the palm.



(a) Single point contact (b) Lateral contact

Fig. 9. Hand with TMC and first thumb axis within palmar plane performing Kapandji Test

The improved configurations shown in Fig. 10 achieve better results since their TMCs are placed in front of the palm and the first axis meets the palm distant from all metacarpals. Both hands use the final thumb position and identical axes orientations. The thumb on the right (Fig. 10b) has inclination and twist (Fig. 4) within the PIP axis[11] to improve grasping of large cylindrical objects (see IV-C2). The position of the thumb of the hand lacking twist and inclination(Fig. 10a) performing the Kapandji Test at the MC of the index finger is more natural (which can easily be determined by comparison) than the one of the design having inclination and twist (Fig. 10b) but the latter performs better for power grasps of large objects (IV-C2 Fig. 13b).



(a) No twist and inklination (b) With twist and inklination

Fig. 10. Kapandji test of three configurations with thumb MC placement in front of the palm

[11]which moves the thumbs tip out of the sagital/middle plane in flexed position

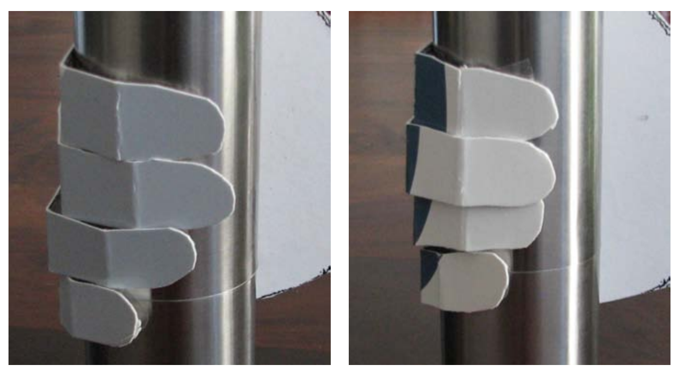
2) Grasping Tests: While the Kapandji Test is used to improve the thumb and its base joint, the grasping tests are used to improve the kinematics of the fingers and the thumbs PIP and DIP.

Finger Joint Axis Inclination Evaluation Performing Power Grasp: Since it is obvious that the bigger the inclination of the PIP and DIP joint of the 4th and 5th finger is, the better it will oppose to the thumb[12], a single test checking incongruous configuration is sufficient to identify proper inclinations. Too large inclinations increases the risk of overlapping of the fingers while performing power grasps, since their proximal phalanges are parallel during power grasp [20]. Therefore, a simple power grasp test was performed. The initial value for the joint inclinations was adopted from [18].

For the chosen length of segments the initial values were clearly too large (identical values for 5th and ring finger). As a result, a considerable overlapping occurred between the middle and the ring finger (Fig. 11b). Hence, the values have been decreased resulting in less overlapping (Fig. 11a) while still enabling proper opposition to the thumb. For fine tuning the inclinations collision checks are performed in simulation to improve accuracy. Overlapping must be avoided since it prevents proper powergrasp.

Measures tuning PIP DIP inclination:

- Start with large inclination angles
- To reduce overlapping of the fingers reduce inclination
- To improve opposition increase inclination
- Start with the finger being closest to the index that has inclination[13]



(a) Medium inclination of ring and 5th finger (b) High inclination: Overlapping between middle and ring finger

Fig. 11. Testing inclination of PIP and DIP joints performing power grasp on a pepper mill. The used prototypes have no mobility within the thumb and the metacarpal joints of the fingers and are fixed using tape for visualization purpose which is not optimal for positioning of the fingers).

Tuning Twist and Inclination of Thumb Joints: As shown in section IV-A the missing 5th DOF within the thumb of the DLR Hand Arm System has to be compensated. The introduction of axis inclination and twist is an efficient solution. Hence, new prototypes with and without joint inclination have

[12]within a meaningful range

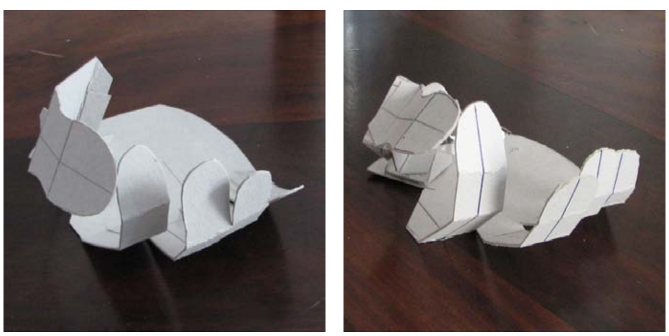
[13]ring finger in our case

been built. These have to undergo the already mentioned tests as well as everyday object grasping tests. Two contradictory grasping tasks are shown in the following:

