DESIGN AND TESTS OF A THREE FINGER HAND WITH 1 DOF ARTICULATED FINGERS

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ABSTRACT- This paper presents the design of a new low-cost, easy operation hand having three 1 dof anthropomorphic fingers with human size. Experimental results on human cylindrical grasping have been used for designing a 1 dof anthropomorphic finger having human size. The mechanical design of this finger has been mainly focused on a suitable articulated mechanism. This mechanism transmits the power to the phalanxes for a human-like grasping motion and it can be embedded in the body of the finger itself. The design of a three finger hand has been presented as based on the designed finger module. Experimental tests on a built hand prototype have been carried out in order to show the feasibility of the proposed design and validate its operation.

INTRODUCTION

Several researchers have investigated different types of devices for achieving the grasping and handling of objects. Mechanical grippers having two fingers are widely used in industrial application and mostly in industrial robots, [1]. However, multi-fingered robotic devices and hands have been also widely investigated, as reported for example in [2-15]. This type of devices tries to mimic the performances of human hands in order to have high flexibility multi-purpouse devices. Significant examples can be identified in the Stanford/JPL hand, [5], the TUAT/Karlsruhe Humanoid Hand, [6], the DLR's Hand II, [7], the BUAA/Bejing University four-fingered hand, [8], Manus Colobi, [9], the TBM hand, [10], the Barrett Hand, [11] and the hands proposed in [12], [13] and [14]. Most of the available multi-fingered prototypes have a high number of degrees of freedom, a complex control and a high cost. The proposed hand is low-cost and easy-operation that means the new prototype has been built with commercial components and it can be controlled easily. Moreover, the new drive-finger mechanism for a 1 DOF anthropomorphic finger can be imbedded in the finger body and it remains in the finger body during its movement. Since a recent past, design and research activities have been carried out at LARM, Laboratory of Robotics and Mechatronics, in Cassino in order to design a low-cost, easy operation anthropomorphic finger having 1 dof, as outlined in [16-21]. A preliminary prototype that has been built at LARM is shown in Fig. 1. The size of this prototype is about 1.5 times bigger then the average human finger. This paper reports the design and test of a new robotic hand with three anthropomorphic fingers of human size. In the previous papers a different hand of bigger size has been investigated. Experiments with the three fingered hand prototype has been presented in this paper. Special care has been addressed to the design of a suitable transmission system embedded in the body of the finger by using articulated mechanisms. A three finger hand has been also designed and built at LARM by using the designed finger module. Experimental tests have been carried out on human grasping and on the built hand. The comparison of the experimental results can validate the design and operation of the built hand.

EXPERIMENTAL TESTS OF HUMAN GRASP

For the design of an anthropomorphic hand a suitable knowledge of the human grasp can be very useful. In particular, dimensions of fingers, grasping forces and contact points between fingers and objects have been investigated in human grasping for design purposes of a new low-cost easy operated hand.

As first step, several videos of the human hand grasping have been processed. Kinematic models of the fingers have been derived from the analysis of the human grasping as proposed in Fig. 2. The dimensions of each phalanx of index, medium and thumb have been measured for five persons. The measured values and average values have been obtained as reported in Table 1 referring to the kinematic models of Fig. 2. It is worth noting that it has been decided to measure only index, medium and thumb since they are the most used in human grasping.

By analyzing several videos of the human cylindrical grasping of a given object it has been observed that there are almost constant ratios between the motions of each phalanx in the approaching motion to the object, as

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KINEMATICS DESIGN OF A 1 DOF ANTHROPOMORPHIC FINGER MECHANISM

The results of the experimental tests on the human hand have been used in order to define the kinematic design of a 1 dof anthropomorphic finger. This finger has the same size of the average human index finger. In particular, data that are reported in Table 1 have been used in order to choose the link lengths of the phalanxes that are defined as the distances $A_0A_1$, $A_1D_1$ and $D_1E_1$ in the kinematic scheme of Fig. 8. This kinematic architecture permits to mimic the movement of human fingers with only 1 dof. It has been decided to actuate the first phalanx corresponding to the links $A_0A_1A_2$ by connecting it directly to a motor or through a proper gear train. The other phalanxes are actuated by an articulated mechanism that is connected with the previous phalanx. 

