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Antagonistically Driven Finger Design for the Anthropomorphic DLR Hand Arm System

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Abstract—**The DLR Hand Arm System is a highly dynamic and fully integrated mechatronic system which uses an anthropomorphic design. It exhibits impressive robustness by using a complete variable stiffness actuation paradigm. It aims at reaching the human archetype in most of its performances and its design. The methodology consists in understanding the human archetype on a functional basis rather than to copy it. However, the design is driven by two antipodal concepts: On one hand, the design has to be simple, robust, and easy to maintain. On the other hand it must be anthropomorphic in shape and size but also, more importantly, in functionality.**

The paper presents a finger design that combines a reduced diversity of parts with the need to build five kinematically different fingers. The fingers are protected against overload by allowing subluxation of the joints. The tendon routing allows for an antagonistic actuation and is optimized to minimize friction and wear. The resulting combination of the link design and the antagonistic actuation is shown to be robust against impacts as well as highly dynamic. They achieve the targeted maximum fingertip force of 30 N in stretched out configuration. The use of antagonistic drives enables to tackle problems of tendon overstretching and slackening that commonly encounter in tendon driven mechanisms. Due to the enhanced capabilities and, in especial, its robustness, the application developers can focus on the use of innovative grasping and manipulation strategies instead of worrying about the integrity of a costly robotic systems. The possibility of storing energy in the elastic elements of the drive opens new opportunities to perform dynamics based actions (e.g. snapping fingers).

I. Introduction

An anthropomorphic hand arm system using variable stiffness actuation has been developed at DLR which is aimed to reach its human archetype regarding size, weight and performance (Fig. 1).

The project focuses on the dynamic performance and the robustness against impacts [1]. It has been shown that during collisions with stiff bodies most of the kinetic energy is introduced into the system within the first control cycle [2]. Therefore, a rigid system, even controlled by an impedance law, cannot withstand collisions with hard surfaces at high speed without severe damage. In contrast, a system with passive compliance can store energy at short-term and consequently reduces the resulting forces in the robot structure and drive train. Furthermore, by measuring the maximum throwing range it has been shown that variable stiffness joints are superior to stiff joints regarding their dynamic properties [3]. Hence, a solution to increase robustness against impact is to change the design paradigm from a mechanically stiff robot (using an impedance control) to a robot using variable stiffness joints. In robotic hands, the impact tolerance plays a dominant role. Indeed, in service robotics applications the hand is the most exposed part of the robot and meanwhile it is designed for relatively small forces (typically a few tens of newtons). In highly unstructured environments the maximum velocity of most robotic hand arm systems is limited by the ability of the hand to withstand impacts. Hand developers built many robotic hands targeted for the use in service robotics [4], [5], [6], [7], [8], [9], [10], [11] but only few have been using variable stiffness to enhance robustness and dynamics of the hand. The ACT hand focuses on research in terms of functionality, control and surgery. Therefore, it mimics the human hand closely [12], [13], [14] and does not satisfy robustness and force requirements for a service robotic application. The Shadow hand is intrinsically antagonistically driven since the used actuators are only able to pull by contraction [5], [6]. The used McKibben type actuators enable variable stiffness in a limited way since the range of achievable stiffness is position dependent [15]. Furthermore, the use of pneumatic actuators can rise mobility issues due to the necessity of a pressurized air source.

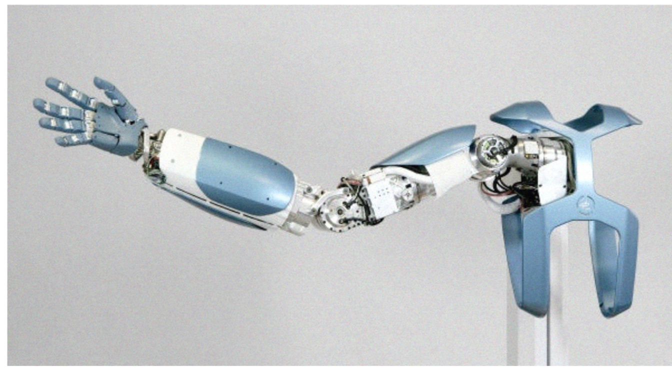

Fig. 1. DLR Hand Arm System

The key point in building a robust and highly dynamic robot finger, while providing needed functionalities, consists in understanding the human hand in a functional abstract way rather than in copying the human physiology. Indeed, the spread between the basic principles and solutions of a bio-mechanic system and a technical system is currently too large

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to be able to copy the human hand. Although, the fingers of the ACT hand have impressively shown that it is possible to build an anatomically correct finger, they lack strength and durability. The available technical materials are not able to withstand the stress and wear of biological solutions since they are not able to regenerate like biological materials of e.g. ligaments, skin or muscles [16], [12]. The paper presents a new approach to hand design that achieves the needed robustness and meets the size objective. The concept transfers the capabilities and functionalities of the human hand to a robotic system using leading edge technology. The design integrates all drives of the hand into the forearm. It routes the tendons through the wrist without limiting its range of motion.

