





# Design of a modular and compliant wrist module for upper limb prosthetics

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## Abstract

In the last decades, there have been great efforts in the development of advanced polyarticulated prosthetic hands; in contrast, prosthetic wrists have drawn less interest. Nevertheless, increasing the dexterity of the wrist improves handling skills because the wrist allows the repositioning of the hand before carrying out a task, avoiding the onset of unwanted trunk or shoulders compensatory movements and potential onset or exacerbation of articular injuries. This study presents a novel 2-degree-of-freedom prosthetic wrist module with active pronation/supination and passive elastic flexion/extension. This system is suitable to be included in hand prostheses to improve anthropomorphism and produce a more physiological motion. The first submodule within the socket is able to rotate a prosthetic hand and an external load of 3 kg at 2.6 rad/s. The second one can guarantee a range of motion of  $\pm 75^\circ$  with a centering elastic torque (compliant mode) or it can keep firm grasps (fixed mode). Compliant mode is based on a Scotch-Yoke mechanism converting wrist flexion/extension into the linear motion of a crossbeam acting on compression springs, while fixed mode is achieved by means of a piston that can be engaged/disengaged. The whole module fits with anthropometry and the modular design ensures the proposed system can be used in a stand-alone way and adapted to different hand prostheses. This device is expected to favor a more physiological dexterity with respect to simpler fixed prostheses that can potentially induce harmful motion of body districts not naturally involved in the reaching and grasping tasks.

Andrea Demofonti and Giorgio Carpino contributed equally to this study.

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## KEYWORDS

compliant joint, hand robotic prosthesis, wrist 2-DoFs mechanism, wrist prosthesis

## 1 | INTRODUCTION

It is estimated that each year around 185,000 and 295,000 people suffer from limb amputation in the United States and in Europe, respectively (Bumbaširević et al., 2020). Since upper limb loss is a traumatic event, prostheses aim to replace the lost functions and contribute to improve the quality of life of people with amputation (Cordella et al., 2016; Ciancio et al., 2016).

In the last decades, there has been great effort in the development of advanced polyarticulated prosthetic hands to replicate the functions of the human one (Belter et al., 2013); conversely, the design of prosthetic wrists has drawn less interest and has modestly progressed so far.

Nevertheless, a recent study has shown that increasing the dexterity of the wrist importantly contributes to the improvement of handling skills (Montagnani et al., 2015).

Since human wrist allows the repositioning of the hand before carrying out a task (Adams et al., 2003; Mell et al., 2005), the absence of forearm rotation causes the amputees to adopt undesired compensation strategies with body districts not naturally involved during reaching and grasping tasks. This negative effect might occur when raising the elbow and using humeral elevation (Carey et al., 2008; Major et al., 2014) and can lead to a greater shoulder range of motion (ROM) than usual, with the consequent potential onset of repetitive strain injury (RSI) on both healthy and residual limbs (Østlie et al., 2011; Gambrell, 2008) and the exacerbation of pre-existing arthritis or injuries (Jones & Davidson, 1999).

The majority of prosthetic wrists proposed in literature includes pronation/supination (P/S) capability, which is the most requested degree of freedom (DoF) by upper limb prosthesis users, followed by flexion/extension (F/E) and radial/ulnar deviation (RUD; Atkins et al., 1996; Bajaj et al., 2015, 2019).

Passive devices include solutions for the manual positioning of the wrist by the contralateral hand. To prevent undesired movements, and related RSI or other adverse effects, and guarantee firm and stable grasps, they are mostly endowed with friction clutches or locking mechanisms. The former relies on the relative friction between components, the latter are composed of sprung catches, pins, or buttons that lock the joint in a limited number of discrete angles. Indeed, elastic elements (e.g., torsional springs) can be used to bring back the wrist in its predefined resting position when an external load is removed.

The introduction of intrinsically compliant mechanisms, also widely adopted in active mechatronic and passive mechanical joints for human-centered and biomechanical applications (Vanderborght et al., 2013; Tagliamonte et al., 2012), ensures an adaptive behavior during the interaction with objects.

A simple solution of passive wrist is a single rotational joint to allow P/S, such as the WE Friction Wrist (*Hosmer*), which incorporates a friction clutch (see Figure 1a) (Fillauer, n.d.-a). An alternative use of a single DoF joint is to enable F/E such as the Sierra Wrist Flex Unit (*Hosmer*) that can be locked in three different angular configurations (see Figure 1b; Fillauer, n.d.-b).