In Fig. 8 one can note that any motion of the first phalanx $A_1B_1D_1$ through the link $B_0B_1$. Similarly, any motion of the second phalanx $D_1E_1C_1$ through the link $A_2C_1$. In order to obtain a robust suitable stiff mechanical finger design, it has been devised to avoid link connections between the phalanxes. The relative positions of the phalanxes have been measured in five different phases of the grasping by taking into account the contact points on the object. The link lengths have been chosen to mimic the movement of human fingers with only 1 dof. 

The overall experimental system has been set up according to the scheme of Fig. 5. The operation of the sensors has been managed by using an acquisition card AT-MIO-16E-2, [25], and a suitable virtual instrument has been developed in LabView environment, [26]. In the experiments the grasping action has been referred to three phases as shown in Fig. 6. In particular, the first phase has been defined when the hand is fully opened and it approaches the object, Fig. 6(a). The second phase concerns with the lifting of the grasped object, Fig. 6(c). The maximum measured grasping force has been of about 11.0 N, as shown in Fig. 7(b). From the plots of Fig. 7(c), sensor 3 has measured a force near to zero, since the grasp configuration has not given contacts with this sensor. When in contact the grasping forces changes as a function of a static grasp and hand motion. Similar results have been obtained in experiences for grasping object of different shapes and materials. The experiments have been carried out several times by five different persons in order to have a statistical confirmation of values. The results of measured forces with the human hand have been used to validate the operation of the hand prototype, by comparing the measured forces of the human hand with the measured grasp forces of the robotic hand prototype during experimental tests.
interference, and to achieve suitable mobility. This design has been studied and solution has been obtained with satisfactory results by looking at the different aspects separately, and by achieving a dimensional synthesis of the mechanism with traditional techniques. Table 3 reports the main dimensions of the designed kinematic chain referring to the scheme of Fig. 8, as obtained by the dimensional synthesis of the articulated mechanism. The dimensional synthesis has been solved to achieve a human-like motion for the finger reproducing.

A kinematic analysis of the mechanism in Fig. 8 can be carried out by writing the closure equations for each four bar linkage that composes the mechanism in the form of vector equation as

\[
\begin{align*}
\mathbf{a} + \mathbf{b} + \mathbf{c} + \mathbf{d} &= \mathbf{0} \\
\mathbf{f} + \mathbf{g} + \mathbf{h} + \mathbf{i} &= \mathbf{0}
\end{align*}
\]

Equations (1) can be written in its scalar form as

\[
\begin{align*}
a \cos \theta_1 + c \cos \theta_2 + b \cos \theta_4 + d \cos \theta_0 &= 0 \\
\end{align*}
\]

\[
\begin{align*}
a \sin \theta_1 + c \sin \theta_2 + b \sin \theta_4 + d \sin \theta_0 &= 0 \\
\end{align*}
\]

\[
\begin{align*}
g \cos \theta_2 + p \cos \theta_3 + f \cos \theta_5 + l \cos \theta_6 &= 0 \\
\end{align*}
\]

\[
\begin{align*}
g \sin \theta_2 + p \sin \theta_3 + f \sin \theta_5 + l \sin \theta_6 &= 0 \\
\end{align*}
\]

Taking into account geometrical considerations one can write

\[
\begin{align*}
\theta_2 &= 2\pi - (\gamma_g \theta_2) \\
\theta_0 &= \theta_1 + \gamma_G
\end{align*}
\]

Equations (3) and (4) can be solved by means of algebraic manipulations when \(\theta_0\) is assumed as given constant and \(\theta_1\) is considered as the input kinematic variable.