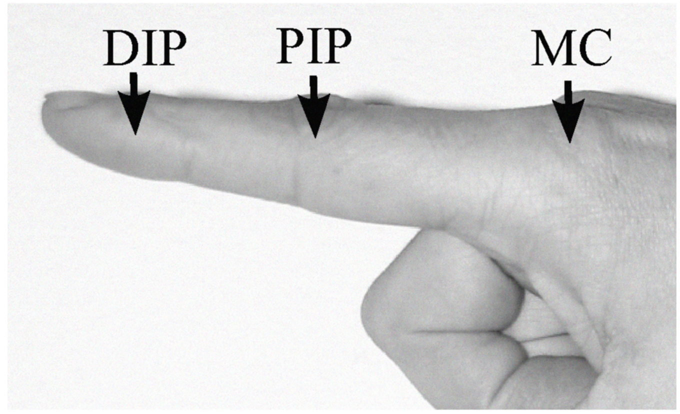
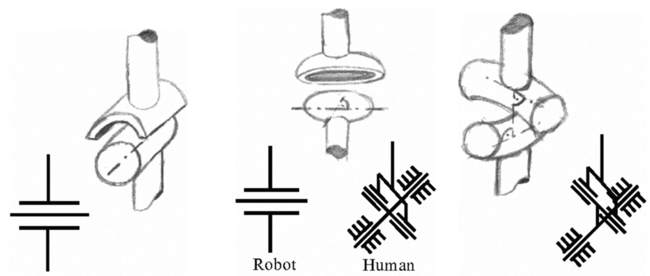


Fig. 2. Joints of the human finger

II. Anatomy of the Human Finger

We think that one key in hand design is not to copy the anatomy of the human hand and its fingers [17], [18] but to understand it in an abstract and functional manner. This abstraction should be the basis of the synthesis of the technical system. This enables to merge the assets of the human hand with the assets of a technical system and to reduce the difficulty of replacing e.g. biological materials with technical ones.
This section presents the anatomy of the fingers and highlights the elements that are important in terms of functionality.



(a) Hinge joint (b) Condyloid joint (c) Saddle joint

Fig. 3. Joint types of the human hand and their representatives. The condyloid joint geometrically seen is a 1 DOF hinge joint, but is used as a 2 DOF joint in biology.

A. The Skeleton of the Human Hand and its Fingers

The skeleton of the human hand can be divided into the bones of the wrist, the palm and the fingers. The fingers of the hand are similar regarding their structure, joints and tendons but differ in a significant way from the thumb having 5 DOF. The thumb, however, has a special opposition function. It is stronger and shorter than the four other fingers and has one bone less than the fingers.

Each finger of the hand has a metacarpal bone building the palm of the hand together with the inter ossei ligaments. The metacarpals are connected to the proximal phalanx (bone) by the 2 DOF metacarpal joint (MC) being followed by the 1 DOF proximal interphalangeal joint (PIP) and the medial phalanx. The medial phalanx ends with the 1 DOF distal interphalangeal joint (DIP) carrying the distal phalanx (Fig. 2).

B. Joint Types of the Human Hand and their Technical Equivalents

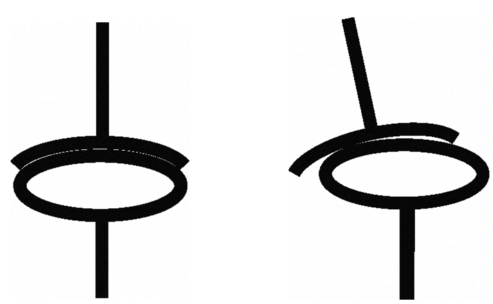
The joints of the human fingers can be categorized into three different types (Fig. 3):

- Hinge joints
- Condyloid joints
- Saddle joints

The DIP and PIP joints of the human fingers are of the hinge joint type. The ridge in the middle of the joint (Fig. 9a) which could be interpreted wrongly as a saddle joint head prevents the finger from being dislocated by axial loads.

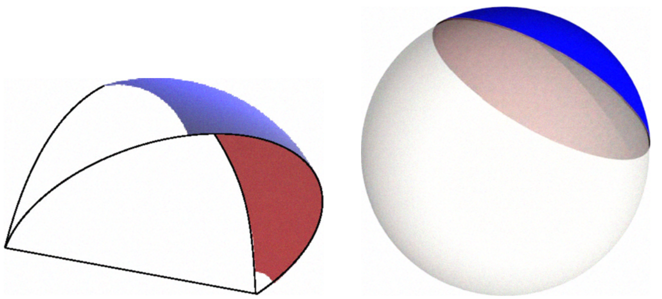
The metacarpal joints of the human fingers, unlike the thumb[1], are of the condyloid (ellipsoidal) [20] type. The ellipsoidal geometry only allows for 1 DOF motion, whereas within the human hand it is used as a 2 DOF joint (the third DOF[2] is blocked by the ellipsoidal geometry of both, the joint socket and the joint head). Motion of such an ellipsoidal joint around any but the main axis inevitably changes surface contact (Fig. 4a) to point contact (Fig. 4b).

