Mechanical Design of a Novel Hand Exoskeleton Driven by Linear Actuators

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Abstract. This paper presents the mechanical design of a novel hand exoskeleton for assistance and rehabilitation therapies. As a solution for the movement transmission, the proposed device uses modular linkage that are attached to each finger by means of snap-in fixations. The linkage is kinematically and dynamically analyzed by means of simulations with AnyBody Simulation Software to obtain an estimation of the range of motion and admissible forces. In order to check the deviations of the real performance respect to the simulated results, due to uncertain variables, a first prototype is built and tested.

Keywords: Hand exoskeleton · Assistive robotics · Rehabilitation robotics

1 Introduction

1.1 State of the Art

In the current literature we can find a wide diversity of robotic devices which can actuate the movements of the human hand [1]. Part of these devices, such as [2–4], are aimed to perform rehabilitation therapies; while many others are pretended to assist the hand motion during activities of daily-living [5–7].

Depending on the application, a hand exoskeleton may require uneven features. For example, a rehabilitation-aimed exoskeleton needs to be fairly backdrivable and allow a wide range of movement, so it is flexible enough to perform different rehabilitation exercises. In contrast, an assistance exoskeleton must be stiff enough to assure a firm grasping of objects present during activities of daily living and can sacrifice flexibility of movement in favor of predefined grasping patterns.

These different requirements result on diverse force transmission architectures:

– Some devices use linkages in order to transmit the force from the actuator to the human joints. This is a stiff architecture that requires a proper alignment

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between kinematic centers of the linkage and human joints, but allows a good control of the hand pose. Due to the flexibility of the design, with the correct sizing, these mechanisms can achieve complex movement patterns with simple actuators.
- Another extended architecture is the cable driven glove. These are more flexible and simpler alternatives, that rely on the own human joints to direct the movement, so they are less prone to uncomfortable poses. In contrast, they require pulleys to achieve high forces and are harder to control in intermediate positions. Additionally, this kind of exoskeletons need a pair of cables in antagonist configuration in order to assist both extension and flexion movements.
- Finally, some devices use deformable actuators, like pneumatic muscles or shape-memory alloys, attached directly to the hand by means of a glove. They result in very light and simple devices, but actuators are not placed in the most advantageous place to achieve great forces.

In general, according to [1] there is a clear trend to use cable driven devices and deformable gloves for assistance purposes while linkage architectures are mainly used in rehabilitation devices.

1.2 Framework and Objective

AIDE Project (H2020) [8] is a project that is developing a multimodal system to assist disabled people in the realization of a wide range of activities of the daily living. One of the main research lines, is the analysis of usage of exoskeletons to assist users during the interaction with their environment [9].

In this framework, we are developing a hand exoskeleton with the concept described in the patent ES2558024B1 [10] as starting point. This device is required to be able to grasp different kind of everyday use objects, such as glasses, adapted cutlery or handles, with a grip that must be firm and safe in order to provide real autonomy to the user.

2 Mechanical Design

Since we consider the grip strength as a decisive factor to achieve our goals, we have chosen an architecture based on a linkage that controls the pose of the phalanxes. Using this type of power transmission, we can tune the leverage between links in order to achieve a satisfying balance between the transmitted force and range of movement; and therefore optimize the weight and power required for the actuators.

As a first approximation, we propose an exoskeleton with three active degrees-of-freedom, corresponding to flexion-extension of index finger, flexion-extension of middle finger and flexion-extension of both ring and little finger. Thumb will have a series of passive-degrees of freedom that will allow to place the thumb in a suitable pose in the installation phase, and will be lockable to allow the thumb to work in opposition during the grasp.

2.1 Finger Mechanism

The proposed solution (Fig. 1) consists on a five-bar-linkage that couples the movement of both proximal and medial phalanxes so that they can be controlled with a single active degree-of-freedom. This mechanical system is driven by a linear actuator fixed to the exoskeleton frame and connected to the link $L2$. We have decided not to actuate on the distal phalanx since it would restrain excessively the movements of the finger, leading to a greater probability of uncomfortable poses.

