Open-Source, Anthropomorphic, Underactuated Robot Hands with a Selectively Lockable Differential Mechanism: Towards Affordable Prostheses

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Abstract— In this paper we present an open-source design for the development of low-complexity, anthropomorphic, underactuated robot hands with a selectively lockable differential mechanism. The differential mechanism used is a variation of the whiffletree (or seesaw) mechanism, which introduces a set of locking buttons that can block the motion of each finger. The proposed design is unique since with a single motor and the proposed differential mechanism the user is able to control each finger independently and switch between different grasping postures in an intuitive manner. Anthropomorphism of robot structure and motion is achieved by employing in the design process an index of anthropomorphism. The proposed robot hands can be easily fabricated using low-cost, off-the-shelf materials and rapid prototyping techniques. The efficacy of the proposed design is validated through different experimental paradigms involving grasping of everyday life objects and execution of daily life activities. The proposed hands can be used as affordable prostheses, helping amputees regain their lost dexterity.

Index Terms: **Robot Hands Design, Anthropomorphism, Underactuation, Differential Mechanisms**

Fig. 1.   The robot hand mounted on the Mitsubishi PA10 robot arm.

I. INTRODUCTION

Roboticists have always been intrigued to understand and be inspired by nature's most versatile and dexterous end-effector, the human hand. Fifty years ago, robot hands were simple grippers with a small number of Degrees of Freedom (DoF) and limited grasping capabilities. During the last decades the pursuit of dexterity led the designers to create multifingered hands with numerous DoF, which were typically equipped with sophisticated sensing elements (in order to perceive the environment surrounding them) [1]. These hands were in most cases rigid, so in order to operate efficiently in human-centric, dynamic and unstructured environments (where uncertainties are ruling), they required complicated control laws.

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Nowadays, the state of the art of robot hands follows a road of increased simplicity, without compromising efficiency in terms of grasping capabilities. Recently, Dollar et al. [2], [3] presented a new paradigm for fabricating intrinsically compliant robot hands based on elastomer materials. These hands exhibit a significant degree of adaptability during grasping, enhancing grasp stability by design. In [4], the authors proposed the i-HY (iRobot-Harvard-Yale) an underactuated, compliant robot hand created not only for robust grasping but also for in-hand manipulation. In [5], the authors proposed a compliant underactuated hand that utilizes electrostatic brakes for locking individual joints, to increase the maximum force for power grasps and adopt configurations that typically require a fully actuated solution. Such underactuated, compliant robot hands were also in some cases open-source [6], [7]. All these efforts led to the creation of open-source initiatives for the dissemination of the proposed designs [8], [9]. An overview of various designs proposed for underactuated robot hands, can be found in [10].

The idea of low-cost prostheses that can be easily fabricated with light-weight material, is definitely not new [11]. In [12] the authors proposed the use of compliant, underactuated, non-anthropomorphic robot hands, as terminal prosthetic devices. Dalley et al. [13] presented an anthropomorphic robot hand that can serve as a myoelectric

prosthesis. This hand employs five independent actuators for driving its 16 joints in a cable driven design. Tavakoli et al. [14], presented a low-cost, underactuated, anthropomorphic hand with elastic joints and soft pads. The hand joints were designed to be compliant enough to achieve adaptability to a wide range of objects. Results report that the developed hand can achieve the ten grasps that are most frequently used by humans, utilizing only three actuators. In [15], a differential mechanism was presented that facilitates execution of multiple grasp configurations using a single actuator. The differential mechanism is incorporated in a robot hand which is able to perform four different grasp types (lateral, precision, precision/power, and power grasps).

Regarding design optimization, Grebenstein et al. [16], initialize their study from a hand design that only satisfies structural constraints and incrementally improve it, by employing a set of tests which evaluate its grasping performance. Moreover, the authors use 'feedback' provided by surgeons, to ameliorate their methods. Finally the application of the proposed methodology to the design of the DLR hand is discussed. In [17], anatomy, surgery and rehabilitation data are presented in order to identify the properties required by robot thumb designs to achieve humanlike manipulation. The outcomes of this study are once again used for the development of the DLR hand arm system [1].