[1]formed like the saddle of a scoliotic horse [19]
[2]rotation about the longitudinal axis of the joint link



(a) Surface contact (b) Edge/line contact

Fig. 4. Condyloid joint motion around second axis



(a) Cardan joint (b) Spherical joint

Fig. 5. Schematic range of motion of joints. The cardan joint has a range of motion depending on the elevation angles in flexion/extension

(a) Carrying an object (b) Wrapping an object (Powergrasp)

Fig. 6. Main functions of the fingers at 90°MC flexion. The first axis of the MC is singular in this position. Therefore the fingers have no motion capabilities sideways.

Therefore, a technical copy of a condyloid joint would cause excessive wear on the joint surfaces due to high contact pressure. In human joints the elasticity of the cartilage surfaces and the joint fluid compensates this inaccuracy.

Kinematically seen replacing a condyloid by a 2 DOF cardan joint is not correct. The second axis of a cardan joint changes its function from pitch to roll at 90°flexion of the first axis and is singular in this position. Therefore, the workspace of the cardan joint has the shape of an orange slice (Fig. 5a) unlike a spherical or condyloid joint which has the shape of a conical section of a sphere (Fig. 5b).

The functional analysis of the metacarpal gives valuable hints about how to replace the condyloid joint. At first a simple test of ones finger can be done. Moving the metacarpal joint of the stretched out finger sideways from one motion limit to the other, while increasingly flexing the metacarpal, shows that the shape of the range of motion is more like an orange slice than a cone though the anatomy of the joint itself lets expect the cone-shaped sphere section depicted in Fig. 5b. At 90°flexion[3] the human fingers have a very restricted motion range sideways but are able to roll about their longitudinal axis.

Functionally seen the finger does not need any motion range in the metacarpal joint at 90°flexion since the fingers functions in this position are mainly:

1) fixing an object in the palm by wrapping it and pressing it against the palm (power grasp Fig. 6b)
2) locking the metacarpal joint position with the DIP and PIP of the finger stretched for example to enable to hold large objects at their edges (Fig. 6a)

Under the assumption that the finger functionality, in the flexed position, is limited to the cited cases, the condyloid joint can be replaced by a cardan joint without any major functional impairment. Nonetheless, care must be taken in the choice of the reference frame for the "orange slice".

[3]Every finger of the human hand, excluding the thumb, reaches its singularity at 90°flexion.

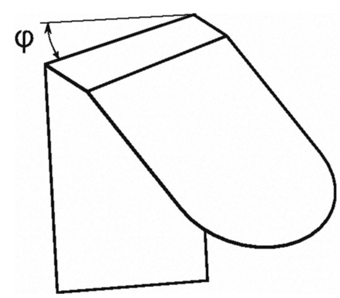
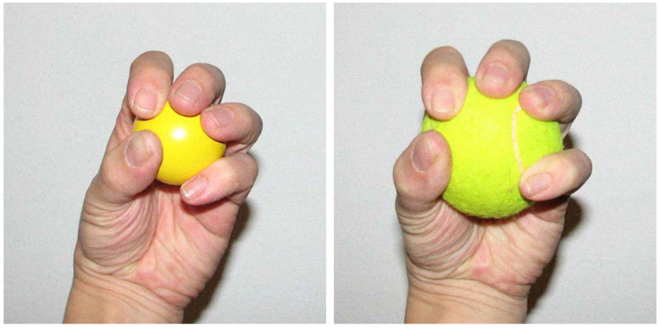


Fig. 7. Rotation of the distal phalanx and reorientation of the medial and distal phalanx due to inclination angle φ. The angle between the phalanges has a maximum of 2 times the inclination angle at 180°flexion, whereas the reorientation angle of the frontal surface of the finger maximizes to the inclination angle at 90°deflection.

C. The Role of Inclinations

Following [17] the axes of the human fingers are not orthonormal to the sagital plane[4]. The inclination of a joint is defined as the angle of deviation of the axes from the normal position within the frontal plane. The inclination of the axes increases from the index to the 5th finger. Functionally seen, the inclination of the axes enables the fingers to be straight in a stretched out position of the joint. This is important to for example carry a heavy box or just push against an object with the flat hand. In a flexed position the inclination lets the phalanges of the finger point towards the middle of the palm increasingly with the angle of flexion which is important for example to grasp a palm size or even smaller ball (Fig.8). Furthermore, it enables opposition of the 5th finger and the thumb. Additionally, the inclination rotates the phalanges towards the inside of the palmpreventing contact of the sides of the fingers with the object and enabling contact of the pulp of the finger (Fig. 7,8).

