A New Dexterous Hand Based on Bio-Inspired Finger Design for Inside-Hand Manipulation

Hussein Mnyusiwalla, Philippe Vulliez, Jean-Pierre Gazeau, and Saïd Zeghloul

***Abstract*—This paper presents a new design of finger proposed by the ROBIOSS team of the PPRIME Institute: it is a fully actuated bio-inspired four-degree-of-freedom (DOF) finger driven by four actuators. It has been developed with the aim to replicate fine manipulation with fingertips with a high degree of interaction with the environment. This paper proposes to realize a robotic hand for inside-hand fine manipulation and adaptive grasping. The robotic hand is equipped with fingers whose design is based on a human anatomical finger model. Thus, several fingers can be assembled for building a human-sized dexterous hand with an anthropomorphic look. The modular design offers the ability to choose the number of fingers to be used as well as to adjust finger placement based on the manipulation task requirement. The tendon-based actuation presents a routing of the tendons that minimizes friction, kinematic, and static coupling between different finger axes in the transmission from motors to joints. Unlike many existing robotic hands, including our first anthropomorphic hand, we address the difficulties by decoupling joint motions with a new solution for the universal joint at the base of the finger. The results obtained demonstrate an excellent dynamic behavior and accuracy of the finger motion. Finally, the new finger design led to the development of a fully actuated mechanical hand with four fingers and with 16 DOF: the ROBIOSS hand. The hand was embedded on an industrial robot. A manipulation task that uses simultaneously abduction–adduction motion and flexion–extension motion of the finger demonstrates the potential of the hand for accurate manipulation.**

***Index Terms*—Design and control, mechanics, mechanism design, multifingered hands, robot, robotic finger.**

I. Introduction

FOR OVER 30 years, advanced multifingered hands have been developed in the academic domain. Over 100 hand designs can be found in [1]–[3]. The spectrum for these hands is large from underactuated hands with a small number of actuators [4] to fully actuated hands with anthropomorphic design [5]–[7]. Because of their complexity, weight, poor reliability, and high cost, most of these hands remain in the prototype stage and do not move out of laboratories.

Thus reproducing the human dexterity and hand versatility remains a real challenge for designers. A lot of these hands could propose adaptive grasping, but only a few could manipulate objects inside the hand with regrasping capabilities.

As a matter of fact, industrial robots and service robots are far from human grasping capabilities. Hands or grippers used in industry have low number of joints and fingers (usually no more than three fingers), while academic hands are more anthropomorphic and may have five fingers. Challenges of developing robotic hands include weight reduction in respect to the robot's payload constraints, the use of modularity to increase flexibility toward manipulation tasks, safety considerations for interaction with the environment, and the real-time coordination of multiple hand-arm systems.

As an illustration of these challenges, a roadmap for human-like dexterous manipulation is specified by the U.S. National Institute of Standards and Technology [8]. In the next five years, low complexity hands with small numbers of independent joints will be capable of robust whole-hand grasp acquisition. In the next 15 years, high-complexity hands with tactile sensing approaching that of humans will be capable of robust whole-hand grasp and dexterous manipulation of objects present in manufacturing environment used by human workers.

However, it remains difficult to meet all these requirements in a unique device. None of the existing hands could be able to reach these requirements.

The aim of this paper was to focus on the development of a novel modular design of a finger. In the hand design process, several fingers could be judiciously assembled to meet the requirements of the targeted manipulation task. Based on human finger kinematics, the number of actuated joints, and the number of fingers and their placement could be optimized by considering different specifications needs. During the design phase, we took several key factors into consideration: ease of construction, control, simplicity, and cost.

This paper is organized as follows. In Section II, issues for tendon-driven mechanisms and bio-inspired designs are discussed. Section III describes the design and modeling of a human-sized anthropomorphic finger. Section IV presents experimental studies of the transmission behavior; performance tests show the effectiveness of the developed mechanism. In Section V, a new four-fingered mechanical hand

Manuscript received March 14, 2015; accepted June 16, 2015. Date of publication August 26, 2015; date of current version May 13, 2016. This work was supported in part by the French Government Research Program "Investissements d'Avenir" through the Robotex Equipment of Excellence under Grant ANR-10-EQPX-44, and in part by the Poitou-Charentes Region 2007–2013 (program project ten images and interactivities), in partnership with the European Union [European Regional Development Fund (FEDER/ERDF)]. This paper was recommended by Associate Editor R. Roberts.

This paper has supplementary downloadable material available at http://ieeexplore.ieee.org, provided by the authors. This includes a video demonstrating the performance of the new ROBIOSS hand. The video presents the synchronous behavior of the fingers and shows the hand performing fine manipulation.

The authors are with the Department of Mechanical Engineering and Complex Systems, PPRIME Institute CNRS UPR 3346, Poitiers University, Futuroscope 86962, France (e-mail: hussein.mnyusiwalla@cnrs.pprime.fr; philippe.vulliez@univ-poitiers.fr; jean.pierre.gazeau@univ-poitiers.fr; said.zeghloul@univ-poitiers.fr).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TSMC.2015.2468678

based on the new finger design is detailed; as a demonstration, an inside-hand manipulation task is proposed. Finally, the conclusion and future trend of work are outlined.

II. Related Work

Research on bio-inspired anthropomorphic hands is first guided by the wish to develop hands with human-like dexterity and versatility [9], [10]. The main advantage of this approach is to easily replicate human hand motion in a teleoperation scheme or in a learning-based control scheme. It may also be preferred and better accepted by humans for assistance robots, humanoid robots, or prosthetic devices. Nonetheless, there is no proof that the anthropomorphic design leads to the maximization of dexterity and versatility for robot hands [3].

In this paper, bio-inspiration refers not only to tendon-driven nature, but also to the human finger kinematics and size. Bio-inspired hands with tendons have been discussed and criticized for issues such as friction and tendon compliance. These hands have advantages including light weight and size, backdrivability, low backlash, high speed, and remote actuation [11].

Robotic hands are typically driven by cables [12]–[16]. Several approaches have been proposed for tendon-driven finger design. The field investigated concerns mechanical hands with a high degree of dexterity which are able to perform in-hand manipulation.

To solve the problem of complexity, different underactuated robotic hands have been developed in the academic laboratories [4], [17], prosthetic devices such as the SPRING hand [18], and commercial prosthetic hands such as the i-Limb hand or the Ottobock Michelangelo hand. In these devices, a reduced number of actuators are employed, and the nonactuated degrees of freedom (DOFs) are coupled with others. Most of these devices allow the execution of stable grasps but do not propose in-hand manipulation capabilities. Recently, by using the concept of postural synergies [19], underactuated hands that could execute grasps and also some in-hand manipulation tasks have been proposed.