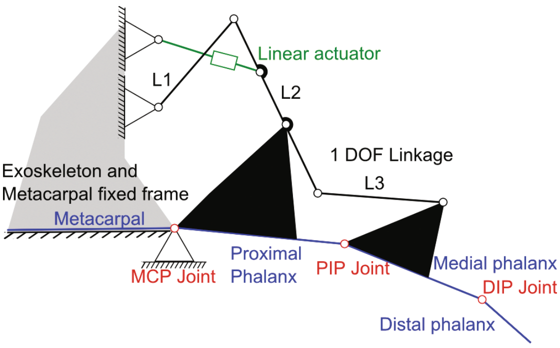

Fig. 1. Proposed linkage for a finger

This linkage forms closed kinematic chains with the finger, but this is only true if the finger is perfectly fixed to the linkage. Unfortunately, the interface between the robot and the human body will introduce an uncertainty that, due to the complexity and high grade of non-linearity of the mechanism, may completely modify the kinematic behavior of the robot. In this regard, similarly to the solution proposed by Ho et al. [11], we have added a pair of circular guides, whose centers match with the joints of a reference finger. In this way, the kinematic chain is closed exclusively by mechanical parts whose dimensional parameters are known.

The addition of the circular guides carries extra dimensional restrictions, due to the possible interference between guides and links. The design developed by Ho et al. consists on a pair of slots in which a train of bearings slide, restricting the movement of the links. This architecture may be effective, but requires substantially good quality in the machined surfaces of the slot and the use of miniature elements in order to be as compact as possible. As an alternative, we propose the use of a doubled edged curved guide which slides between a group of 4 V-shaped bearings (Fig. 2). This results on a simple but effective option, that can be easily built with technologies like 3D-printing or plastic moulding.

Regarding the linear actuator, size and weight are the main limiting design factors. Despite pneumatic actuator may result attractive for this kind of devices due to their reduced dimensions and high force, we consider that electric drives

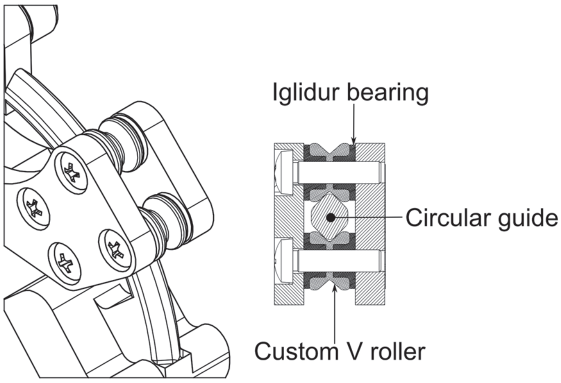

Fig. 2. Detailed view and section of the designed circular guide, using bearings with V-shaped profile

are more suitable for domestic environments, since it is easier and cheaper use the household electric installation than providing a compressed air supply to the user. Among the different existing technologies, we consider that Actuonix PQ12 Linear Actuator [12] provides an adequate balance between size, weight and maximum force. Moreover, this actuator has two interesting features for this application: in one hand, the screw transmission allows to have a high backdrive force that avoid the releasing of the grasped object in case of accidental lose of the power supply; in the other hand, it has a built in potentiometer, so no additional space is required to set up an external one.

The sizing of the whole mechanism can not be easily done by mathematical means, since complex and non-linear kinematics result on multiple solutions or unstable convergence. Additionally, elements like screws or shafts can be found just in specific sizes, so any optimization of the link sizes would hardly be compatible with these normalized parts. Therefore, we have used a parametric CAD model of the device in order to obtain a satisfying solution by manually changing the geometric variables. Figure 3 shows a detailed view of the resulting finger mechanism with the extreme theoretical pose of the finger. At this stage of design, this linkage and dimensions will be the same for each finger except thumb.

Unlike the rest of fingers, thumb can not be approximated as a planar mechanism due to its degree of freedom of opposition. However, many common grasps can be done by just maintaining firmly the position of the thumb while the rest of fingers perform the whole movement. So, at this design stage, we have designed a mechanism that allow to place manually the user's thumb in a comfortable pose and then block it.