[4]The sagital plane is the plane spanned by the adduction/abduction (first) axis of the metacarpal joint and the proximal phalanx



(a) Small ball (b) Palmsize ball

Fig. 8. grasping of small balls

III. Design of a Robotic Finger on a Functional Basis

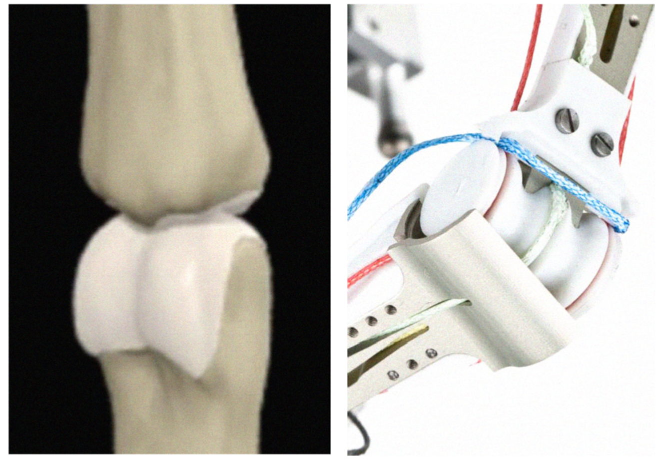
The fingers of the DLR Hand Arm System are antagonistically driven and are human sized. They can withstand very large deflection angle by allowing a subluxation of each of the joints.
This section presents the design of the joints, with a strong focus on the metacarpal joint. The finger structure and the actuation principles are presented too.

A. DIP and PIP Joint

The design of the DIP and PIP joints is quite straight forward since the hinge joints of the human hand are transferable to the robotic hand. Since the weakest parts of the finger are the joints, they have to withstand large impacts without damage. They also require a range of motion of 90°for the DIP and 135°for PIP. In order to limit the control complexity of the fingers no additional non-linearities should be introduced by the tendon actuation. Therefore the tendons are, in contrast to the human hand [16], [17] fixed on a cylindrical pulley providing a constant moment arm. The external loads at the joints are relatively small with respect to the loads introduced by the pretension of the tendons. The index finger provides a 30N force at the fingertip in stretched out position, which is the vicinity of what a human can exert. The relation of the phalanx length to the maximal pulley diameter, which is constrained by the targeted outer geometry of the hand is in between 5.7/1 [5] and 10.8/1 [6] .

The overall load reaching >350N at the PIP of the middle finger excludes the use of ball bearings (considering a bearing size compatible with the envelop constraints). The tendon pretension forces enable to use a open hinge joint consisting of a cylindrical joint head and a joint pan of less than 180°. This open hinge joint does not prevent dislocations by form closure. Hence, the joint can be dislocated by external loads, that are producing forces bigger than the actual tendon forces, without structural damage. Axial movement of the joint is constrained by ridges in the cylindrical shape of the joint head and pan similarly to the human PIP and DIP joints (Fig. 9a, Fig. 9b).

[5]DIP of 5th finger
[6]PIP of middle finger



(a) Human joint (b) Robot joint

Fig. 9. Human and robot PIP- Joint. For geometrical reasons the cylinders of the robot joints have two ridges each.

To prevent damage of the joint surfaces in case of dislocation the ridges have to be rounded to prevent point or edge contacts. Forces parallel to the joint axis have to be carried by force closure. Therefore the insertion points of the tendons, particularly the flexors, have to be located as far from the opposed end of the cylinder as possible. Indeed, it increases the relationship of the levers. Because tendons can only pull, two flexors and one extensor (which is placed within the sagital plane. See Fig. 9b)) are used to create a force triangle.

B. Metacarpal Joint

As shown in II-B, the metacarpal of the human hand can be approximated by a cardan joint without offending the functional needs of grasping if the orientation of the first axis is chosen properly. Since the singularity of the human metacarpal joint is at 90°flexion, the 1st axis of the metacarpal has to be oriented approximately orthogonal to the palm. Because the metacarpal joint has to carry the complete tendon load of the finger column, the applied load on the joint can reach 1.3kN in the middle finger. Therefore, and because of the spacial restrictions, a cardan joint can not be used. A solution has been found analyzing the human thumb. Its base joint (trapezometacarpal joint) is a saddle joint [18], [19] having two non intersecting axis. It carries the loads introduced by the tendons of the human thumb, which is the strongest finger of the hand. The surface pressure in a saddle joint is much lower than in a condyloid joint. Moreover, the saddle joint is geometrically exact and can remain in line contact within the hole range of motion. The metacarpal joint of the fingers has orthogonal, but non intersecting axes. Therefore a pair of hyperboloids is chosen for the metacarpal joint sliding surfaces building a hyperboloid saddle joint (Fig. 10, Fig. 11a, Fig. 11b).