Typically if we do not consider underactuated hands, the tendons number for a finger with N joints varies from $N+1$ to $2N$ tendons. It is well known that the minimal number of tendons required to fully control the DOFs of an N-joint robotic finger is $N + 1$; some hands were designed by using this rule [9], [15], [18]. As tendons can only pull, other hands fell in another category, they use a pair of agonist–antagonist tendons for each joint [6], [20]; for an N-joint robotic finger, this means $2N$ tendons. Some designs were also based on a bio-inspired approach that attempts to closely reproduce the anatomy of the human hand [5], [21], [22]. Awiwi hand mimics some important human hand functionalities, for example, it can absorb and store energy during impacts. Another design approach is based on the use of optimization procedures to enhance grasping capabilities [23]; however, with such an optimization scheme, it is difficult to transpose theoretical result to a feasible mechanical solution with a good transmission behavior.

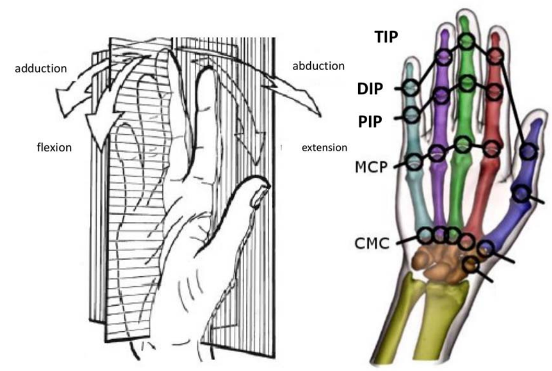


Fig. 1. Anatomy of the human hand.

Maximizing dexterity means maximizing the capability of changing the position and orientation of a manipulated object from a given reference configuration to a different one, arbitrarily chosen within the hand workspace. This definition refers clearly to the inside-hand manipulation capability, and not only to adaptive grasping.

Yet it remains difficult with robotic hands to produce fine dexterous manipulation with regrasp capability because of the transmission behavior between joint and actuation. If we wish to manipulate an object inside the hand, the finger behavior has first to be reliable and accurate. It is a necessary condition for the motion synchronization between the fingers. Very few experimental results are detailed in the literature that illustrate inside-hand manipulation with existing hands and furthermore with the regrasp capability.

III. Finger Design

The aim of the design was to meet the requirements of an inside-hand manipulation task with fingertips.

A. Finger Kinematics and Structure

Human finger kinematics play a key role for the finger's performance. As our finger needs to reproduce human finger motions, the geometry was matched to have human DOFs, range of motion, and size.

Each finger in the human hand consists of a metacarpal bone located in the hand and three phalanges named the proximal, medial, and distal phalanges. The thumb consists only of a metacarpal and two phalanges; it does not have a medial phalanx. In the human hand, the thumb is able to oppose each finger. This functionality is named thumb-finger opposition and is essential to produce stable grasp. Fig. 1 presents the human hand with finger motions and joints; the figure is adapted from Kapandji's work [24].

Inspired by the human anatomy, our finger, metacarpophalangeal joint (MCP) is modeled by a 2-DOF universal joint whereas carpometacarpal, proximal interphalangeal (PIP), and distal interphalangeal (DIP) have 1 DOF.

The universal joint is able to produce flexion–extension with respect to the frontal plane and adduction–abduction with respect to the sagittal plane as described in Fig. 1.

This motion is essential for the production of in-hand manipulation (screwing a lamp for instance); both motions

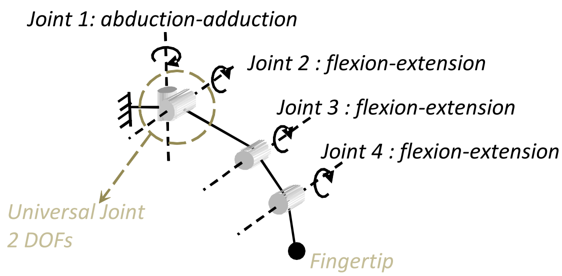


Fig. 2. Kinematics of the finger.

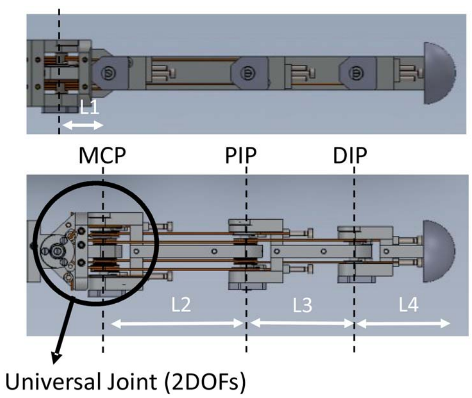


Fig. 3. 3-D model of the finger—side view and top view.

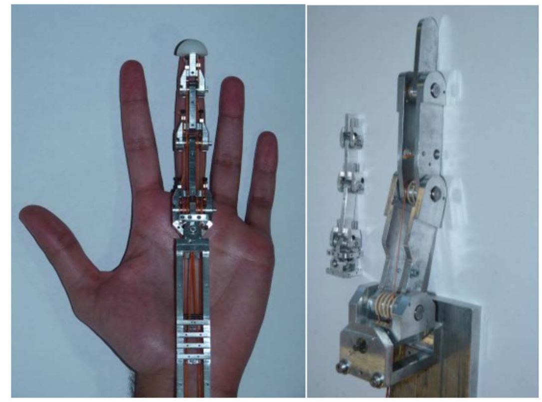
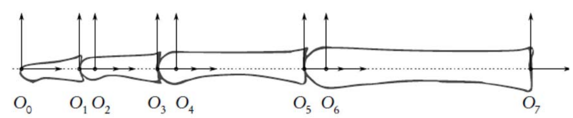


Fig. 4. Finger prototype—scale 1:1 versus scale 2:1.



Segment	Thumb	Index	Middle	Ring	Little
O_7O_6	1,567	2,049	1,906	1,719	1,578
O_6O_4	1,134	1,489	1,683	1,563	1,254
O_4O_2	—	0,864	1	0,994	0,719
O_2O_0	0,974	0,757	0,798	0,778	0,698

Reference length

Fig. 5. Anatomical finger dimensions.

must be controlled independently without any coupling relation. Fig. 2 illustrates the kinematic structure of our finger and Fig. 3 presents a 3-D model of the finger.

The four finger joints are actuated via wires connected to four rotary dc actuators. Actuators are located outside the finger part.