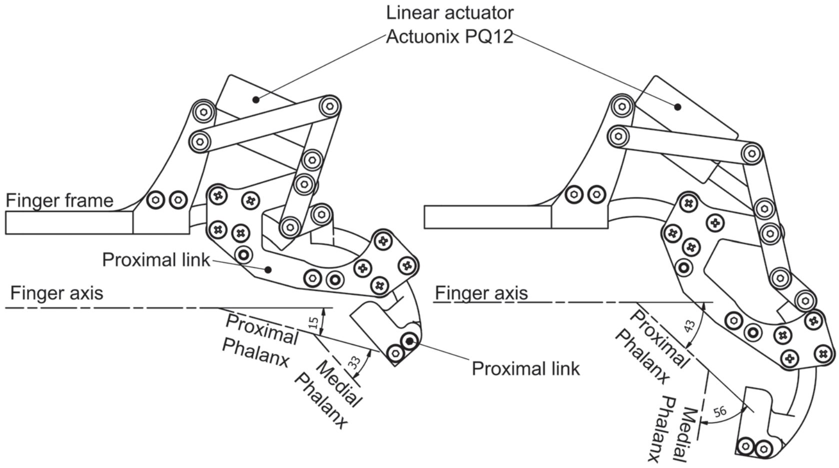

Fig. 3. Drawing of a finger mechanism with extreme positions. (Left: Maximum extension. Right: Maximum flexion)

2.2 Hand Interface

Since the designed linkage is kinematically determinate by means of circular slides, it is necessary to design an interface able to deal with misalignment between human joints and robot rotation centers, as well as the deviation between the reference finger size and actual user's dimensions.

As an interface between moving parts of the exoskeleton and human fingers, we have designed a snap-in fixing system by using elastic ring-like pieces that can be inserted in certain points of the finger linkage (Fig. 4). This system allows a quick attach-detachment process, reducing the time required in the set up and allowing a fast reaction against any dangerous situation. The stiffness of the ring can be designed to automatically release itself if a certain force threshold is overcome. Additionally, the diameter of each ring can be chosen accordingly to the real dimensions and misalignment, in order to provide the user with the most comfortable experience.

Each finger mechanism must be attached to a frame fixed with respect to the metacarpal section of the hand, but the optimal placement varies significantly depending on hand's dimension. As a solution, we propose an attachment similar to the finger's one (Fig. 5). In this case, the finger frame has a slot in which a double wedge-like part is inserted. This wedge constraints two translation degrees-of-freedom, but allows the movement along the slot direction, so that the position of the linkage along the finger metacarpal axis can be adjusted. Once the linkage is correctly placed, the friction between the frame and the wedge prevents it from displacing.

Finally, each wedge is screwed to a semi-rigid hand orthosis that wraps both palm and back of the hand. As a result, we obtain a modular hand exoskeleton

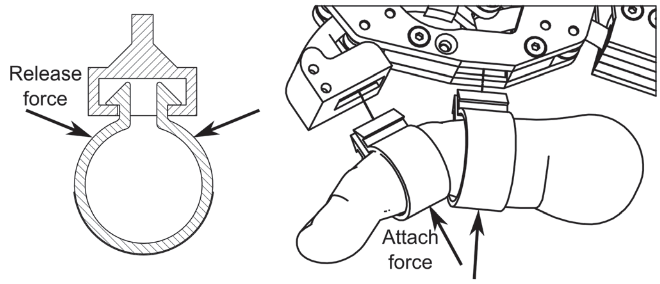

Fig. 4. Finger-Exoskeleton fixing system. Left: Section of the ring-box assembly with the force needed for releasing. Right: Detailed view of the attachment points in the finger linkage.

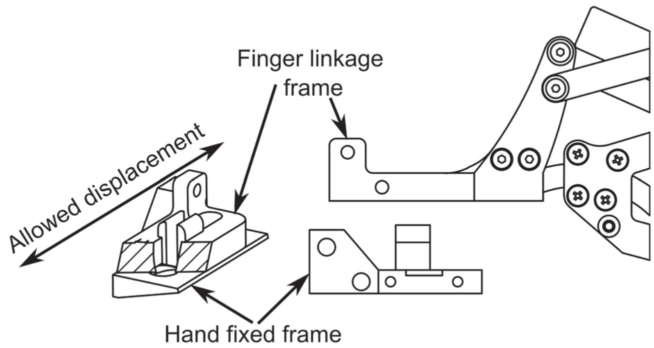

Fig. 5. Hand-Exoskeleton fixing system. Left: Section that shows the wedge-like part inserted in the slot of the finger frame. Right: Detailed view of the connection system before attachment.

that can be easily modified to the user's needs, since just the necessary phalanxes or even finger linkages may be set up.

3 Biomechanical Analysis

In order to study how do exoskeleton kinematics affect the finger kinematics, we have decided to use the AnyBody Simulation Software [13] with the human finger model proposed by Wu et al. [14]. We have included the kinematics and dynamics of the finger linkage to this model (Fig. 6), paying attention in modeling the finger-linkage interface as accurately as possible, to obtain realistic reaction forces. In detail, the ring snap-in fixation has been modeled as a cylindrical slide whose axis is aligned with the phalanx longitudinal axis, attached rigidly to the exoskeleton's link through a bar with length equal to the radius of the ring.