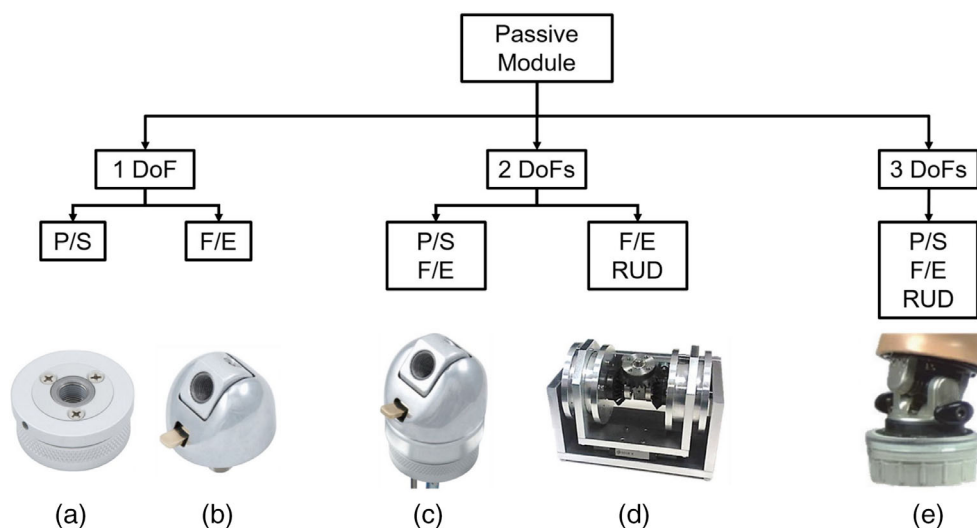
Higher number of DoFs in passive wrists is often achieved by stacking multiple single DoF units. The Four Function Wrist (*Hosmer*; see Figure 1c; Fillauer, n.d.-c) is a combination of the *Hosmer's* Rotation and Sierra Wrist: it enables P/S and F/E with 18 and 3 different locking positions, respectively. Nevertheless, the use of single DoF units connected serially can increase the overall encumbrance of the prosthesis. This problem is partly overcome in (Montagnani et al., 2013; see Figure 1d) and (Myolino-Wrist, n.d.). The former implements F/E and RUD using bevel gears differential mechanism and two elastic joints; the latter is a spherical joint where the roll axis is constrained by a pin.

Some prosthetic wrists are endowed with three DoFs. The Motion Control MultiFlex Wrist (see Figure 1e) uses a 1-DoF rotator in series with a universal joint (Archer et al., 2011). Conversely, the prosthetic hand described in (Laurentis & Mavroidis, 2002) employs a passive spherical joint as wrist.

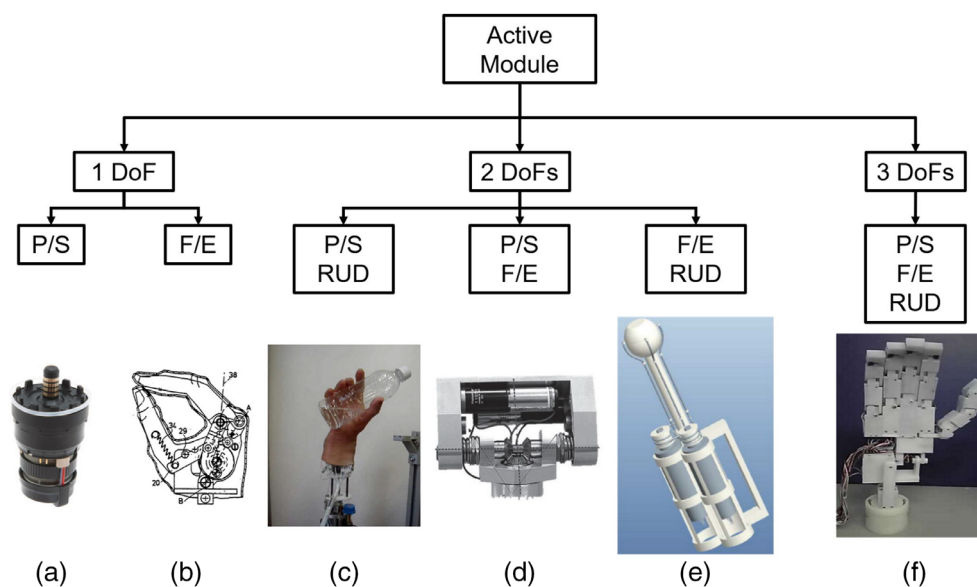
Among active 1-DoF prostheses available as pronators, a common solution is the 10S17 Electric wrist rotator (*Ottobock*; see Figure 2a; 10S17 *Ottobock*, n.d.). Active flexors tend to be incorporated into existing robotic hands: this reduces the overall length of the system but increases its distal weight and makes the wrist not compatible with other hands (see Figure 2b; Rennerfelt, 1988).