The solutions for equations (3) and (4) can be expressed as

\[
\begin{align*}
\theta_2 &= \tan^{-1}\left(-\frac{2C \pm \sqrt{(2C)^2 - 4(A + B)(A - B)}}{2(A + B)}\right) \\
\theta_3 &= \tan^{-1}\left(-\frac{2E \pm \sqrt{(2E)^2 - 4(D + F)(D - F)}}{2(D + F)}\right)
\end{align*}
\]

in which

\[
\begin{align*}
A &= (a^2 - b^2 + c^2 + d^2) + 2 a \cos(\theta_1 - \theta_0) \\
B &= 2 a c \cos \theta_1 + 2 c d \cos \theta_0 \\
C &= 2 a c \sin \theta_1 + 2 c d \sin \theta_0 \\
D &= (a^2 + b^2 + d^2 - c^2) + 2 a d \cos(\theta_1 - \theta_0) \\
E &= (2 a d \cos \theta_1 + 2 b d \cos \theta_0) \\
F &= (2 a b \sin \theta_1 + 2 b d \sin \theta_0)
\end{align*}
\]

A similar position analysis can be carried out for the second four bar linkage to obtain similar expressions for \(\theta_3\) and \(\theta_5\).

The functions for \(\theta_2\), \(\theta_3\), \(\theta_4\) and \(\theta_5\) like equations (7) have been numerically implemented in order to simulate the operation of the designed mechanism. Figure 9 shows the configurations of the finger when the input angle varies from 0 to 80 deg with a step of 10 deg. Additional results of the kinematic numeral simulation are reported in Fig. 10 as the transmission ratios during the finger motion.

The comparison of the experimental results in Fig. 6 to 7 with the numerical results of simulation in Fig. 9 to 10 shows that the configurations of the phalanxes of the designed mechanism give a good approximation of the cylindrical grasping for an average human finger.

In addition, equations (7) give a velocity analysis of the proposed mechanism in the form
\[
\begin{align*}
\dot{\theta}_2 &= -\dot{\theta}_1 \frac{a \sin(\theta_4 - \theta_1)}{c \sin(\theta_4 - \theta_2)} \\
\dot{\theta}_4 &= -\dot{\theta}_1 \frac{a \sin(\theta_2 - \theta_1)}{b \sin(\theta_2 - \theta_4)} \\
\dot{\theta}_3 &= -\dot{\theta}_2 \frac{g \sin(\theta_5 - \theta_2)}{p \sin(\theta_5 - \theta_4)} - \dot{\theta}_6 \frac{1}{p \sin(\theta_5 - \theta_5)} \\
\dot{\theta}_5 &= -\dot{\theta}_2 \frac{g \sin(\theta_3 - \theta_2)}{f \sin(\theta_3 - \theta_4)} - \dot{\theta}_6 \frac{1}{f \sin(\theta_3 - \theta_5)}
\end{align*}
\] (9)

A further differentiation of equations (9) gives

\[
\begin{align*}
\ddot{\theta}_2 &= -a \cos(\theta_1 - \theta_4) \dot{\theta}_1^2 - b \dot{\theta}_4^2 - c \cos(\theta_2 - \theta_4) \dot{\theta}_2^2 + a \sin(\theta_4 - \theta_1) \ddot{\theta}_1 \\
\ddot{\theta}_3 &= -g \cos(\theta_2 - \theta_2) \dot{\theta}_2^2 - f \dot{\theta}_5^2 - p \cos(\theta_3 - \theta_3) \dot{\theta}_3^2 + \\
&\quad -1 \cos(\theta_6 - \theta_5) \dot{\theta}_6^2 + g \sin(\theta_5 - \theta_2) \dot{\theta}_2^2 + 1 \sin(\theta_5 - \theta_5) \ddot{\theta}_6 \\
\ddot{\theta}_4 &= -c \sin(\theta_2 \dot{\theta}_2 - a \sin(\theta_1 \dot{\theta}_1) - (a \cos(\theta_1 \dot{\theta}_1^2 + b \cos(\theta_4 \dot{\theta}_4^2 + c \cos(\theta_2 \dot{\theta}_2^2 \\
\ddot{\theta}_5 &= -g \sin(\theta_2 \dot{\theta}_2 - p \sin(\theta_3 \dot{\theta}_3 - l \sin(\theta_6 \ddot{\theta}_6 + (g \cos(\theta_2 \dot{\theta}_2^2 + p \cos(\theta_3 \dot{\theta}_3^2 + l \cos(\theta_6 \dot{\theta}_6^2 + f \cos(\theta_5 \dot{\theta}_5^2 \\
\) )
\] (10)