With this numerical model, we can easily solve the kinematics of the mechanism and compute the relationship between the angles of both metacarpophalangeal (MCP) and proximal interphalangeal (PIP) joints. This result is shown

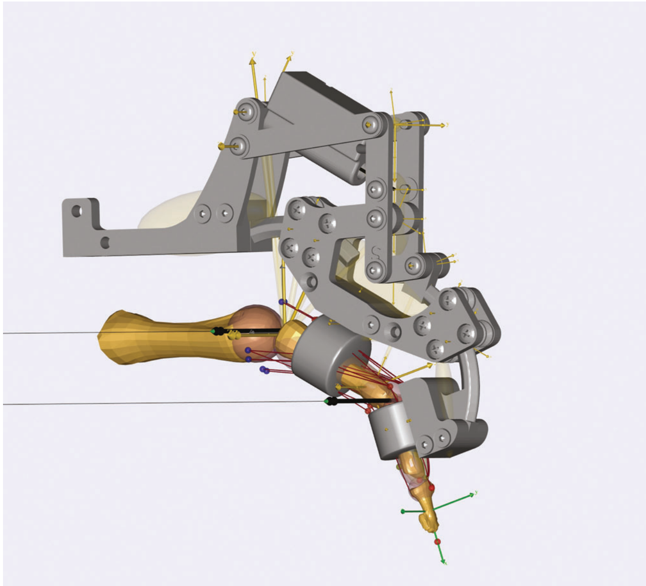

Fig. 6. Human finger [14] and exoskeleton model in AnyBody

in Fig. 7. Despite the internal non-linearity of the mechanism and interface, along the working range defined by the actuator's stroke, the output angles present a fairly linear behavior; so we may use two simple expressions to obtain an estimation of the hand's pose with just measuring the stroke of the motor.

According to Chen et al. [15] reaction torques in each joint of the finger, and the ratio between them, may vary greatly depending on the user and the type of grasp. Therefore, in order to compute in which working points (MCP torque, PIP torque) our exoskeleton can work properly, we have performed an inverse dynamics study computing the force that must exert the actuator to balance the mechanism, applying different torque combinations in the joints of the finger. Taking the maximum force required in each simulation for each combination of MCP and PIP torque, we have computed the admissible load assumptions for our exoskeleton (Fig. 8).

We have performed a preliminary calculation in order to check whether these admissible loads are suitable for the required applications:

The heaviest object that will be considered to be grasped will be a full bottle of water with a capacity of 1.5 L, which can be considered as a mass of 1.5 kg. According to the study of O'Meara and Smith [16], the human skin has a static friction coefficient of 0.8, so to lift a weight of 1.5 kg, a hand must exert a total of approximately 2 kg of force over it.

As a simplification, the applied force is distributed as follow: half the force is exerted by the thumb (1 kg) and the other half is distributed equally between

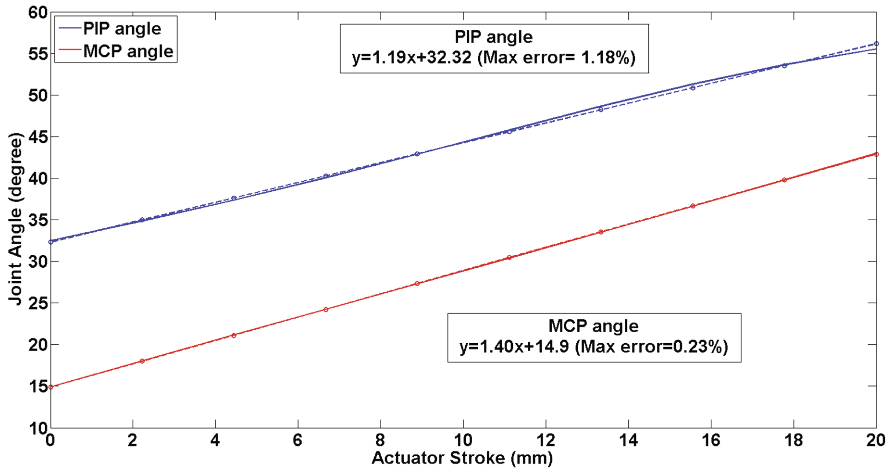

Fig. 7. Angles of the MCP and PIP joints for each actuator stroke. Solid lines represent the output of the simulation. Dashed lines represent the corresponding linear fit. Linear fit equations are provided, where y refers to the joint angle and x to the motor stroke. Angles are measured as in Fig. 3.