As described in Fig. 3, each phalanx is built by using the same mechanical approach. It could be extended for proposing a finger with more than 4 DOFs. The length of the phalanx is a design parameter that could be easily adjusted. In a same way, finger scale could be changed. The minimum size of the finger is the human finger size (scale 1:1) as shown in Fig. 4. A finger prototype with a bigger scale (scale 2:1) was developed to evaluate the universal joint feasibility.

The ROBIOSS finger is close to the size of an adult human hand as shown in Fig. 4. The weight of the finger structure made of aluminum alloy is 43 g. The weight of each dc actuator outside the finger part is 70 g (Harmonic Drive PMA-5).

B. Sensory System

The finger is equipped with angular position sensors for the measurement of joints angles and also position sensors on the dc motors shafts. This instrumentation is necessary if we wish to analyze the tendons' behavior. Elongations of tendons could be computed by the difference between motor encoders and joints position sensors. Based on this analysis, the tendons' behavior will be integrated in the control scheme. Two different strategies will be used for force sensing. In [7], a learning-based method using the tendons' elongation was used for force evaluation. Fingertips will also host force-sensitive resistors sensors and a force sensor will be designed with strain gauges and added to the finger distal phalanx.

C. Finger Dimensions

It is well known that large differences exist in the dimensions and the joint positions of the human hand among different subjects without significantly affecting grasping and manipulation capabilities [25]. Based on anatomical studies [26], [27], Fig. 5 proposes a summary of human finger dimensions. The reference phalange O_4O_2 is the medial phalange of the middle finger with a length of 1.

The study of human anatomy led to the definition of a set of dimensions for the index, middle, ring, and little fingers, and another set of dimensions for the thumb. The sizes of the finger and palm will be approximately the same as those of humans for the ROBIOSS hand (see Section V). Table I presents the dimensions of the finger phalanges and a comparison with human-sized robot dexterous hands.

We can observe that the finger's dimensions are quite similar for the five hands. DEXMART hand and ROBIOSS hands are quite different because the metacarpal (MCP) joint is not really a universal joint. As for the human, (MCP) joints are condyloid joints; for our finger, the design choice was that the two rotational axes do not intersect as it is the case in the true universal joint. The reason is that, with such an arrangement of axes, it is difficult to route the tendons through the center of the joint (Section III-D). The design of the MCP joint is essential for efficiency of flexion–extension motions in the sagittal plane and abduction–adduction motions in the frontal plane. This will be discussed in Section III-D. For our finger and for DEXMART hand, as given in Table I, the ratio for L2 is lower than other hands due to the design of MCP joint; the

TABLE I
DIMENSIONS OF FINGERS AND COMPARISON WITH OTHER DEXTEROUS ROBOT HANDS

	L1	L2	L3	L4
ROBIOSS Hand				
Index, Middle, Ring, Little (mm)	15,2	45	35	22
Ratios	0,43	1,29	1,00	0,63
Thumb (mm)	15,2	53	40	21
Ratios	0,38	1,33	1,00	0,53
Shadow Hand				
Index, Middle, Ring, Little (mm)		45	25	26
Ratios		1,80	1,00	1,04
Thumb (mm)		38	32	27,5
Ratios		1,19	1,00	0,86
DEXMART Hand (Palli, 2014)				
All fingers	20,2	45	29,9	21,8
Ratios	0,68	1,51	1,00	0,73
DLR Hand-Arm System (Chalon, 2010)				
Index ratios		1,86	1,00	0,81
Middle ratios		1,72	1,00	0,74
Ring ratios		1,70	1,00	0,78
DLR-HIT Hand II (2008)				
All fingers (mm)		55,00	25,00	25,00
Ratios		2,20	1,00	1,00

TABLE II
ANGLES DEFINING THE UPPER AND LOWER JOINT LIMITS OF FINGERS

	CMC Flex.		CMC Abd.		MCP Flex.		MCP Abd.		PIP Flex.		DIP Flex.	
Human Fingers	-	+	-	+	-	+	-	+	-	+	-	+
Thumb	-25	35	-30	60	-10	80	-30	60	-15	80	-	-
Index	-	-	-	-	0	90	-15	42	0	100	-10	90
Middle	-	-	-	-	0	90	-8	35	0	100	-10	90
Ring	0	15	-	-	0	90	-20	14	0	100	-20	90
Small	0	30	-	-	0	90	-40	19	0	100	-30	90
ROBIOSS Fingers	-	+	-	+	-	+	-	+	-	+	-	+
Thumb	-	-	-	-	-90	90	-30	90	-110	110	-110	110
Others	-	-	-	-	-90	90	-30	30	-110	110	-110	110

equivalent ratio is given by sum of L1 and L2. Thus our finger ratio is about 1.7 for the index, middle, ring, and little fingers like for Shadow hand and German Aerospace Center (DLR) hand-arm system and it is equal to 2.2 for the thumb; it is similar to the one of DLR-HIT (Harbin Institute of Technology) hand II.

Particular attention was paid to joint limits. León *et al.* [28] gave the angles defining the upper and lower joint limits of the human hand. Based on this analysis, the design of our finger allows to exceeding these limits as given in Table II.

The extended workspace of our finger compared to a human finger should increase the ability of planning more complex manipulation tasks. It encompasses also the workspace of the Laboratoire de Mécanique des Solides (LMS) hand that we developed in 1996 (Fig. 7).

D. Tendons-Based Transmission

For tendon-driven robotic fingers, one of the critical issues is the tendon routing and a second one is passive stiffness.

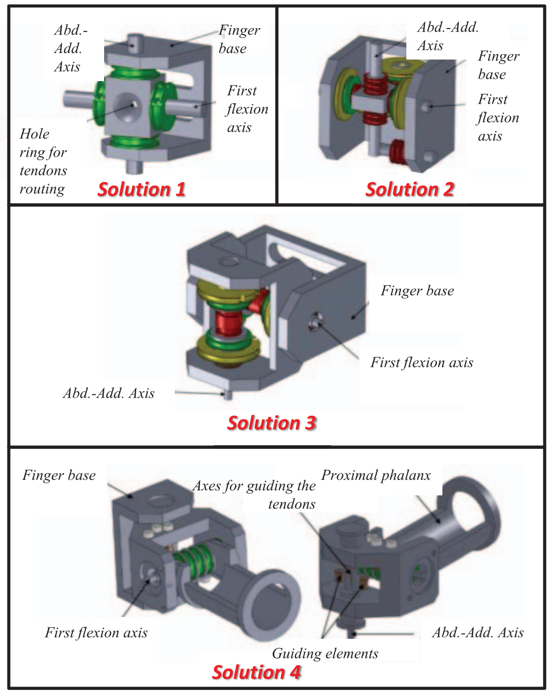


Fig. 6. Two DOFs (MCP) joint.