Equations (9) and (10) have been implemented in a numerical simulation in order to compute the velocities and accelerations of the phalanges during the operation of the designed mechanism. In particular, Figs. 11 and 12 show the plots of the velocities and accelerations as function of the input angle for the finger motion of Fig. 9.

A force analysis has been carried out in order to verify that the forces that each phalanx can apply are comparable with the ones that have been measured experimentally on the human fingers. Two cases have been considered, namely, the first case in which it has been assumed that the contact occurs only on one phalanx; a second case in which it has been assumed that all the forces at contact points have same value.

The first force case can be studied through the principle of virtual works and it has been applied referring to the model in Fig. 13. It has been assumed that the resultant of gasping force on each phalanx is applied in the middle of the phalanx itself.

By using this assumption one can write the principle of virtual works as

\[
C_m \ddot{\theta}_1 = F_1 V_1 + F_2 V_2 + F_3 V_3
\] (11)

The second case of force analysis has been examined as based on the assumption that the grasping force is distributed equally among the three contact points. By using this assumption one can write three expressions

\[
F_i V_i = \frac{C_m \ddot{\theta}_i}{3} \quad i = 1, 2, 3
\] (12)
Figures 14 and 15 show the results of a numerical simulation that has been carried out by implementing Eqs (11) and (12), respectively. It is worth noting that the magnitude of the forces in Fig. 14 is higher than the forces in Fig. 15. In fact, in the case of Fig. 14 the grasp forces are assumed to be applied in the middle of one phalanx. In the case of Fig. 15 the grasp forces are assumed to be applied simultaneously in all the contact points.

A MECHANICAL DESIGN OF A FINGER PROTOTYPE AND A THREE FINGERED HAND
The mechanical design of the new finger prototype has been based on the kinematic model of Fig. 8. A 3D CAD model has been developed in Autodesk Inventor environment, [22], by considering the sizes of the links in the kinematic model. It has been decided to use commercial aluminum alloy for manufacturing the links since it is low-cost and lightweight. It has been also decided to embed the articulated parallelograms that transmit the motion inside the finger body in order to have a compact design.

The developed 3D model has been used in order to check the feasibility of assembling all the components. Figure 16 shows a detail of the assembling of all the components of the fingers. Moreover, the developed 3D model has been used in order to carry out several simulations of the operation of the finger. These simulations have been useful in order to check the feasibility of the proposed dimensions for avoiding any link interference and for properly mimicking the human index finger motion as reported in Fig. 17. Figure 18 shows a comparison of the designed 3D model with a built prototype.

A three fingers robotic hand has been designed by using the new 1 dof finger module. The results obtained in the tests of grasping, which have been carried out with the human hand at LARM, have been taken into account for the design. Each mechanical component of the hand has been designed by using Autodesk Inventor, for the analysis of mechanical interference and to simulate the grasping, before the construction of the prototype.

Two hand models have been proposed as based on low-cost and compact design constraints as shown in Fig. 19. The principal difference between the first model and the second proposed hand is the design of the palm. In fact, the first hand has a more compact and simple model of palm as shown in Fig. 19(a). The second hand has a different shape of the palm as shown in Fig. 19(b). The shape of the palm of the second hand has a different orientation of the fingers and location of actuators respect to the first model hand. These aspects make the second design more anthropomorphic. Moreover, the actuation of the second proposed hand can be either pneumatic or electric. Figure 20 shows the new hand prototype with 3 fingers of human sizes that has been built at LARM in Cassino.