Regarding prosthetic studies, Belter et al. [18], [19] performed a detailed analysis of the mechanical characteristics of anthropomorphic prosthetic hands comparing several commercially available prostheses: 1) Vincent hand, 2) iLimb, 3) Bebionic, and 4) Michelangelo. Some of the findings of this study are: 1) the total weight of the prosthesis should be below 500 g[1], 2) highly functional hands should be designed with a minimum number of actuators and transmissions that facilitate various grasping postures and 3) compliance in the mechanical design is highly recommended.

In [20], the authors gathered multiple studies on upper-limb amputations as well as amputees comments, suggestions and remarks regarding their prostheses. Most of the subjects expressed their disappointment for: 1) the large cost of buying and maintaining a prosthesis[2], 2) the increased weight of the device and 3) the difficulties they face with repairs. Another important outcome of this latter study is that the fear of damaging the prosthesis leads most of the amputees to avoid using them in everyday life tasks and use instead simple hooks or two-fingered grippers. On the other hand the same study reported that when the amputees are involved in the selection / preparation of the prosthesis (e.g., replication of an open-source design), the likelihood of prosthesis acceptance[3] is increased 8 times. These findings confirm that what amputees need is: a highly functional, personalized, affordable and light-weight prosthesis that can be easily developed and repaired.

In this paper we propose an open-source design for the development of anthropomorphic, underactuated robot hands of low complexity and cost (see Fig 1). Our hands utilize a novel differential mechanism (a variation of the whiffletree or "seesaw mechanism" [21]) that can block the motion of each finger, allowing the user to select multiple grasping postures in an intuitive manner. Humanlikeness of both robot structure and motion is achieved by employing an index of anthropomorphism in the design process [22] that utilizes parametric models derived from hand anthropometry studies [23]. The proposed hands can be easily reproduced with off-the-shelf materials and can be fabricated with rapid prototyping techniques (3D printers), conventional machining processes (mill) and non-conventional machining processes (laser cutting machines). The efficiency of the proposed design is experimentally validated with a wide range of experimental paradigms, involving grasping of everyday life objects and execution of daily living activities. To the best of our knowledge the proposed design is the most light-weight (300 g) and low-cost (< 200 USD) prosthesis solution ever proposed. All required files (CAD files and source code) for the replication of the proposed hands, are freely available at our website (www.openbionics.org).

The rest of the paper is organized as follows: Section II presents the open-source, anthropomorphic design describing the different hand parts, the differential mechanism, the idea of design personalization and the fabrication techniques, Section III discusses the robot hand performance and the experiments conducted to validate the efficacy of the proposed design, while Section IV concludes the paper.

II. ROBOT HAND DESIGN

A. Anthropomorphism

Recently [22], we presented a complete methodology based on computational geometry and set theory methods for quantifying anthropomorphism of robot hands. The main idea was to use the human hand as a reference for assessing the humanlikeness of robot hands, in terms of motion capabilities and morphology. This latter study was motivated by the fact that the objects and the environments surrounding us, have been crafted in order to be used by the human hand. Thus, by designing robot hands as anthropomorphically as possible we maximize their ability to grasp everyday life objects. The main contribution of the aforementioned paper was the introduction of a new comprehensive index for evaluating humanlikeness of robot hands. The index outputs a normalized score that ranges between 0 (non-humanlike) and 1 (human-identical). In this study, we are employing this index and parametric models derived from hand anthropometry studies [23], in order to conclude to an anthropomorphic design in terms of: 1) the finger phalanges lengths and 2) the positions of the finger base frames. More details regarding the proposed design, are provided in the following sections.

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[1]Actually they reported three studies dictating that the prosthesis weight should be less that 500 g, 400 g and 370 g respectively.

[2]Nowadays prosthetic hands cost several thousands of USD.

[3]The prosthesis acceptance is evaluated by the amount of time that the amputee spends using the device, in everyday life tasks.

B. Finger Design

In this paper we propose a multifingered, anthropomorphic robot hand. Thus, the robot index, middle, ring and pinky fingers consist of three phalanges (proximal, middle and distal) and three rotational Degrees of Freedom (DoF), while the robot thumb consists of two phalanges (proximal and distal) and two rotational DoF. All phalanges are stitched on flexure joints that are implemented with silicone sheets of different widths. In order to derive anthropomorphic lengths for the robot finger phalanges we use the aforementioned parametric models [23], providing only two human hand parameters: 1) the desired hand length (HL) and 2) hand breadth (HB), as described in [22].