- key grasp
- power grasp of a cylinder

To perform a key grasp, the pulp[14] of the thumb has to be tangent to the longitudinal axis of the distal or medial phalanx of the index finger. In contrast to perform a power grasp the sagital (middle) plane of the thumb has to be almost parallel to the sagital plane of the index finger to bring the pulp[15] of the thumb in contact to the object.

Key Grasp:
Performing a key grasp it can be seen that a thumb with inclination and twist[16] does not bring the front of the thumbs tip in perfect contact to the side of the index finger (Fig. 12b) whereas a thumb without these performs an almost perfect key grasp (Fig. 12a). But the angle of the inclined and twisted version is small enough to be compensated by the soft materials of the fingers housings.

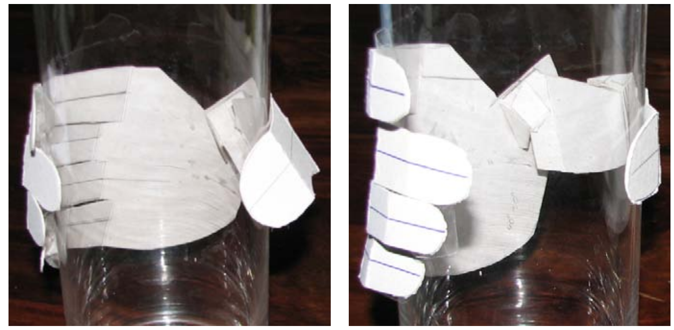


(a) No twist or inclination (b) Twist and inclination

Fig. 12. Key grasp with a thumb without and with inclination and twist

Power Grasp of Large Cylindrical Object
During powergrasp, the angle between the frontal surface of the thumb and the object is far from ideal if it is lacking inclination and twist (Fig. 13a). During this type of grasp, the thumb is almost stretched out. Therefore, a twist of the thumbs joint axis is more effective than an inclination.

Due to the superior performance during power grasp (which is a much more common grasp in robotic applications than key grasp) the thumb configuration using inclination and twist has been chosen.
Measurements tuning thumb inclination and twist:



(a) No inclination and twist (b) With inclination and twist

Fig. 13. Power grasp of large cylindrical flower vase

- To improve contact doing keygrasp twist PIP joint outward of the palm.
- To improve contact performing large object grasps twist PIP inward.
- To improve powergrasp of small objects increase/ decrease inclination of thumb PIP and in especial DIP. Inclination of in especial DIP does not affect keygrasp and large object powergrasp too much since DIP is almost stretched out.

It has to be clearly stated that to balance the values for inclination and twist of the thumb joints to meet the requirements of the aimed hand, is the most difficult part of the design and needs several iterations. Final fine tuning is performed in simulation in parallel to the cardboard tests to help the visualization of the finger pulp shape.

3) Contrary Tests/ Measurements: In the following above mentioned tests are shown that are conflicting and therefore need further attention:

- Kapandji Test ⇔ grasping of large objects:
  If the intersection point of the first axis of the thumb is located too low and close to the thumbs base joint the singularity on the backside gets closer to large objects surface of contact to the thumb. This results in limited motion range of the thumb doing this kind of grasp. Therefore, a compromise between both has to be found. The Kapandji Test should be passed completely because it is related to the most frequent grasp and manipulation situations.
- Key grasp ⇔ grasping of large objects:
  No rule can be given to solve this conflict. Parameters must be balanced out.
- Inclination: Kapandji Test ⇔ overlapping:
  Overlapping disables powergrasp. The inclination should not create any overlapping.

V. Discussion and Future Works

A fast and effective method to generate and improve a hand kinematics to fulfill the *functional* needs of the DLR Hand Arm System has been presented. This method is a tool for hand designers to drive the design toward more functionality. A set of fast and reliable tests, derived from hand surgery and everyday grasping situations, is used to check the functionality

[14]the soft frontal surface of the distal phalanx

[15]The pulp is much softer than the side of the thumb and therefore offers better grasping. Contact of the side of the thumb during strong power grasps also would be painful.