EXPERIMENTS WITH THE THREE FINGERED HAND PROTOTYPE
Figure 21 shows a test-bed prototype of the proposed anthropomorphic hand that has been assembled with three 1 dof articulated fingers that have been designed and built at LARM in Cassino. The prototype has been constructed by using commercial aluminum bars having U shape side 19mm, and thickness of 3 mm.

It is worth noting that the contact points between the grasped objects and fingers are not constant depending on the object. In this case we have used a compliant plastic object in order to guarantee the contact between all the phalanxes of the fingers and the grasped objects during experimental tests.

The overall experimental system that is shown in Fig. 4(b) has been settled up according to the scheme of Fig. 5. The operation of the sensors has been managed by using an acquisition card AT-MIO 16E-2, [25], and a suitable virtual instrument that has been developed in LabView environment, [26]. Moreover, the operation of the DC motors has been managed by using a PLC LOGO!, [27]. It is worth noting that the PLC LOGO! is a low-cost and easy operation PLC that can be programmed by using the commercial software PLC LOGO! Soft, [27]. The PLC LOGO! has been programmed in order to achieve the opening and closing of the hand. In particular, a close loop force control has been implemented by using the signal of the force sensor 1. The motors stop when the grasp force that is measured by sensor 1 is over a threshold value. This threshold value has been chosen as equal to 1,5 N after experimental calibration.

Figure 23 shows the forces that have been measured by the first five force sensors during the static grasping of an object. In particular, Fig. 23(a) shows the plots of the force measured by sensor 1 on the palm. Figures 23(b), (c) and (e) show the plots of the forces measured by sensors 2, 3 and 5 that are located on the phalanxes 2, 3 and 1 of the finger III, respectively, as shown in Fig. 22. Figure 23(d) shows the plot of the force measured by sensor 4 that is located on the phalanx 1 of the finger II. Figure 24 shows the forces that have been measured by the others five sensors during the static grasping of an object made of compliant plastic. In particular, Figs. 24(b) and (e) are the plots of the forces measured by sensors 7 and 10 that are located on the phalanxes 2 and 3 of the finger II, respectively. Figures 24(a), (c) and (d) are the plots of the forces measured by sensors 6, 8 and 9 that are located on the phalanxes 1, 2 and 3 of the finger I, respectively. The maximum measured grasping force has been about 2 N, as shown in Fig. 23(d).
It is worth noting that the plots of Figs. 23 and 24 show that all sensors have measured a non-zero force, since the grasp has given contacts with all sensors. The experimental tests have been carried out by using a compliant plastic object. This compliant plastic object adapts its geometry to the surface of the phalanxes. Thus, it is possible to have all the sensors in contact with this object. Values of the measured forces equal to zero have been measured by some sensors in experimental tests with rigid objects. In fact, in these tests the grasp has not given contacts with all sensors. This is direct consequence of the rigid structure of the fingers. In fact, the rigid structure of the fingers does not allow the fingers to adapt their geometry to the surface of different objects. The comparison of the results of the experimental tests on the human grasping and on the above-mentioned three-fingers hand test-bed show satisfactory results. In fact, this comparison validates the operation of the built prototype since the plots of the grasping forces with the human hand and the built prototype have the same shape and comparable magnitudes. The hand prototype shows measured grasping forces that are similar to the human hand for the grasping of different objects, as illustrated in [20].

CONCLUSION
In this paper the design of a new hand with 1 dof low-cost easy operation robotic finger has been presented. Particular attention has been devoted to the design of 1 dof articulated mechanism, which transmits the power from the input shaft to all the phalanxes. Human grasps have been investigated with experimental tests and numerical simulations have been performed in order to design an anthropomorphic finger with human size and human like operation. Experimental tests have been performed in order to validate the operation of the prototype. The experimental results show the practical feasibility of the prototype as a module for a three finger robotic hand, which has been built and tested at LARM in Cassino.