One key advantage of passive stiffness is the possibility to increase safety for human interaction.

Within our development, particular attention is given to back drivability of finger's joints, meaning the capacity for a mechanism to transmit motion from input to output and vice versa. A necessary condition for back drivability is to minimize internal friction for each joint.

Many hands suffer from friction, as an example, as discussed in [29], since tendons of the Shadow hand unavoidably slide over multiple surfaces. Putting them under tension could cause so much friction that compliance advantage could be lost.

In tendon-based actuation, one fundamental design issue is how tendons are routed from motors to joints. We followed some basic rules in our implementation.

1) Minimize sheaths or sliding surfaces.
2) Use pulleys and bearings to reduce friction forces acting along the tendon.
3) Make the path of each tendon as straight as possible in order to minimize tendon path curvature.

Based on these rules, the first step in the finger design was to propose a feasible and efficient solution for the MCP joint; this means a solution able to route the tendons through the abduction–adduction and flexion–extension motions of the joint.

Fig. 6 proposes four solutions for a 2-DOFs MCP joint at the finger base.

In solution 1, the tendons were routed through the center of rotation of the MCP joint, obtaining a complete decoupling between consecutive joints movements. The main disadvantage in this solution is the difficulty to route more than two tendons through the small ring hole without increasing friction. In solution 2, the abduction–adduction actuator is integrated in

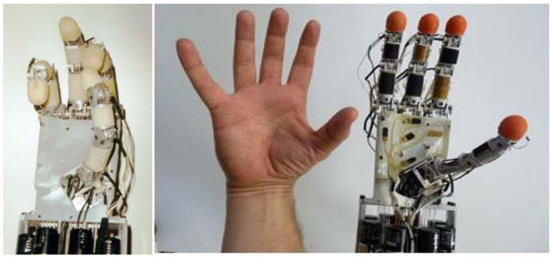


Fig. 7. LMS hand—the first dexterous hand of the ROBIOSS team.

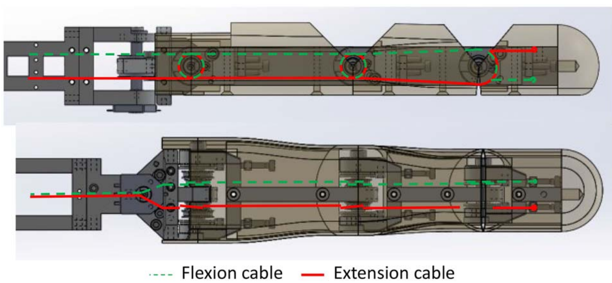


Fig. 8. Routing of the finger tendons—example of the distal phalanx.

the finger proximal phalanx and both axes of the joint intersect. With such a solution, it becomes difficult to route a high number of tendons because this increases the number of small mechanical pieces (bearings and pulleys) and also the assembling complexity; this solution is used in [15]. However, it is an interesting solution, if a coupling exists between distal and medial phalanges. Solution 3 corresponds to the mechanical solution for the thumb of the LMS hand, the first dexterous hand that we developed in 1996 (Fig. 7). With this solution, it was difficult to find small size bearings compatible with the pulleys size and the limited width of the phalanx.

Solution 4 matches all requirements. Each tendon routes through the rotation axis as illustrated in Fig. 8 which presents the tendon routing for the distal phalanx.

As discussed in [11] and [30], for tendon-driven robotic mechanisms, there are two routing techniques. The first is known as open-ended tendons as shown in Fig. 9(a); one end of the tendon is fixed to the controlled joint while the other end is attached to the driving actuator. The characteristic of such open-ended tendon drives is that tendons transmit forces in a unidirectional sense. The second routing technique is known as endless tendons; this means the pulley can be driven in both directions by using two tendons. Thus one tendon will be under higher tension while the other one is under lower tension.

Our design is based on endless type tendons routing as shown in Figs. 9 and 10. Flexion and extension cables are attached on one end to the driving pulley (fixed to the actuator) and on the other end to the driven pulley (fixed to the moving link).

Intermediate pulleys are used for tendon routing on the finger axes. As an example (see Fig. 8), two intermediate pulleys are used for the routing of the flexion cable of the distal phalange and another two intermediate pulleys are used for the extension cable. The transmission may require periodic maintenance to keep tension on the wires; a small-screw-based mechanism is used on each cable to adjust the tension.

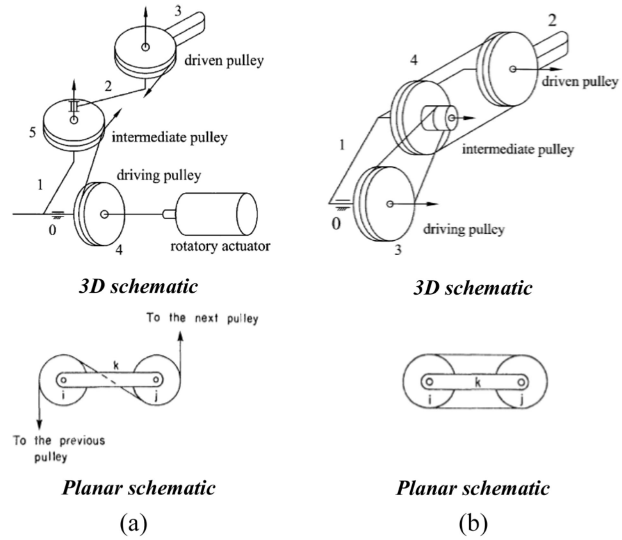


Fig. 9. (a) Open-ended type. (b) Endless type tendon routing.

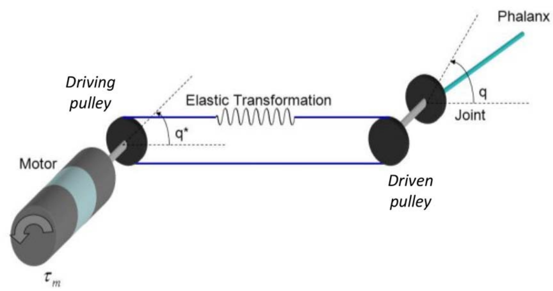


Fig. 10. Model of the finger transmission.

E. Modeling

Fig. 11 shows the fingertip's workspace. The mechanical finger is much longer than the human finger and thus includes the human finger workspace.

The Denavit–Hartenberg model is given in Fig. 12. As shown in this figure, joint parameter q_1 corresponds to the abduction–adduction motion, and q_2–q_4 correspond to flexion–extension motions of the finger.