[16]The inclination of the joint axis does not change orientation of the thumbs tip during key grasp since PIP and DIP are in (almost) stretched out position.

of the kinematics designed based on a functional analysis of the joints of the human fingers. A catalog of measures that helps the hand designers to improve the kinematics depending on the tests results is proposed. The application of this method to the hand of the DLR Hand Arm System is shown. The method was primarily developed as an alternative, or a parallel, to complex simulation environments. The small ressources requirement and the short iteration time permit to reduce the design effort involved in realizing kinematics prototypes. Thanks to its simplicity it can be used by hand designers easily.

The method could be improved by enhancing the set of tests to be performed and defining a set of grasping situations (e.g. for standardization purpose). A more objective rating of the test results would help hand designers to balance contradictory measures, but certainly at the expense of effectiveness.

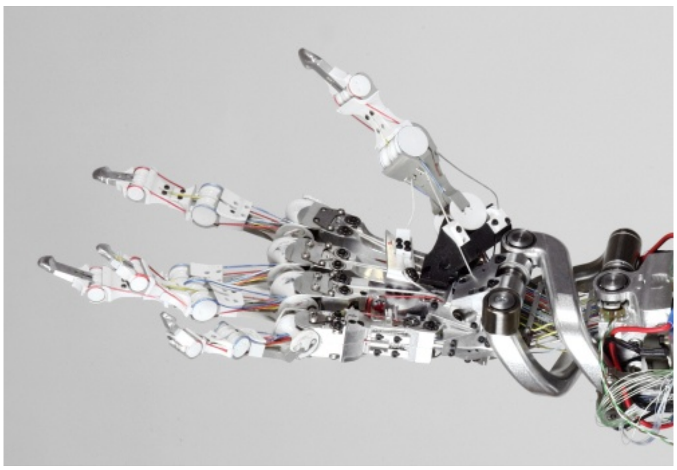


Fig. 14. Final hand

Fig. 14 shows the kinematics model used in the DLR Hand Arm System. A first evaluation has been done using dataglove input to articulate a kinematic simulation. The Kapandji Tests are performed sucessfully. The hand will be tested in various grasping and manipulation situations in the future work.

VI. Acknowledgement

The authors would like to thank A. Kapandji for the fruitful discussions about the human hand, thumb kinematics and "potato mechanics". This work was partly funded by the FP7 project THE Hand Embodied Grant agreement no.: 248587.

References

[1] M. Grebenstein and P. Smagt van der, "Antagonism for a Highly Anthropomorphic HandArmSystem," *Advanced Robotics*, no. 22, pp. 39 – 55, 2008.

[2] F. Lotti, P. Tiezzi, G. Vassura, L. Biagiotti, C. Melchiorri, and G. Palli", "UBH 3: A Biologically Inspired Robotic Hand," in *"Proc. of IEEE International Conference on Intelligent Manipulation and Grasping IMG 04, Genova, Italy, 1-2 July 2004"*.

[3] C. S. Lovchik and M. A. Diftler, "The Robonaut hand: a dexterous robot hand for space," in *Proc. IEEE International Conference on Robotics and Automation*, vol. 2, May 10–15, 1999, pp. 907–912.

[4] A. Miller and P. K. Allen, "Graspit!: A Versatile Simulator for Robotic Grasping," *IEEE Robotics and Automation Magazine*, vol. 11, no. 4, pp. 110–122, Dec 2004.

[5] W. B. Griffin, R. P. Findley, M. L. Turner, and M. R. Cutkosky, "Calibration and mapping of a human hand for dexterous telemanipulation," *ASME IMECE 2000 Conference on Haptic Interfaces for Virtual Environments and Teleoperator Systems Symposium*, 2000.

[6] D. J. Giurintano, A. M. Hollister, W. L. Buford, D. E. Thompson, and L. M. Myers, "A virtual five-link model of the thumb." *Medical Engineering and Physics*, vol. 17, no. 4, pp. 297–303, June 1995.

[7] A. Hollister, W. L. Buford, L. M. Myers, D. J. Giurintano, and A. Novick, "The axes of rotation of the thumb carpometacarpal joint." *J Orthop Res*, vol. 10, no. 3, pp. 454–460, May 1992.