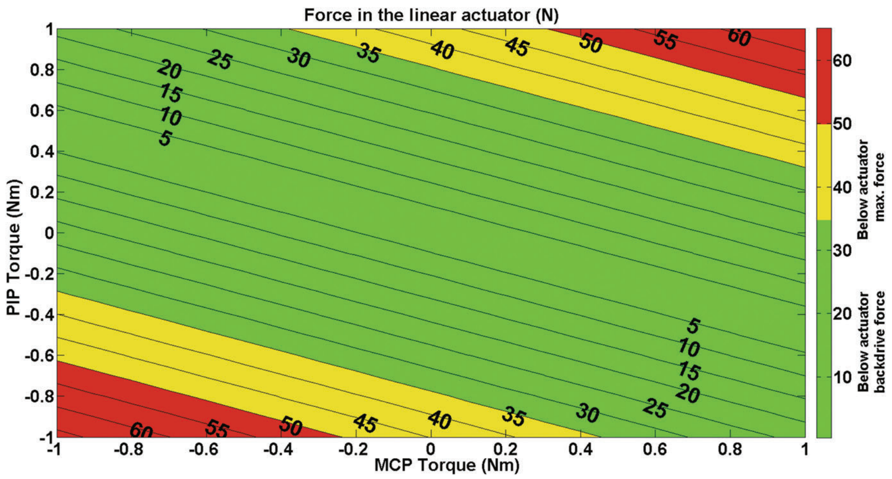

Fig. 8. Module of the force required to the linear actuator in order to stand a specific torque combination. Green area shows the working points in which the actuator can stand torques even without electrical power. Yellow zone defines working points that necessarily require powered actuator. Red zone contains torque combinations not standed by the mechanism.

index and middle finger (0.5 kg each). If the force is applied in the middle of each phalanx and only the MCP and PIP joints are actuated, the required torque for each joint can be summarized in Table 1. With this load hypothesis, each finger would be working inside the safety zone of Fig. 8.

Table 1. Loads required to grasp 1.5 kg bottle with a simplified grasp model

Joint	Next phalanx average length (m)	Applied force (N)	Joint torque (Nm)	Required torque (Nm) Safety factor >2
IndexMCP	0.058	2.5 N	0.0725	0.15
IndexPIP	0.022	2.5 N	0.0275	0.6
MiddleMCP	0.053	2.5 N	0.06625	0.14
MiddlePIP	0.026	2.5 N	0.0325	0.7
Thumb-MCP	0.032	10 N	0.16	0.32

4 Prototype Stage

There are many factors, such as clearances in the interfaces or joint misalignment, that can not be easily evaluated with simulations, so it is mandatory to build a prototype to check the real performance of the designed exoskeleton.

In this prototype, the exoskeleton will have 3 finger modules that control index finger, middle finger and the pair formed by ring and little fingers, in addition to the aforementioned thumb blocking linkage.

Each finger module is built in Polylactic Acid (PLA) material by Fused Deposition Modeling (FDM) 3D printing technology, which allows fast and cheap fabrication of complex geometries. Despite this fact, all parts have been designed or subdivided in geometries that can be easily built by computer numerical control (CNC) machining in order to allow the production of further prototypes using traditional materials. We have particular interest in studying the resistance of the PLA 3D printed parts in order to check the feasibility of building the exoskeleton using technical polymers, to reduce as much as possible the weight of the final device. Additionally to the finger modules, we have similarly built a set of rings with diameters that cover the range from 15 mm to 25 mm with a step of 1 mm. Finally, as an interface with the hand, we have chosen a commercial hand orthosis, were the fixations for the finger module and thumb blocking linkage have been rigidly attached. Figure 9 displays the modules that compose the whole exoskeleton (which can be easily attached and detached), the device set up on a hand, and a grasp test in which the device is capable of holding a bottle of half liter of water.