Because of the routing of tendons through the different axis of the finger (see Section III-D), we have coupling relations between joint motions and actuator motions. These relations can be written as

$$\Delta q = A_f \cdot \Delta q*$$

with

$$A_f = \begin{bmatrix} D_0/D_1 & 0 & 0 & 0 \\ 0 & D_0/D_1 & 0 & 0 \\ 0 & -D_2/D_1 & D_0/D_1 & 0 \\ 0 & D_3 - D_2/D_1 & -D_3/D_1 & D_0/D_1 \end{bmatrix} \quad (1)$$

for the index, middle, and ring fingers and where:

1) $\Delta q = (q_1, q_2, q_3, q_4)$ is the configuration vector of the finger and corresponds to the joint position given by joint sensors;

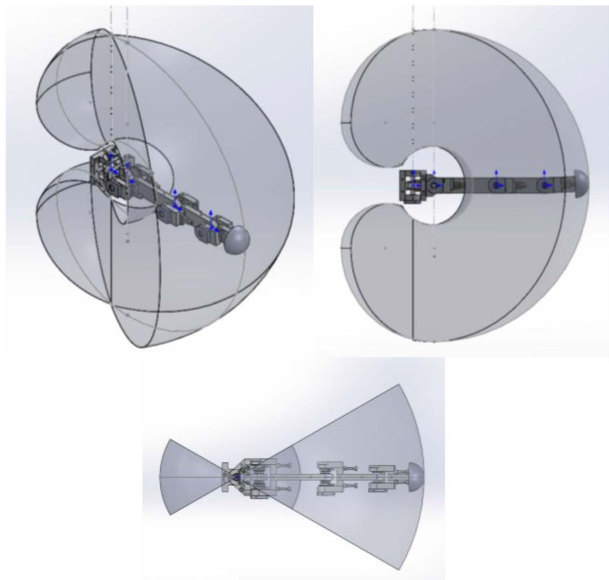
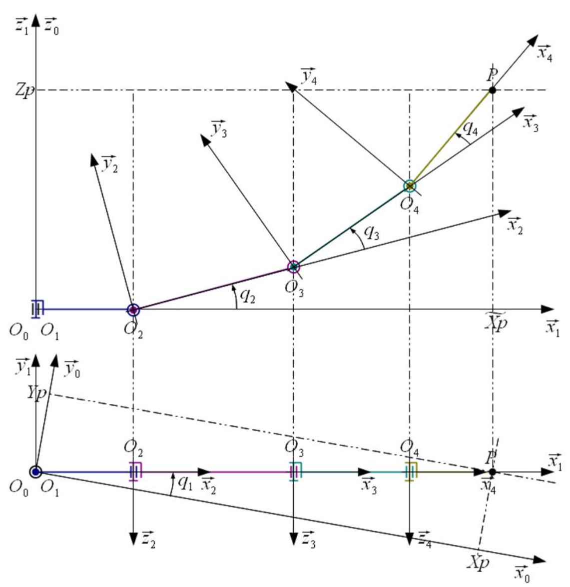


Fig. 11. Fingertip workspace.



Joint	σ_i	α_i	d_i	θ_i	r_i	q_i *figure*
1	0	0	0	q_1	0	>0
2	0	$\pi/2$	L_1	q_2	0	>0
3	0	0	L_2	q_3	0	>0
4	0	0	L_3	q_4	0	>0

Fig. 12. Denavit–Hartenberg parameters of the ROBIOSS finger.

2) $\Delta q* = (q_1*, q_2*, q_3*, q_4*)$ is the configuration vector of the actuators and corresponds to the actuator position given by actuator encoders;
3) D_0 is the diameter of the driving pulley on the actuator axis and D_1 is the diameter of the driven pulley on the joint axis; we have $D_0 = 10.2$ mm and $D_1 = 10.2$ mm for the human finger size (Fig. 4);
4) D_2 is the diameter of the intermediate pulley for the MCP joint and D_3 is the diameter of the intermediate pulley for the PIP and DIP joints; we have $D_2 = 8.6$ mm and $D_3 = 7$ mm for the human finger size (Fig. 3).

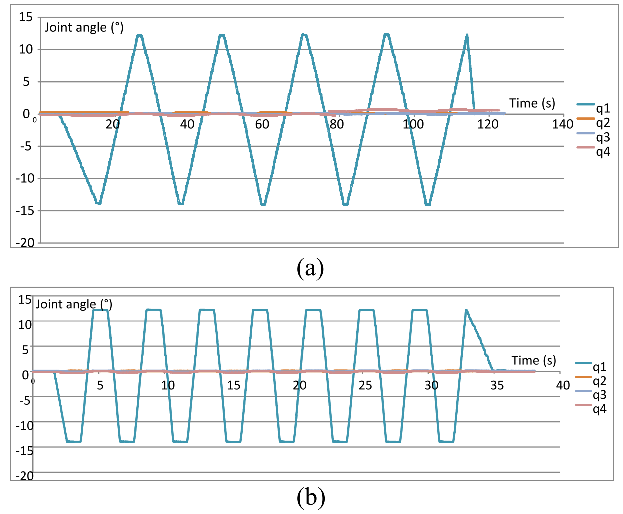


Fig. 13. Abduction–adduction motion control (q_1 parameter). (a) Rotation speed: 1.5°/s. (b) Rotation speed: 15°/s.

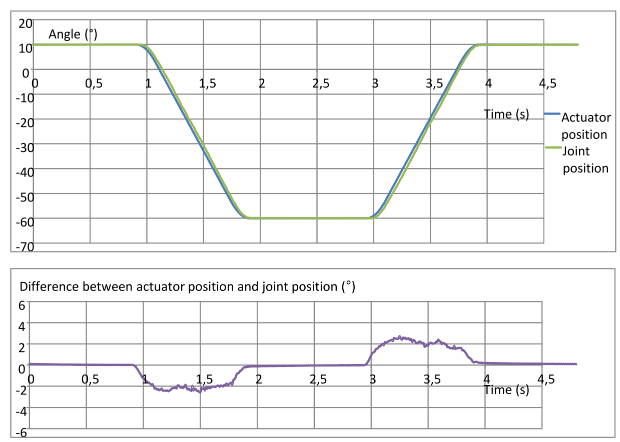


Fig. 14. Tendon elongation for the proximal flexion (q_2 parameter)—rotation speed: 70°/s.

Each joint can be controlled independently by using these relations in the control scheme. We can observe that in the ROBIOSS hand, tendon routing is designed to eliminate kinematic and static couplings between the abduction/adduction movement and the proximal/distal flexion/extension movements. The next section presents experimental results that illustrate the excellent behavior of the finger.