Regarding the finger actuation and transmission system, we propose a bioinspired design that structurally reproduces the flexion and extension movements of human fingers. For each finger, extension is mechanically implemented in a passive fashion through the use of appropriate elastomer materials, while flexion is implemented with cables (Dyneema fishing line), driven through low-friction tubes. The joints are made from silicone or polyurethane sheets, so as to be lightweight but also stiff enough to produce a force range that corresponds to everyday life tasks.

Regarding the fingertips, the following materials were used: 1) deformable sponge-like tape (deformation during contact leads to larger contact patches that reduce the impact of contact forces to the grasped object and enhance grasp stability [24]), 2) rubber tape (in order to increase friction during contact and constrain the sponge like tape on the robot phalanges) and 3) anti-slip tape (in order to maximize friction during contact, enhancing again grasp stability).

C. Palm

In this subsection we present the robot palm. The palm consists of two parallel sheets of Plexiglas (acrylic) that accommodate: 1) the finger base frames, 2) the thumb mechanism, 3) the selectively lockable differential mechanism (i.e., the whiffletree and the buttons) and 4) the actuator base.

1) Finger Base Frames Positions and Orientations: In order to compute anthropomorphic finger base frames positions and orientations, we utilize the aforementioned index of anthropomorphism [22] and the parametric models [23], in order to come up with a robot hand workspace that maximizes its intersection with the human hand workspace. For doing so we compute the workspaces of the finger base frames positions and the workspaces of the finger base frames orientations and we compare them with the human workspaces, as described in [22]. Moreover, we guarantee that the selected finger base frames orientations, allow for efficient execution of the Kapandji test, as described in [25].

2) Thumb locking mechanism: A selectively lockable toothed mechanism that can implement 9 different opposition configurations, is proposed for the thumb (see Fig. 2). The 9 discrete positions were chosen so as for the hand to able to attain the configurations described in the Kapandji test [25] and to allow the user to select different grasping strategies, according to the task to be executed (e.g., key

grasp or full grasp). It must be noted that the proposed mechanism substitutes the three DoF that implement the human thumb opposition with only one rotational DoF. The position of the base frame of the thumb and the desired range of motion, were extracted using the methodology described in the previous subsection.
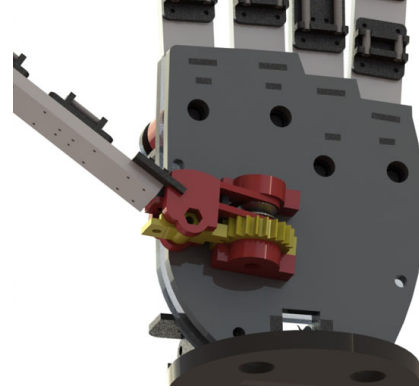

Fig. 2. The thumb mechanism consists of the red and golden parts. The red parts are mounted in appropriate slots on the robot palm to facilitate installation of the thumb mechanism. The golden parts are: 1) a pulley that routes the thumb tendon to the back of the hand and 2) the toothed, selectively lockable mechanism that allows adjustment of thumb's opposition. The robot thumb can be passively positioned by the user, in 9 discrete configurations.

The proposed mechanism is completely stiff when it is locked, in contrast to friction based mechanisms [26] that are affected by torsional forces inherent in dynamic / unstructured environments (these forces can result to large, uncontrolled displacements of the thumb for these mechanisms). It must be also noted that the tendon of the thumb is not connected with the differential mechanism. A completely separate tendon routing system is used and the tendon is terminated to a separate servo pulley. The thumb servo pulley allows for smaller motor angular displacements to produce similar joint angle displacements with the other fingers. Moreover, in order to select the diameters of the different pulleys we chose the values that score the best results while performing the Kapandji test [25].