The tendons actuating the metacarpal joint are connected to the hyperboloid in maximum distance w.r.t the perpendicular of the axes. It reduces tendon loads and provides a constant

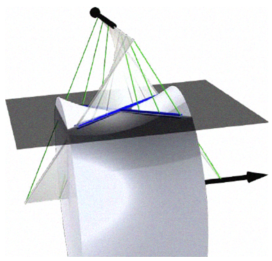
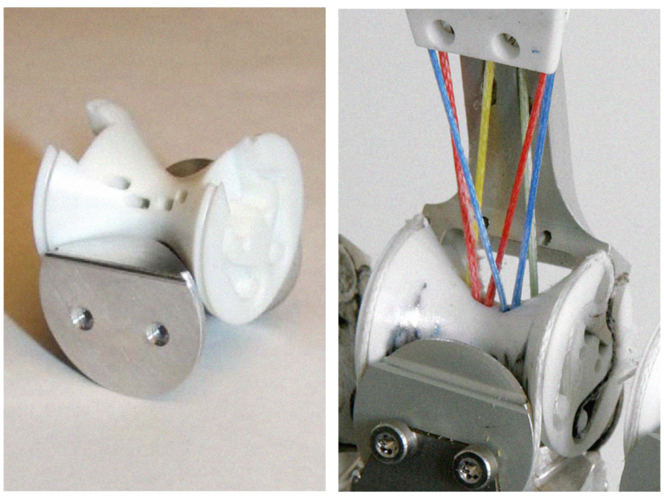


Fig. 10. Hyperboloid generatrix. A line of contact between two rotational geometries having orthogonal non intersecting axes can be found connecting equidistant points on both axis of rotation by straight lines and intersecting these with a plane orthogonal to the perpendicular to both axis. If the line of contact is rotated around one of the axis of rotation it generates a hyperboloid.



(a) Hyperboloids of the MC (b) Assembled MC joint

Fig. 11. Hyperboloid based metcarpal joint

moment arm (Fig. 11b).

C. Structure

The design of the structure of the fingers is pretty straight forward. The use of a endoskeleton like in the human archetype reduces the number of parts and allows to add "pulp"' between the structure and the outer surfaces of the finger. This is crucial to improve the grasp quality and redistribute the stress more uniformly.

D. Tendons

The tendons of the hand have a central role in the design of the hand and its fingers. In contrast to most of the tendon driven hands, proposed design does not need a tensioning mechanism and has no problems caused by geometric inaccuracies (the pulleys, etc...). Indeed, the antagonistic actuation offers intrinsic tendon tensioning. Consequently, the creep properties are not a limiting factor in the choice of the tendon material. After some preliminary experiments on different tendon types it appears that the most important parameters are:

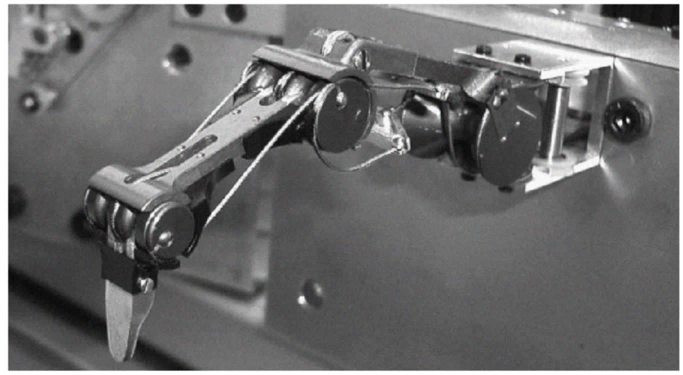


Fig. 12. First finger prototype with external tendon routing

- possible termination/ fixation of the tendons
- robustness against folding during assembly
- wear
- colors (it reveals to be very important during assembly and maintenance)

In order to fit in the desired envelop, especially within the 5th finger, the termination and the fixation of the tendons are crucial. The terminations have to be compact, reliable and reproducible. The steel cables used within the first finger prototype (Fig. 12) turned out to be inapplicable because the terminals are created at production time and too bulky to be inserted into the palm and in especial the hyperboloids during assembly and maintenance. Folding of the tendons during assembly drastically reduces the tendons lifetime and is unfortunately not avoidable. Kevlar or Aramid tendons are much better regarding wear, folding and don't have creep. However their termination is complicated since knots weaken the tendon significantly and are difficult to realize. The tendons braiding prevents splicing which is the best termination technique in our eyes. Tests of the Dyneema tendons revealed a significantly smaller wear than the steel or the Kevlar tendons (especially in sliding contact). Termination can be placed accurately by splicing, it is easy to do and reliable. Therefore, in contrast to [21] Dyneema is selected as the tendon material.

The tendon routing from the insertion points in the joint towards the palm (Fig. 13) has to fulfill the following constraints:

- Linear transmission characteristics
- Minimal friction
- Easy maintenance

When redesigning the routing in the MC joint with the Dyneema tendons, it has been decided to route the tendons internally (Fig. 13). It reduces the coupling of MC-joint motion and DIP/PIP motion drastically (i.e. a motion of the finger base has little, if no, influence on the PIP and DIP joint positions). This routing also reduces the wear of the tendon since the tendons are changing direction only in a planar way (in the first design the tendon "rolled" on the guiding surface).