IV. Transmission Behavior

As tendon routing minimizes friction, this allows the use of a simple controller architecture for the finger's control. All joints are driven by dc actuator model PMA-5A with Harmonic Drive gears (gear ratio 1:80) and encoders (1024 pulse/rev). Actuators are embedded in the forearm. First, we evaluated the decoupling between abduction–adduction motion and flexion–extension motions of the fingers. As shown in Fig. 13, by using coupling relations, when we control the abduction–adduction motion, the other joints do not move. The evaluation was done for different rotation speeds. This demonstrates the efficiency of solution 3 (see Section III-D) for the routing of the tendons through the MCP joint.

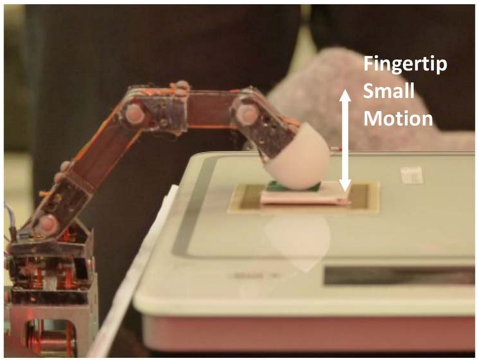


Fig. 15. Experimental setup for the interaction of finger with environment.

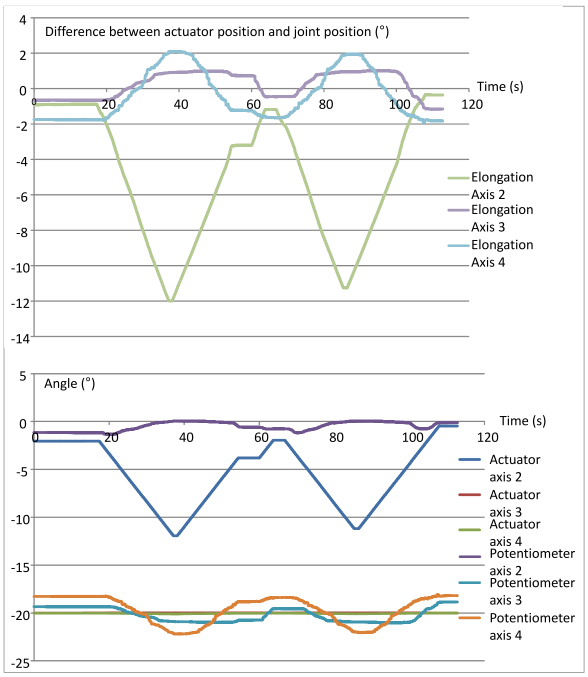


Fig. 16. Contact with a surface using control of the first flexion of the finger (axis 2).

Fig. 14 illustrates our experiments for evaluating the motion transmission between actuators and joints. These experiments show the excellent reproducibility of the finger's behavior. As an example, Fig. 14 focuses on the first flexion of the finger (q_2 parameter). Tendon elongation is given by the difference between actuator position and joint position. The result clearly demonstrates the good quality of the transmission.

The evolution of the joint motion fits the evolution of the actuator motion; this means a low hysteresis. If the rotation speed is low (typically less than 10°/s), then the elongation of the tendon is almost zero.

Fig. 14 illustrates the dynamic behavior of the finger with a rotation speed equal to 70°/s. Due to the inertia of the moving parts, during the acceleration stage and deceleration stage, the tendons elongate; when the acceleration is back to zero, the elongation after a short transition stage is also back to zero. The visible effects are dynamics effects which illustrate the high quality of the tendons routing.

The last experiment focuses on the finger's interaction with the external environment by using the experimental setup

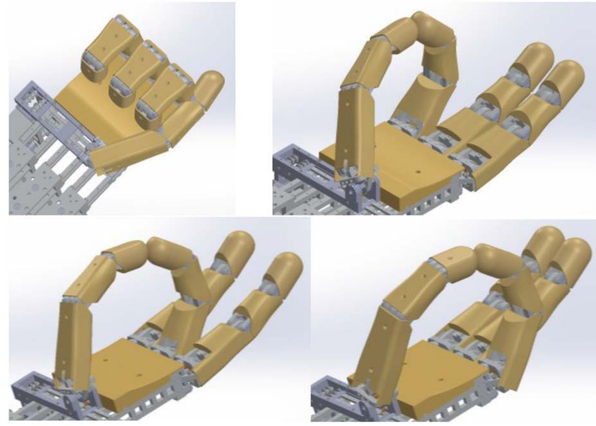


Fig. 17. Design of a new dexterous robot hand—a bio-inspired design.

of Fig. 15. Fig. 16 illustrates the experimental results. At the beginning, the fingertip contact is established. Thus the first flexion of the finger (parameter q_2) is controlled alternatively in order to increase and decrease the contact force of the fingertip with a rigid surface; the abduction–adduction motion is kept fixed.

Fig. 16 shows an important cable elongation on axis 2 that increases as the contact force increases.

Fig. 16 presents also the measurement of joint parameters based on the potentiometers measure. It shows the transition stage as the rotation direction changes. We can assume a linear evolution of the elongation for the first flexion, which mimics the actuators motion with a short delay. Future work will integrate this behavior of the cable for force control and safe interaction with the surroundings [7].

V. Four-Fingered Mechanical Hand

Based on the finger design, an anthropomorphic dexterous robot hand with four fingers was built. To achieve a high degree of modularity, all four fingers are identical; only the length of the phalanx for the thumb was adapted to specific dimensions. The use of the same finger design for the whole hand leads to the same behavior of all the fingers during a manipulation task inside the hand. Thus the objective was to demonstrate that it is possible with the modular design of the finger to build one of the most complex existing grippers: a human-sized robotic hand, bio-inspired, and fully actuated with 16 DOFs.

With its implantation of fingers and thumb on the palm, the mechanical hand allows the particular configurations characteristic of the human hand (see Fig. 17); this means the natural opposition of the thumb with index, middle, and ring fingers.

Fig. 18 presents the real hand embedded on a 6-DOF industrial robot (Staubli robot).

Once the mechanical hand was built, a first objective was to evaluate the hand behavior when performing fine manipulation tasks. The motion strategy developed in [1] was used for computing the fingertips motion. The first manipulation task concerns the rotation of a ruler inside the hand (Fig. 19). Such a manipulation task requires the coordinated motion of the fingers and also the control of both abduction–adduction

Fig. 18. New ROBIOSS hand (2014).