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REFERENCES
Fig. 1. A preliminary prototype of a 1 dof anthropomorphic finger built at LARM in Cassino, [14, 16].

Fig. 2. A kinematic model for human hand fingers: (a) thumb in front of index finger; (b) thumb in front of middle finger (Crosses indicate usual contact points).

Fig. 3. Phases of a human cylindrical grasping: (a) opening of the hand and moving to the object; (b) first contact of the finger with the object; (c) second contact between the object and the finger; (d) approaching motion of the finger to the object; (e) stable grasping of the object.
Fig. 4. Sensors installed on a human hand: (a) position of the sensors; (b) FSR150CP12 force sensor with the main dimensions in mm, [15].

Fig. 5. A scheme for the measuring system for investigating human grasp experimentally.
Fig. 6. Grasping phases for force measure in experimental tests: (a) approaching motion; (b) static grasp; (c) lifting the object.
Fig. 7. Plots of the measured forces during the grasping of a cubic object in Fig. 6 by using the sensored grove of Fig. 4: (a) by sensor 1; (b) by sensor 2; (c) by sensor 3; (d) by sensor 4; (e) by sensor 5; (f) by sensor 6.
Fig. 8. A design scheme of the articulated mechanism for a 1 dof anthropomorphic finger.

Fig. 9. A simulated motion for the designed mechanism mimicking human finger motion.
Fig. 10. Numerical transmission ratios for the simulated motion of Fig. 9: (a) $\theta_1$ versus $\theta_2$; (b) $\theta_1$ versus $\theta_3$. (the angles are expressed in degrees)

Fig. 11. Velocity diagrams for the finger motion of Fig. 9: (a) $\theta_1$ versus $2 \theta_2$, (b) $\theta_1$ versus $\theta_3$.

Fig. 12. Acceleration diagrams for the finger motion of figure 9: (a) $\theta_1$ versus $\ddot{\theta}_2$, (b) $\theta_1$ versus $\ddot{\theta}_3$. 
Fig. 13. A model for the forces acting on one finger during cylindrical grasping, assuming one contact for each phalanx.

Fig. 14. Results of the first numerical simulation of grasping force: (a) $F_1$ versus $\theta_1$ (when the only contact point is $P_1$); (b) $F_2$ versus $\theta_1$ (when the only contact point is $P_2$); (c) $F_3$ versus $\theta_1$ (when the only contact point is $P_3$).
Fig. 15. Results of the second numerical simulation of grasping force (when the grasp forces are applied simultaneously in all the contact points): (a) $F_1$ versus $\theta_1$; (b) $F_2$ versus $\theta_1$; (c) $F_3$ versus $\theta_1$.

Fig. 16. Parts of the new 1 dof articulated finger of Fig 8.
Fig. 17. CAD simulation of the closing movement for the designed 1 dof finger, referring to the configuration in Fig 9: (a) $\theta_1=0$ deg; (b) $\theta_1=20$ deg; (c) $\theta_1=40$ deg; (d) $\theta_1=60$ deg; (e) $\theta_1=80$ deg.

Fig. 18. The new 1dof finger module: (a) a 3D-CAD scheme; (b) a prototype built at LARM in Cassino.

Fig. 19. Proposed designs for a robotic hand with the articulated finger of Figs. 9 and 18: (a) First model, (b) Second model.
Fig. 20. The new built hand prototype with 3 fingers of human sizes.

Fig. 21. A built test-bed prototype of the proposed hand with three 1 dof anthropomorphic fingers.
Fig 22. 3D-CAD scheme of the built test-bed prototype with the sensors position.