3) A Selectively Lockable Differential Mechanism: The design of the proposed differential mechanism is motivated by the fact that humans develop over their lives a tremendous ability to select the most appropriate grasping strategy for a given task. A well known differential mechanism is the whiffletree [21], which is typically used to interconnect the index, middle, ring and pinky fingers of underactuated, multifingered robot hands. In this case, the whiffletree consists of three bars: one bar connecting the index and middle fingers (bar1), one bar connecting the ring and pinky fingers (bar2) and the main bar that connects bar 1 and bar 2, as depicted in Fig. 3. Upon contact of one finger with the environment or the object surface, the whiffletree facilitates the motion of the rest unconstrained fingers. The whiffletree allows one motor to control multiple fingers in a coordinated fashion, so a small linear displacement of the tendon causes a proportional angular displacement at all robot joints.
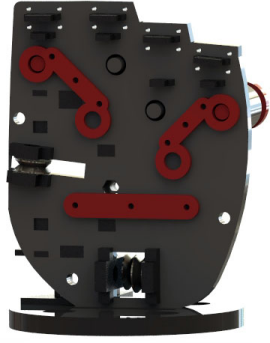
Fig. 3. Inner side of the palm. The three bars of the proposed whiffletree are depicted with red color. The holes of the upper two bars are filled by the elongated parts of the corresponding buttons, constraining the motion of different fingers. In this instance the motion of the index and pinky fingers is constrained, resulting to a change at the inclination of the differential mechanism finger bars.

a) thumb mechanism   b) servo base

Fig. 4. Subfigure a) depicts the thumb mechanism in red and golden colors. Subfigure b) depicts the servo base of the HerkuleX servo motor in red. In both subfigures the buttons that implement the differential tree locking are denoted with black color.

Front	Side 1	Side 2	Back

Fig. 5. Different views of a robot hand developed.

Recently Gosselin et al. [26] also proposed a variation of the whiffletree, that constraints the motion of the fingers using a mechanical selector. The proposed selector is utilized as a way of mechanically programming the motion of the different fingers by blocking them. This latter approach has three disadvantages: 1) each selector can have mechanically programmed only three modes (more interchangeable selectors are required to achieve more grasping postures), 2) it is not an intuitive, fast or easy way (from a human perspective) to select a wide variety of grasping postures, 3) the idea necessitates the fabrication of multiple selectors (e.g., with CNC machinery) and attachment of a small ball on each finger's tendon (such attachment is technically difficult for tendon drive hands), increasing the complexity of the hand.

In this paper we propose a differential mechanism that can block the motion of each finger, using a simple locking mechanism that works like a button. The proposed mechanism allows the user to select in an intuitive manner the desired finger combinations and implement different grasping postures or gestures. More precisely, the top two bars of our whiffletree have appropriately designed holes and the palm accommodates a set of buttons that upon pressing are elongated. When a button is pressed the elongated part fills the corresponding finger hole and the motion of this particular finger is constrained. The differential mechanism is depicted in Fig. 3 and the locking buttons in Figs. 4 and 5 where we present also different views of the robot hand. A total of $2^4 = 16$ different finger combinations can be implemented using the differential mechanism and a single motor, which combined with the 9 discrete positions of the thumb, produce a total of 144 different grasping postures.

D. Fabrication Techniques and Personalized Design

The proposed design is essentially 2D so various fabrication techniques can be used for developing the proposed robot hands. Appropriate 3D models (.stl files) are freely available to be used with rapid prototyping methods like 3D printing, while 2D models (.dwg, .dxf and other CAD files) of the different parts facilitate fabrication with laser
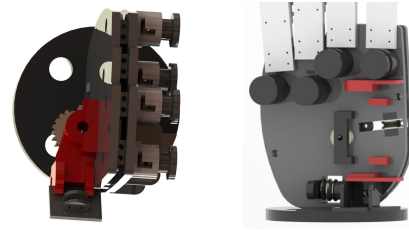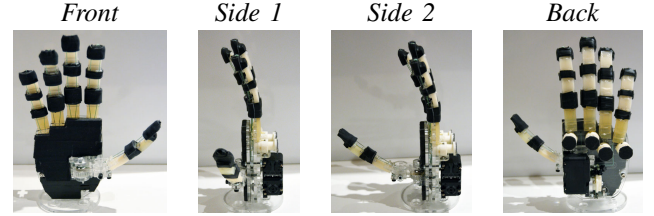
cutting machines or other standard machining tools. The proposed hands can also be fabricated using off-the-shelf, low-cost materials. All required materials can be easily found in hardware stores around the world. For our design we use Plexiglas (acrylic) as the main material, but any other plastic like ABS can also be used.