[8] A. Hollister, D. J. Giurintano, W. L. Buford, L. M. Myers, and A. Novick, "The axes of rotation of the thumb interphalangeal and metacarpophalangeal joints." *Clinical Orthopaedics & Related Research*, no. 320, pp. 188–193, November 1995.

[9] P. van der Smagt, M. Grebenstein, H. Urbanek, N. Fligge, M. Strohmayr, G. Stillfried, J. Parrish, and A. Gustus, "Robotics of human movements," *Journal of Physiology-Paris*, vol. 103, no. 3-5, pp. 119 – 132, 2009.

[10] H. Geuss, "Development of a anthropometry measurement system for the CAD man model RAMSIS," Ph.D. dissertation, TU Munich, 1994.

[11] F. Purschke, M. Schulze, and P. Zimmermann, "Virtual reality-new methods for improving and accelerating the development process in vehicle styling and design," jun 1998, pp. 789 –797.

[12] V. Santos and F. Valero-Cuevas, "Anatomical variability naturally leads to multimodal of denavit-hartenberg parameters for the human thumb," vol. 2, sept. 2003, pp. 1823 – 1826.

[13] V. J. Santos and F. J. Valero-Cuevas, "A bayesian approach to biomechanical modeling to optimize over large parameter spaces while considering anatomical variability," in *Proc. 26th Annual Int. Conf. of the IEEE Engineering in Medicine and Biology Society IEMBS '04*, vol. 2, 2004, pp. 4626–4629.

[14] T. Yoshikawa, *Foundations of Robotics: Analysis and Control*. Cambridge, Massachusetts: MIT Press, 1990.

[15] M. T. Rosenstein and R. A. Grupen, "Velocity-dependent dynamic manipulability," department of Computer Science University of Massachusetts Amherst, MA 01003 USA mtr@cs.umass.edu, grupen@cs.umass.edu.

[16] J. Craig, *Introduction to Robotics: Mechanics and Control*. Addison-Wesley, 1989.

[17] S. Arimoto, J.-H. Bae, and K. Tahara, "Stability on a manifold: Simultaneous realization of grasp and orientation control of an object by a pair of robot fingers," in *IEEE International Conference on Robotics and Automation*, 2003, pp. 2336–2343.

[18] I. A. Kapandji MD, *The Physiology of the Joints, Volume 1: Upper Limb*. Churchill Livingstone, 2007.

[19] A. Benninghoff and D. Drenckhahn, *Anatomie. Makroskopische Anatomie, Histologie, Embryologie, Zellbiologie, Bd 1.* Munich: Urban & Fischer at Elsevier Munich, 2002.

[20] M. Grebenstein, M. Chalon, G. Hirzinger, and R. Siegwart, "Antagonistically driven finger design for the anthropomorphic DLR hand arm system," in *Proc. 10th IEEE-RAS International Conference on Humanoid Robots HUMANOIDS 2010*, 2010.

[21] R. Tubiana, *The Hand Volume I*, R. Tubiana, Ed. W. B. Saunders Company, 1981.

[22] M. Chalon, M. Grebenstein, T. Wimboeck, and G. Hirzinger, "The thumb: Guidelines for a robotic design," in *Proceedings 2010 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2010.

[23] X. D. soras, D. Guinard, F. Moutet, and P. Gerard, "Fiche de cotation fonctionelle," in *Ann. Hand Surg*, 1994, vol. 13, no. 5, pp. 297–307.

[24] S. Schulz, C. Pylatiuk, and G. Bretthauer, "A new ultralight anthropomorphic hand," in *Proceedings of the IEEE International Conference on Robotics and Automation*, vol. 3, 2001, pp. 2437–2441.

[25] M. R. Cutkosky, "On grasp choice, grasp models, and the design of hands for manufacturing tasks," vol. 5, no. 3, pp. 269–279, 1989.

[26] K. Kuczynski, "The thumb and the saddle." *Hand*, vol. 7, no. 2, pp. 120–122, Jun 1975.

[27] J. Butterfass, M. Fischer, M. Grebenstein, S. Haidacher, and G. Hirzinger, "Design and experiences with DLR hand II," in *Proceedings of the World Automation Congress*, vol. 15, 2004, pp. 105–110.

[28] C. Borst, M. Fischer, S. Haidacher, H. Liu, and G. Hirzinger, "DLR Hand II experiments and experience with an anthropomorphic hand," vol. 1, sept. 2003, pp. 702 – 707.

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