Fig 23. Plot of the measured forces during the grasping of an object made by using a compliant plastic object with the hand of Fig. 21: (a) by sensor 1; (b) by sensor 2; (c) by sensor 3; (d) by sensor 4; (e) by sensor 5.
Fig. 24 Plot of the measured forces during the grasping of an object made by using a compliant plastic with the hand of Fig. 21: (a) by sensor 6; (b) by sensor 7; (c) by sensor 8; (d) by sensor 9; (e) by sensor 10.
Table 1. Measured dimensions of human hand fingers referring to the kinematic model of Fig. 2.

<table>
<thead>
<tr>
<th>Person</th>
<th>Thumb Lt1 [mm]</th>
<th>Lt2 [mm]</th>
<th>Li1 [mm]</th>
<th>Li2 [mm]</th>
<th>Li3 [mm]</th>
<th>Lm1 [mm]</th>
<th>Lm2 [mm]</th>
<th>Lm3 [mm]</th>
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<tbody>
<tr>
<td>1</td>
<td>37.7</td>
<td>30.5</td>
<td>25.7</td>
<td>22.5</td>
<td>24.1</td>
<td>28.1</td>
<td>24.9</td>
<td>25.8</td>
</tr>
<tr>
<td>2</td>
<td>40.3</td>
<td>34.9</td>
<td>27.4</td>
<td>23.5</td>
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<td>32.5</td>
<td>25.7</td>
<td>28.4</td>
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<td>3</td>
<td>39.0</td>
<td>34.7</td>
<td>26.2</td>
<td>19.4</td>
<td>28.8</td>
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<td>28.3</td>
<td>23.1</td>
<td>25.3</td>
<td>31.7</td>
<td>25.1</td>
<td>27.0</td>
</tr>
<tr>
<td>Average</td>
<td><strong>38.9</strong></td>
<td><strong>33.2</strong></td>
<td><strong>26.9</strong></td>
<td><strong>21.5</strong></td>
<td><strong>25.1</strong></td>
<td><strong>30.3</strong></td>
<td><strong>24.3</strong></td>
<td><strong>27.2</strong></td>
</tr>
</tbody>
</table>

Table 2. Joint angles for phalanx links that are obtained from the image processing of human cylindrical grasping shown in Fig. 3.

<table>
<thead>
<tr>
<th>Phase</th>
<th>(a)</th>
<th>(b)</th>
<th>(c)</th>
<th>(d)</th>
<th>(e)</th>
</tr>
</thead>
<tbody>
<tr>
<td>θ_1 [deg]</td>
<td>9.7</td>
<td>23.9</td>
<td>46.8</td>
<td>69.9</td>
<td>79.9</td>
</tr>
<tr>
<td>θ_2 [deg]</td>
<td>12.5</td>
<td>38.5</td>
<td>68.5</td>
<td>94.7</td>
<td>137.8</td>
</tr>
<tr>
<td>θ_3 [deg]</td>
<td>16.9</td>
<td>44.9</td>
<td>74.7</td>
<td>100.2</td>
<td>182.7</td>
</tr>
</tbody>
</table>

Table 3. Dimensions of the new finger prototype with mechanism design of Fig. 8.

<table>
<thead>
<tr>
<th>Link length [mm]</th>
<th>Angle size [deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A_0A_1</td>
<td>γ_0</td>
</tr>
<tr>
<td>A_1B_1</td>
<td>γ_1</td>
</tr>
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<td>B_1B_2</td>
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<td>C_1D_1</td>
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<td>γ_6</td>
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<td>D_1E_1</td>
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</tbody>
</table>

| 40.5 | 5.4 | 40.9 | 4.8 | 5.4 | 26.0 | 25.0 | 23.6 | 51.0 | 129.0 | 127.0 |
LIST OF CAPTIONS

Fig. 1. A preliminary prototype of a 1 dof anthropomorphic finger built at LARM in Cassino, [14, 16].

Fig. 2. A kinematic model for human hand fingers: (a) thumb in front of index finger; (b) thumb in front of middle finger (Crosses indicate usual contact points).

Fig. 3. Phases of a human cylindrical grasping: (a) opening of the hand and moving to the object; (b) first contact of the finger with the object; (c) second contact between the object and the finger; (d) approaching motion of the finger to the object; (e) stable grasping of the object.