The finger characteristics for a robot hand with hand length 19 cm, are reported in Table I, while the different characteristics of the robot hand are reported in Table II. As it can be noticed both the weight and the cost of the robot hand are significantly low, 300 g and <200 USD respectively. Moreover, the use of human hand anthropometry studies parametric models allows for the development of custom-made, personalized designs. The only parameters that we need in order to derive the finger phalanges lengths and the personalized finger base frames positions and orientations, are the human hand length (HL) and the human hand breadth (HB). All files (CAD files, codes) required for the replication and control of the proposed robot hands, are available for download through the OpenBionics [9] website at the following URL: http://www.openbionics.org

TABLE I

FINGER CHARACTERISTICS FOR A ROBOT HAND WITH LENGTH 19CM

Finger	Weight	Length	Breadth	Width
Index	30 g	88 mm	16.2 mm	15 mm
Middle	30 g	98 mm	16.2 mm	15 mm
Ring	30 g	95 mm	16.2 mm	15 mm
Pinky	25 g	76 mm	16.2 mm	15 mm
Thumb	20 g	68 mm	16.2 mm	15 mm

TABLE II

HAND CHARACTERISTICS

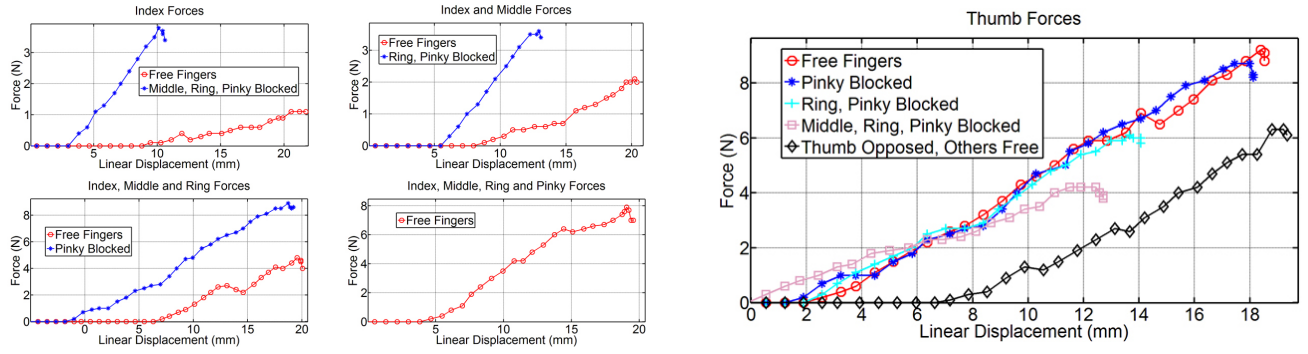| Cost	Weight	Length	Breadth	Width
< 200 USD	300 g	190 mm	90 mm	62.50 mm

Fig. 6. Relationship between the tendon displacement and the finger forces for different grasping postures.

III. Results and Experiments

In this section we validate the efficacy of the proposed design through extensive experimental paradigms that include: 1) grasping of a wide range of everyday life objects, 2) execution of a series of daily living tasks. In order to conduct the different experiments, we used an Arduino Micro platform [27] to control the HerkuleX DRS0201 servo motor, a custom made PCB module that connects the arduino platform with the servo motor and the ROS package (written in Python) that we created within the context of the OpenBionics initiative.

A. Force Exertion Capability

In this subsection we present an experimental analysis of force exertion capability of the hand in different grasping postures. In Fig. 6, we present the relationship between the tendon displacement and the forces exerted by different combinations of fingers. As it can be noticed, by blocking different combinations of fingers we are able to maximize the force applied by the fingertips of the free fingers (for precision grasps). PIP joint has a bigger range of motion as it is implemented with 4mm silicone sheet (to optimize Kapandji test [25]). If we want to use a grasp involving less than five fingers, we can block the subsidiary fingers and maximize the force transmitted from the servo motor to the active fingertips.