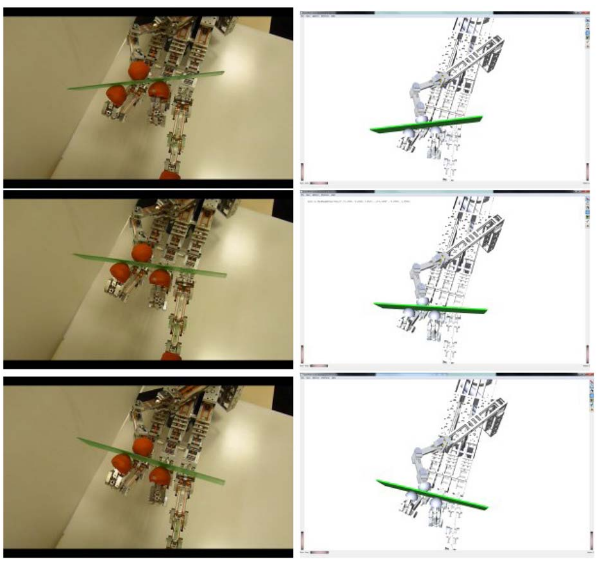


Fig. 19. Rotation of a rule inside the hand.

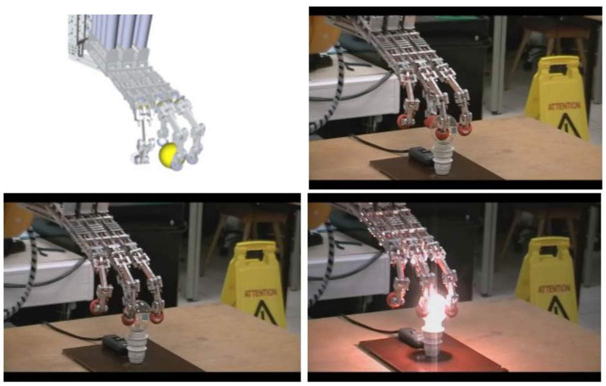


Fig. 20. Screwing of a lamp.

and flexion–extension motions. The video of the manipulation demonstrates the excellent behavior of the mechanical hand.

The second manipulation concerns the screwing of a lamp (Fig. 20). This kind of manipulation is quite difficult for dexterous hands, because it requires the full coordination between fingers, and a right behavior of the MCP joint as all the motions of the fingers should be controlled together.

VI. Conclusion

A new finger design has been presented which offers a high level of modularity for the development of a gripper or robot hand: the choice for the number of fingers and the degree of actuation depends on the targeted application. As a demonstration of the fingers' modularity and dexterity, a mechanical hand was built and proposed in this paper. Based on the study of existing solutions, the finger design challenge was addressed with the goal to develop the finger as part of a future robot hand that could produce fine dexterous manipulation with regrasp capability and adaptive grasping. With such an approach, it becomes possible to develop robot hands or grippers on demand by considering the robot task. The field of application is wide and will help increase the robot flexibility. Based on the finger design, a new alternative gripper can be assembled with a given degree of actuation and a given number of joints and fingers. Thus an alternative to basic industrial grippers and also to fully actuated dexterous robot hands that could not be embedded and used outside of academic research is offered by using this approach.

The new MCP joint design was a key issue in the design approach of the finger. As we employed a tendon-driven mechanism to drive the fingers, the MCP joint was designed to propose an efficient routing of the tendons through the joint.

Generally, such a wire-driven mechanism suffers from nonlinear behavior due to the routing of the tendons, combined with elasticity and friction. Experimental results demonstrate the efficiency of the proposed design with low hysteresis, low friction, and a natural safe interaction with the environment using the natural compliance of the cable.

Future work will concern the use of the dexterous hand for collaborative robotic applications. This means the development of strategies to allow human interaction with the hand within a defined scenario including fine manipulation of an object inside the hand. We also wish to evaluate the force sensing strategy using cable elongation for safety interaction. This will be based on our previous work; a neural-network-based approach was proposed in [7] for force evaluation with the LMS hand (see Fig. 7). And a model of the transmission behavior will be studied and integrated in the control scheme.

Based on this finger design, we also plan to develop an underactuated mechanical gripper able to grasp a wide variety of objects and able to produce small motions on an object inside the hand for precision assembling. Further work will demonstrate the efficiency of this gripper in an industrial case study.

References

[1] N. Daoud, J. P. Gazeau, S. Zeghloul, and M. Arsicault, "A real-time strategy for dexterous manipulation: Fingertips motion planning, force sensing and grasp stability," *Robot. Auton. Syst.*, vol. 60, no. 3, pp. 377–386, Mar. 2012.

[2] A. Bicchi, "Hands for dexterous manipulation and robust grasping: A difficult road toward simplicity," *IEEE Trans. Robot. Autom.*, vol. 16, no. 6, pp. 652–662, Dec. 2000.