The connection of the flexors of each joint to the wrist tendons is located within the palm. Indeed, a direct connection between the MC joint and PIP joint would have introduced a

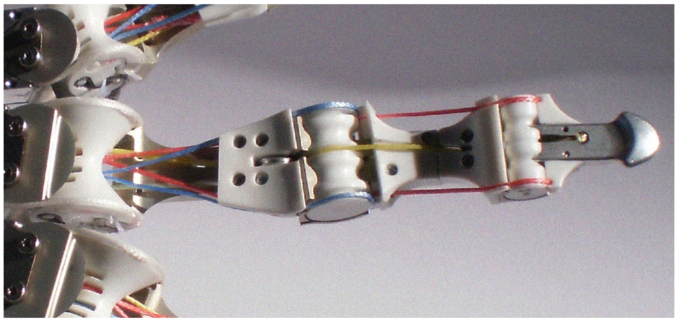


Fig. 13. Second version of finger using internal tendon routing

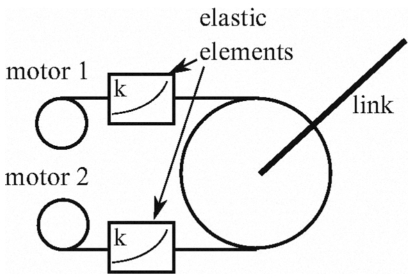


Fig. 14. Antagonistic drive principle

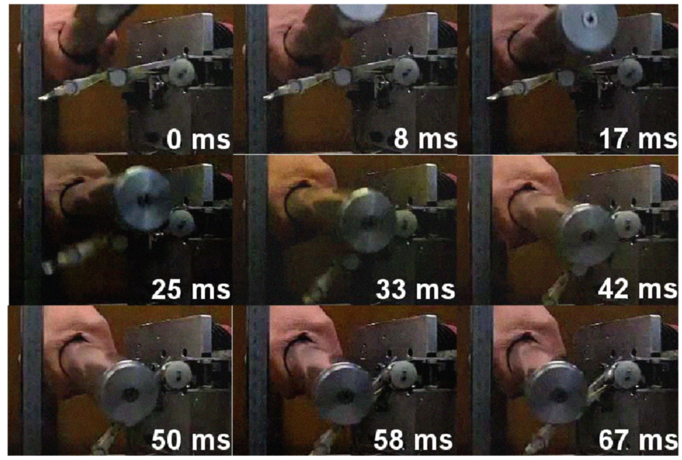


Fig. 15. Highspeed pictures of collision. The finger is hit with a 788g aluminum cylinder at a speed of 3.8m/s without any damage

non linearity in the transmission characteristics. It would not be possible for the fingers with a PIP inclination. The guiding of the tendon towards the insertion points is done via sliding surfaces. The guiding parts have been machined out of low friction bearing plastics to reduce overall tendon friction to a minimum[7].

E. Actuation

The fingers of the hand are actuated antagonistically (Fig. 14) using two motors and two elastic elements for each DOF. To prevent dislocation of the joints a minimum tension of 5-10N is applied to each tendon during operation. Since the drivetrain is not backdrivable the tendons remain under tension in poweroff. All 38 motors necessary to actuate the 19 active DOF of the hand are located in the forearm. More detailed information can be found in [1].

IV. Results/ Validation

A complete set of fingers for left and right hands has been built. An index finger prototype using steel cables and the final index finger design using Dyneema tendons have both been tested on a finger testbed. The same properties of the actuators, the spring characteristics and storable energy were used to perform a series of design validations. In especial, the dynamical and robustness properties have been validated in experiments. The hand (Fig. 21) is currently assembled to the arm system and initial tests are performed.

A. Robustness Against Impact

To test the robustness of the final finger design, the motors were set to minimum stiffness control (approx. 10N tendon force)[8]. While controlling the direct drive motors in position control the finger was hit by a cylindrical bar at a speed of 3.8 m/s at the cylinders tip. During the impact high speed pictures at a framerate of 600/s have been taken (Fig.15). The motor positions, motor currents, and the elastic element elongations were recorded simultaneously.

The finger withstood the collision without damages to structure, joints or tendons. The measured position data of the motors and the elastic elements have been transformed to angular positions/ velocities of the joints. The elastic element stores the impact energy at short-term which reduces the required motor speed to 475°/s, in contrast to a maximum joint speed of 2950°/s (Fig. 17, Fig. 16) measured by the elastic elements. The duration of the impact is extended from 5ms at the elastic elements to 25 ms at the motors (Fig. 17,16). The drives of the hand would not be able to withstand the impact without the elastic elements due to the resulting impact forces and their limited maximum velocity of 540°/s.