B. Implementing Different Grasping Postures and Gestures

The first set of experiments focuses on validating the efficacy of the proposed selectively lockable differential mechanism. For doing so, the user presses the different buttons locking different combinations of fingers. Such a functionality is not only important for grasping (where the user is able to choose the preferred grasping strategy / posture), but also for: 1) implementing specific gestures (e.g., making the peace sign or showing a number), 2) reaching an object located at a narrow space (task that may require less than five fingers), or 3) execute non-prehensile manipulation tasks (e.g., press a button or move a slider on a console). In Figs. 7 and 8 different postures are depicted. The motion of each locked finger is constrained by the corresponding button of the differential mechanism.
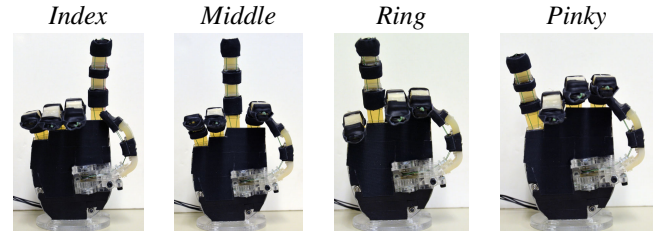

Fig. 7. Four different postures are depicted. All fingers except one are closing. The locked finger can be used to: 1) press buttons, 2) to reach something in narrow spaces, 3) to implement specific gestures or 4) to execute non-prehensile manipulation tasks (e.g., moving a slider).
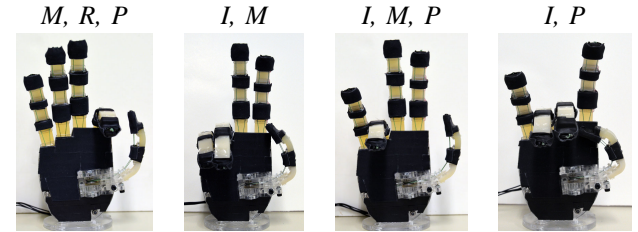

Fig. 8. Four different postures are depicted. The differential mechanism allows for different grasping postures and hand gestures to be achieved. With the letters I, M, R and P we denote that the motion of the index, middle, ring and pinky finger respectively, is constrained.

C. Grasping of Everyday Life Objects

The second set of experiments focuses on grasping a wide range of everyday life objects, to execute daily living activities. The objects used are: 1) a mug, 2) a soap, 3) a magazine, 4) a marker, 5) a pair of sunglasses, 6) a large rectangular box, 7) a glass cleaner spray, 8) a 1.5L bottle of water, 9) a glass of water and 10) a spoon. Regarding the daily living tasks, the hand is used: 1) to serve water from a 1.5L bottle to a glass, 2) to stir the water inside the glass with a spoon and 3) to position a series of tools to their cases and put them inside a rectangular box. Instances of the conducted experiments, can be found in Fig. 9.

All experiments were recorded and the video can be found (in HD quality), at the following URL:

http://www.openbionics.org/videos/
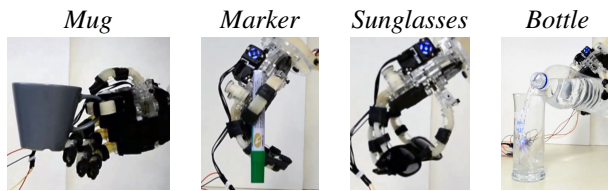
Mug   *Marker*   *Sunglasses*   *Bottle*

Fig. 9. Images from the experiments conducted. Five different everyday life objects are grasped in order to execute different tasks: 1) a coffee mug is grasped from the handle in order to drink from it, 2) a marker is grasped in order to write, 3) a pair of sunglasses is picked up and 4) a 1.5L bottle is grasped in order to serve water.

IV. Conclusions

In this paper we presented an open-source design for the development of anthropomorphic, underactuated robot hands that utilize a selectively lockable differential mechanism. The major advantage of the proposed design is it's ability to allow the robot fingers to move independently using a single motor. The user of the robot hand can switch to different grasping postures using the buttons attached at the finger bases, in an intuitive manner. The thumb configuration can be easily adjusted by the user, using the lockable, stiff opposition mechanism. An index of anthropomorphism is employed in order to maximize humanlikeness of the proposed design. The proposed hands can be easily fabricated with low-cost, off-the-shelf materials and rapid prototyping techniques. The efficiency of the proposed robot hands is experimentally validated using two different scenarios: 1) grasping of a wide range of everyday life objects and 2) executing a series of everyday life tasks.

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