[3] C. Melchiorri and M. Kaneko, "Robot hands," in *Springer Handbook of Robotics,* B. Siciliano and O. Khatib, Eds. Berlin, Germany: Springer, 2008, pp. 345–360.
[4] L. Birglen, T. Laliberté, and C. Gosselin, *Underactuated Robotic Hands* (Springer Tracts in Advanced Robotics), vol. 40. Berlin, Germany: Springer, 2008.
[5] M. Grebenstein *et al.*, "The hand of the DLR hand arm system: Designed for interaction," *Int. J. Robot. Res.,* vol. 31, no. 13, pp. 1531–1555, 2012.
[6] Shadow Robot Company, "Design of a dexterous hand for advanced CLAWAR applications," in *Proc. 6th Int. Conf. Climb. Walk. Robot. Support. Technol. Mobile Mach.*, Catania, Italy, Sep. 2003, pp. 691–698.
[7] J. P. Gazeau, S. Zeghloul, and G. Ramirez, "Manipulation with a polyarticulated mechanical hand: A new efficient real-time method for computing fingertip forces for a global manipulation strategy," *Robotica*, vol. 23, no. 4, pp. 479–490, Jul. 2005.
[8] J. Falco, "A roadmap to progress measurement science in robot dexterity and manipulation," U.S. Dept. Commer., Nat. Inst. Std. Technol., Gaithersburg, MD, USA. Tech. Rep. NISTIR 7993, 2014. [Online]. Available: http://dx.doi.org/10.6028/NIST.IR.7993
[9] J. K. Salisbury and M. T. Mason, *Robot Hands and the Mechanics of Manipulation*. Cambridge, MA, USA: MIT Press, 1985.
[10] R. O. Ambrose *et al.,* "Robonaut: NASA's space humanoid," *IEEE Intell. Syst. Appl.*, vol. 15, no. 4, pp. 57–63, Jul./Aug. 2000.
[11] L. W. Tsai, "Design of tendon-driven manipulators," *J. Mech. Design*, vol. 117, pp. 80–86, Jun. 1995.
[12] V. Bundhoo and E. Park, "Design of an artificial muscle actuated finger towards biomimetic prosthetic hands," in *Proc. 12th Int. Conf. Adv. Robot. (ICAR)*, Seattle, WA, USA, Jul. 2005, pp. 368–375.
[13] M. C. Carrozza *et al.,* "Design of a cybernetic hand for perception and action," *Biol. Cybern.*, vol. 95, no. 6, pp. 629–644, Dec. 2006.
[14] Y. Kurita, Y. Ono, A. Ikeda, and T. Ogasawara, "Human-sized anthropomorphic robot hand with detachable mechanism at the wrist," *Mech. Mach. Theory*, vol. 46, no. 1, pp. 53–66, Jan. 2011.
[15] J. Martin and M. Grossard, "Design of a fully modular and backdrivable dexterous hand," *Int. J. Robot. Res.*, vol. 33, no. 5, pp. 783–798, Feb. 2014.
[16] Z. Xu, V. Kumar, and E. Todorov, "A low-cost and modular, 20-DOF anthropomorphic robotic hand: Design, actuation and modeling," in *Proc. IEEE-RAS Int. Conf. Humanoid Robots (Humanoids)*, Atlanta, GA, USA, Oct. 2013, pp 368–375.
[17] L. Odhner and A. Dollar, "Dexterous manipulation with underactuated elastic hands," in *Proc. IEEE Int. Conf. Robot. Autom.*, Shanghai, China, May 2011, pp. 5254–5260.
[18] M. C. Carrozza *et al.*, "The SPRING hand: Development of a self-adaptive prosthesis for restoring natural grasping," *Auton. Robot.*, vol. 16, no. 2, pp. 125–141, Mar. 2004.
[19] D. Prattichizzo, M. Malvezzi, M. Gabiccini, and A. Bicchi, "On motion and force controllability of precision grasps with hands actuated by soft synergies," *IEEE Trans. Robot.*, vol. 29, no. 6, pp. 1440–1456, Dec. 2013.
[20] S. Jacobsen, E. Iversen, D. Knutti, R. Johnson, and K. Biggers, "Design of the Utah/MIT dextrous hand," in *Proc. IEEE Int. Conf. Robot. Autom.*, San Francisco, CA, USA, Apr. 1986, pp. 1520–1532.
[21] M. Vande Weghe *et al.*, "The ACT hand: Design of the skeletal structure," in *Proc. IEEE Int. Conf. Robot. Autom.*, New Orleans, LA, USA, Apr./May 2004, pp. 3375–3379.
[22] S. Shirafuji, S. Ikemoto, and K. Hosoda, "Development of a tendon-driven robotic finger for an anthropomorphic robotic hand," *Int. J. Robot. Res.*, vol. 33, no. 5, pp. 677–693, Apr. 2014.
[23] J. Inouye and F. J. Valero-Cuevas, "Anthropomorphic tendon-driven robotic hands can exceed human grasping capabilities following optimization," *Int. J. Robot. Res.*, vol. 33, no. 5, pp. 694–705, Apr. 2014.
[24] I. Kapandji, *The Physiology of the Joints.* Edinburgh, U.K.: Churchill Livingstone, 1982.
[25] J. Napier and R. H. Tuttle, *Hands*. Princeton, NJ, USA: Princeton Univ. Press, 1993.
[26] F. Touvet, "Approche bioinspirée pour le contrôle des mains mécaniques," Thèse de doctorat, Robotique et Neurosciences, Univ. René Descartes—Paris V, Paris, France, Oct. 2012.
[27] E. Y. Chao, *Biomechanics of the Hand: A Basic Research Study*. Teaneck, NJ, USA: World Scientific, 1989.
[28] B. León, A. Morales, and J. Sancho-Bru, "The model of the human hand," in *From Robot to Human Grasping Simulation.* ser. Cognitive Systems Monographs, vol. 19. Berlin, Germany: Springer, 2014, pp. 123–173.
[29] V. Kumar, Z. Xu, and E. Todorov, "Fast, strong and compliant pneumatic actuation for dexterous tendon-driven hands," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, Karlsruhe, Germany, May 2013, pp. 1512–1519.
[30] Y. H. Lee and J. J. Lee, "Modeling of the dynamics of tendon-driven robotic mechanisms with flexible tendons," *Mech. Mach. Theory*, vol. 38, no. 12, pp. 1431–1447, Dec. 2003.
[31] Y. J. Ou and L. W. Tsai, "Kinematic synthesis of tendon-driven manipulators with isotropic transmission characteristics," *J. Mech. Design*, vol. 115, no. 4, pp. 884–891, Dec. 1993.
[32] G. C. Palli *et al.*, "The DEXMART hand: Mechatronic design and experimental evaluation of synergy-based control for human-like grasping," *Int. J. Robot. Res.*, vol. 33, no. 5, pp. 799–824, Apr. 2014.

Hussein Mnyusiwalla received the M.S. degree in computer science from the University of Poitiers, Poitiers, France, and the engineering degree in mechanics and avionics from École Nationale Supérieure de Mécanique et d'Aérotechnique, University of Poitiers in 2012, where he is currently pursuing the Ph.D. degree in robotics with the ROBIOSS Laboratory, PPRIME Institute CNRS UPR 3346.

His current research interests include grasping and dexterous manipulation with robotic hands.

Philippe Vulliez received the engineering degree from the École Normale Supérieure de Cachan, Cachan, France, in 1981, and the M.S. degree from the Laboratoire de Mécanique et Technologie, Cachan, France, both in mechanical engineering. He is currently pursuing the Ph.D. degree in robotics with the University of Poitiers, Poitiers, France.

He is currently an Assistant Professor with the Faculty of Fundamental and Applied Sciences, University of Poitiers, where he teaches mechatronics. His current research interests include mechatronics and design and control of dexterous robot hands.

Jean-Pierre Gazeau received the M.S. degree in mechanical engineering and the Ph.D. degree in mechanics from the University of Poitiers, Poitiers, France, in 1994 and 2000, respectively.

He is currently a CNRS Research Engineer with the PPRIME Institute CNRS UPR 3346. He is in charge of the animation of the multiscale manipulation workgroup, French Robotics Research Group, GDR Robotique. His current research interests include object manipulation with mechanical hands, robot control, and electronic design for embedded systems.

Saïd Zeghloul received the Ph.D. degree in mechanics and the Doctor ès Sciences degree in physics from the University of Poitiers, Poitiers, France, in 1983 and 1991, respectively.

He is currently a Professor with the Faculty of Fundamental and Applied Sciences, University of Poitiers, where he teaches robotics and mechanics. His current research interests include robot design, computer-aided design for robotics, and object manipulation with mechanical hands and robots collision free path-planning.