Once the user wears the hand exoskeleton, we have observed that, despite that the mechanism holds its position, rings allow certain freedom of movement of the fingers so the user can accommodate them to a more natural pose. This adjustment introduces an error in the kinematics that varies each time the devices is attached and removed from the hand. Figure 10 shows the result of the measurement of the angles of the joints for a same user after installing the exoskeleton several times. These measures were taken approximately by photogrametry, with a precision of about $\pm$ 1°. For both joints we can observe that the error with respect to the simulated values is remarkably high for low angles and becomes

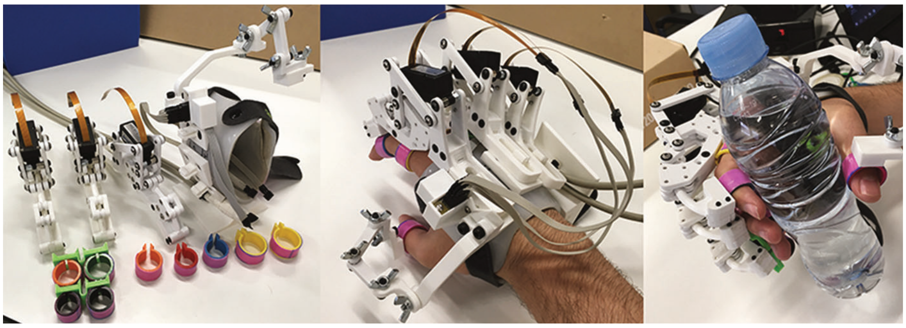

Fig. 9. Left: Disassembled exoskeleton with finger modules, hand orthosis and finger rings. Center: Exoskeleton attached to a human hand. Right: Grasp test of a bottle of 0.5 L of water.

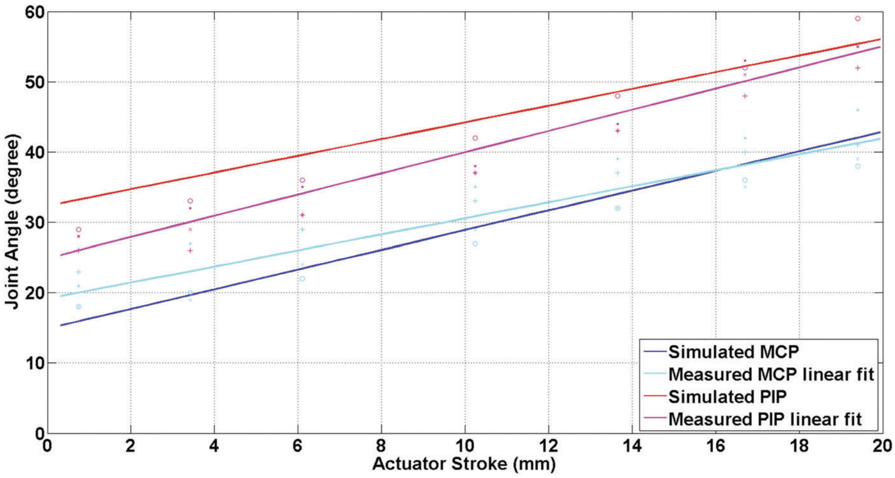

Fig. 10. Mismatch between simulated and measured angles due to clearances in the rings and misalignment between joints. Sparse points correspond to measurements for a same subject after different exoskeleton set-ups.

lower in closed poses. This phenomenon is due to the alignment between both rings of the finger, since it allows the finger to move along the axial direction of the ring. When the exoskeleton becomes more closed, misalignment between rings restrict the displacement along them and the real behavior becomes closer to the simulated model.

5 Conclusion and Future Work

According to the first tests with the prototype, the designed device has proven to be feasible to grasp certain objects present in the activities of daily living, such as small bottles, glasses or adapted cutlery. In comparison with other existing devices, we want to remark several features that may suppose an improvement in this kind of devices:

– Snap-in fixations together with the modular finger mechanisms allow a quick installation and removal of the device as well as eases the maintenance of the hardware and the substitution of worn up parts.
– The use of elastic rings as interface with fingers, despite that they introduce uncertainty in the actual hand pose, provide a comfortable fixation to the user allowing the proper accommodation of the finger. Additionally, rings add safety measure when extending the hand since they will detach at a certain interaction force.
– As PLA has proven to be tough enough to stand the hand loads, the use of technical plastics as structural materials seems to be feasible. These kind of materials will result on lightweight devices as well as will allow cheap mass manufacturing process like molding or injection.
– Since grasping contact forces mainly fall to rings, so they can be coated with adherent materials to improve the safety of the grip.

Future works will consist in an exhaustive validation of the device as well as in exploring additional potential applications, such as rehabilitation therapies. Implementation of a force measurement system is a short-term objective, since it will provide valuable data required for validation tests and studies with disabled users. This force measurement will extend the functionality of the devices because of the utility in control loops or detection of movement intention.

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