B. Dynamics of the Fingers

Using the setup from IV-A the dynamic properties of the final design have been evaluated measuring the maximum speed generated by the energy stored within the elastic elements. Starting with a 17°deflection (from zero position) at the MC joint the finger is released while the position controllers keep the MC joint motors at zero position. Highspeed pictures and measured data are used to evaluate finger joint speed (Fig. 18). The finger reached a maximum angular speed of 1680°/s in the MC joint without active joint actuation. The slight change of the motor position is the controller steady-state error under load. It is limited to 64°/s. The active maximum speed of the joint motors is 540°/s and increases maximum MP- joint velocity further.

V. Conclusion

The existing hand arm systems used in service robotics are still not able to compete with the performance of the human

[7]measured friction coefficient <0.1

[8]The minimum stiffness is set to prevent tendon dislocation at the pulleys

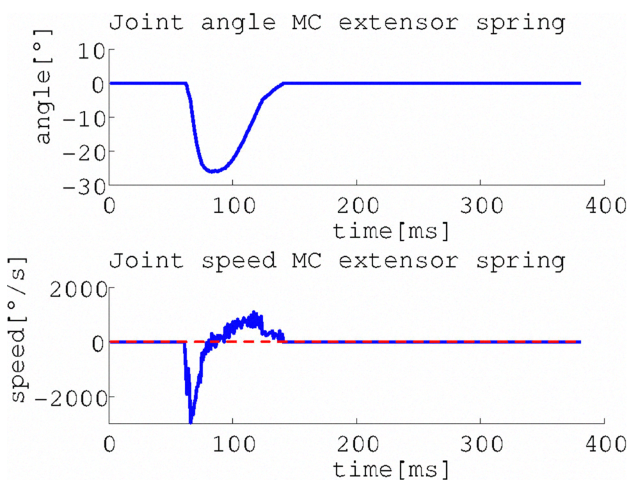


Fig. 16. MC elastic element positions of extensor and velocities of extensors (blue) and flexors (red) during collision. The positions and velocities are calculated as the average of both flexor/extensor motors and elastic element and transformed to the MC joint

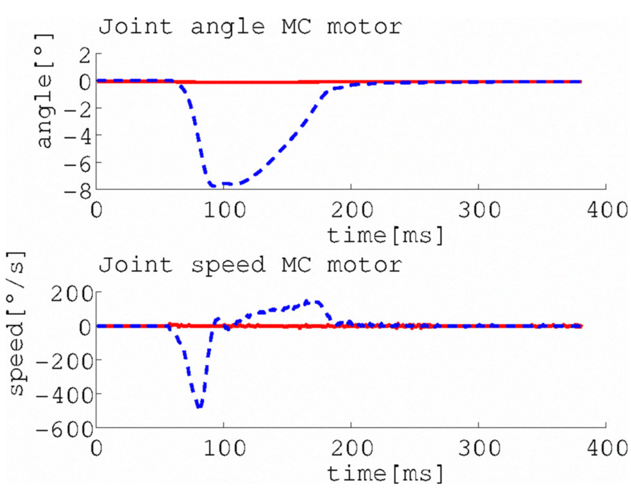


Fig. 17. MC motor positions and velocities during collision (flexors red, extensors blue dashed). The duration of the impact (first motion until maximum deflection) is extended 5 times.

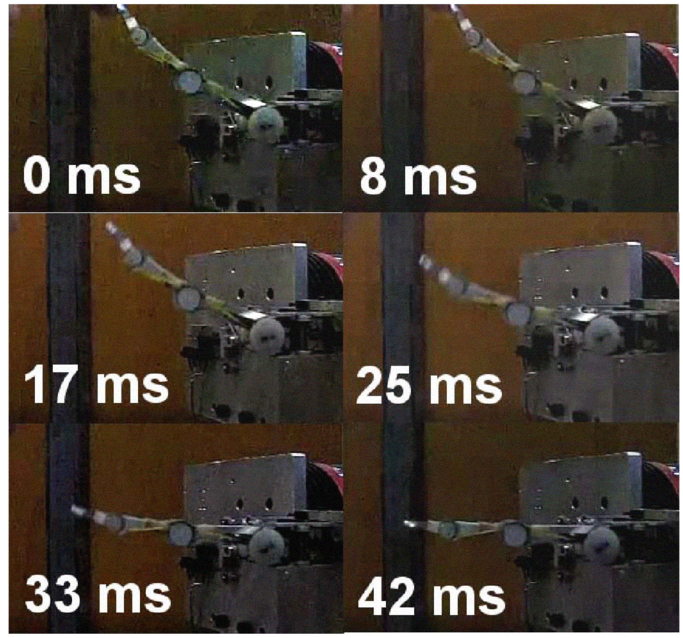


Fig. 18. Highspeed pictures of finger during flipping. The finger is released from a position of 17°deflection within the MC joint.