Fig. 4. Sensors installed on a human hand: (a) position of the sensors; (b) FSR150CP12 force sensor with the main dimensions in mm, [15].

Fig. 5. A scheme for the measuring system for investigating human grasp experimentally.

Fig. 6. Grasping phases for force measure in experimental tests: (a) approaching motion; (b) static grasp; (c) lifting the object.

Fig. 7. Plots of the measured forces during the grasping of a cubic object in Fig. 6 by using the sensor grove of Fig.4: (a) by sensor 1; (b) by sensor 2; (c) by sensor 3; (d) by sensor 4; (e) by sensor 5; (f) by sensor 6.

Fig. 8. A design scheme of the articulated mechanism for a 1 dof anthropomorphic finger.

Fig. 9. A simulated motion for the designed mechanism mimicking human finger motion.

Fig. 10. Numerical transmission ratios for the simulated motion of Fig.9: (a) $\theta_1$ versus $\theta_2$; (b) $\theta_1$ versus $\theta_3$. (the angles are expressed in degrees)

Fig. 11. Velocity diagrams for the finger motion of Fig. 9: (a) $\theta_1$ versus $\dot{\theta}_2$, (b) $\theta_1$ versus $\dot{\theta}_3$.

Fig. 12. Acceleration diagrams for the finger motion of figure 9: (a) $\theta_1$ versus $\ddot{\theta}_2$, (b) $\theta_1$ versus $\ddot{\theta}_3$.

Fig. 13. A model for the forces acting on one finger during cylindrical grasping, assuming one contact for each phalanx.

Fig. 14. Results of the first numerical simulation of grasping force: (a) $F_1$ versus $\theta_1$ (when the only contact point is $P_1$); (b) $F_2$ versus $\theta_1$ (when the only contact point is $P_2$); (c) $F_3$ versus $\theta_1$ (when the only contact point is $P_3$).
Fig. 15. Results of the second numerical simulation of grasping force (when the grasp forces are applied simultaneously in all the contact points): (a) $F_1$ versus $\theta_1$; (b) $F_2$ versus $\theta_1$; (c) $F_3$ versus $\theta_1$.

Fig. 16. Parts of the new 1 dof articulated finger of Fig 8.

Fig. 17. CAD simulation of the closing movement for the designed 1 dof finger, referring to the configuration in Fig 9: (a) $\theta_1=0$ deg; (b) $\theta_1=20$ deg; (c) $\theta_1=40$ deg; (d) $\theta_1=60$ deg; (e) $\theta_1=80$ deg.

Fig. 18. The new 1dof finger module: (a) a 3D-CAD scheme; (b) a prototype built at LARM in Cassino.

Fig. 19. Proposed designs for a robotic hand with the articulated finger of Figs. 9 and 18: (a) First model, (b) Second model.

Fig. 20. The new built hand prototype with 3 fingers of human sizes.

Fig. 21. A built test-bed prototype of the proposed hand with three 1 dof anthropomorphic fingers.

Fig 22. 3D-CAD scheme of the built test-bed prototype with the sensors position.

Fig 23. Plot of the measured forces during the grasping of an object made by using a compliant plastic object with the hand of Fig. 21: (a) by sensor 1; (b) by sensor 2; (c) by sensor 3; (d) by sensor 4; (e) by sensor 5.

Fig 24 Plot of the measured forces during the grasping of an object made by using a compliant plastic with the hand of Fig. 21: (a) by sensor 6; (b) by sensor 7; (c) by sensor 8; (d) by sensor 9; (e) by sensor 10.

Table 1. Measured dimensions of human hand fingers referring to the kinematic model of Fig. 2.

Table 2. Joint angles for phalanx links that are obtained from the image processing of human cylindrical grasping shown in Fig. 3.

Table 3. Dimensions of the new finger prototype with mechanism design of Fig. 8.