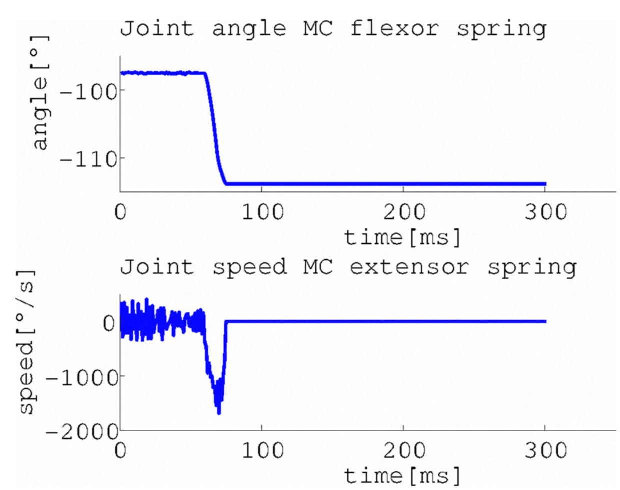


Fig. 19. MC elastic element positions and velocities of flexors during finger flipping. All angles and positions transformed to MC joint

archetype in especial regarding robustness against impacts and dynamics. Therefore a paradigm change is made at DLR to build an athropomorphic hand arm system. The system uses variable stiffness actuation to enable short-term energy storage. For this system a antagonistically driven hand is built which should enable to develop and execute complex tasks without the risk of serious damage to the robot and in especial the robot hand. A finger design based on a functional analysis of the human hand using bio- inspired, dislocatable joints has been developed and realized (Fig. 21). The final fingers have been validated using antagonistic actuation and showed up to reduce the motor speed necessary to withstand an impact to 1/6 of the speed needed without the elastic elements. The available time to absorb impact energy is 5 times the one without use of the elastic elements. Therefore a significant gain in robustness is achieved. Further it is shown that the usage of elastic elements drastically enhances dynamics using the stored energy.

VI. Acknowledgment

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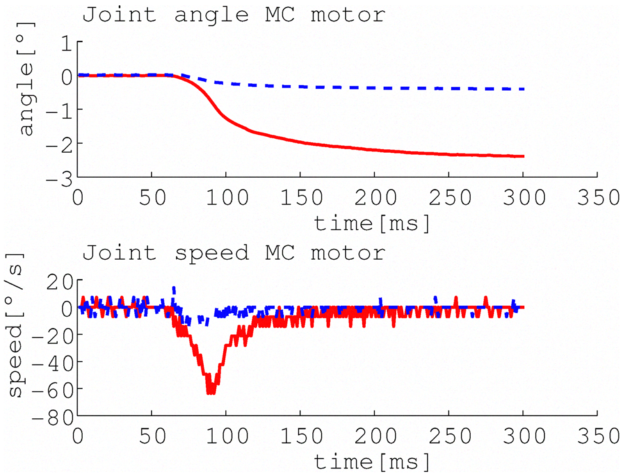
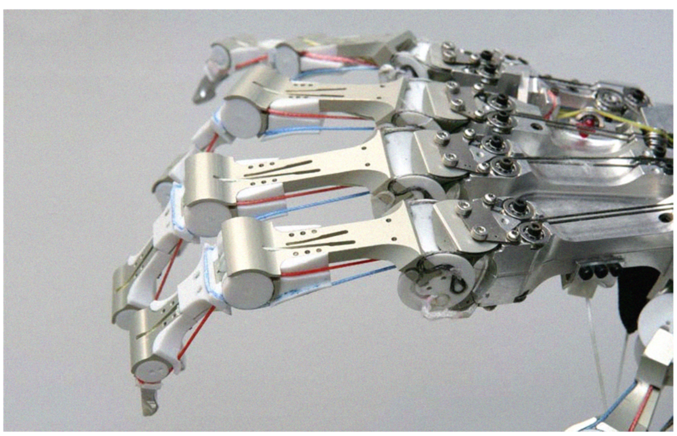
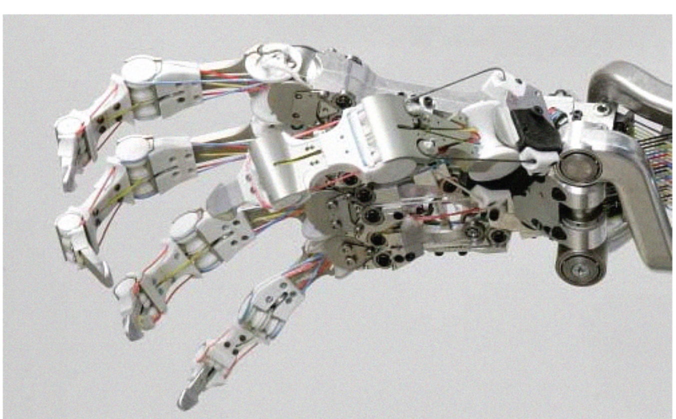


Fig. 20. MC motor positions and velocities during finger flipping. The extensor (dashed blue) motor moves to compensate the regained tendon pretension of the flexor (red) after release . This motion decreases joint speed. All angles and positions transformed to joint.



(a) Fingers without housings



(b) Assembled Hand

Fig. 21. Final design of fingers and hand

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