A higher number of DoFs in active wrists is obtained using mechanical transmissions such as tendon or Bowden cables (Takeda et al., 2009; Kyberd et al., 2011), differential mechanisms (Ahmad et al., 2012), or actuators with orthogonal rotation axes (Mahmoud et al., 2010; see Figure 2c-f).

Regardless of the actuation mode, some devices are already integrated in hand prostheses such as Michelangelo hand. The system has a wrist rotator that partially



**FIGURE 1** Taxonomy of the passive wrists. (a) WE FrictionWrist (Hosmer; Fillauer, n.d.-a); (b) SierraWrist flex unit (Hosmer; Fillauer, n.d.-b); (c) four FunctionWrist (Hosmer; Fillauer, n.d.-c); (d) Montagnani et al. (2013); (e) motion control MultiFlexWrist (Archer et al., 2011)



**FIGURE 2** Taxonomy of the active wrists. (a) 10S17 electric wrist rotator (Ottobock; 10S17 Ottobock, n.d.); (b) Rennerfelt (1988); (c) Takeda et al. (2009); (d) Kyberd et al. (2011); (e) Ahmad et al. (2012); (f) Mahmoud et al. (2010)

fits within the body of the hand itself and a passive joint for the F/E that can be locked/unlocked in a desired position by the user. The use of integrated solutions allows the reduction of the overall system's encumbrance, but it limits the modularity and compatibility of wrist devices with hand prostheses (Puchhammer, 2014).

This study aims to present a novel prosthetic wrist endowed with two submodules, that is, an active DoF for P/S and a passive elastic DoF for F/E. This architecture has been introduced to improve anthropomorphism and dexterity of current prostheses, guaranteeing a physiological hand motion and reducing undesired trunk or shoulders compensatory movements occurring when fixed wrists are adopted.

The P/S submodule allows the user to actively preposition the hand before task's execution; the F/E submodule can work in compliant and fixed modalities. In

the first operating mode, the submodule is able to elastically return to the neutral position when no external force is applied, thus conferring adaptability of the system especially during the interaction with the environment. Conversely, the fixed mode allows firm and stable grasps during object manipulation. Since the F/E is passive, the submodule does not include actuators and/or mechanical transmissions to be integrated in the prosthetic hands or in the socket. This ensures the system can be used potentially in a stand-alone way and be compatible with the prosthetic hands available on the market. Indeed, the double operating modes for the F/E are available only in solutions integrated with prosthetic hands and, for this reason, the proposed approach has been already patented by the authors (Carpino et al., n.d.).

The study is organized as follows: Section 2 describes the design requirements of the wrist module. Section 2.1

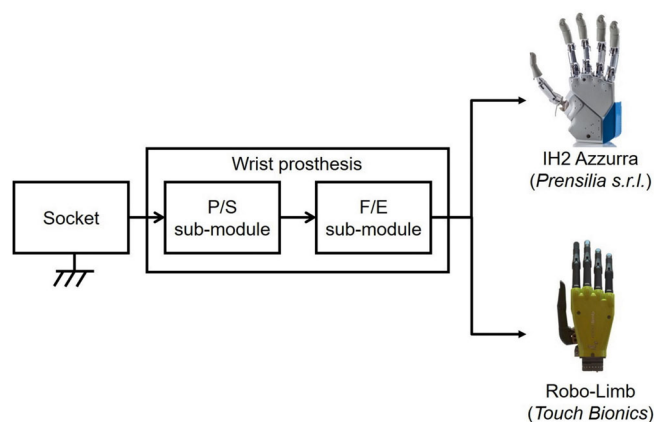


FIGURE 3 Block diagram of the proposed prosthetic wrist

reports the working principle of the F/E compliant sub-module, while Section 2.2 is dedicated to present the design of the whole wrist module and the prototype. Discussion and conclusions are reported in Sections 3 and 4, respectively.

## 2 | DESIGN REQUIREMENTS

The general design requirements for the proposed wrist prosthesis are lightness, compactness, dexterity, ease of use, reliability, and robustness. The anthropomorphism of the module, that is, the capability to be compatible with the anthropometric dimensions and the functional capabilities of the human hand, is a crucial feature to promote users' acceptability (Belter et al., 2013).

Based on the human anatomy, from a mechanical point of view, the wrist can be considered as a serial RU mechanism where R and U indicate a revolute joint (one DoF) and universal joint (one DoF), respectively (Bajaj et al., 2019). The first joint is responsible for P/S and it occurs within the forearm, implying that the radius crosses over the ulna in a twisting motion when moving from supinated to pronated positions (Bajaj et al., 2015). The second one is responsible for both F/E and RUD since it allows the rotations around two orthogonal axes at the carpal bones.

The design of the device proposed within this study is inspired by the human wrist, but it neglected the RUD motion, which is recognized to be only barely required by prostheses users due to its limited ROM ( $\pm 35^\circ$ ) when compared to P/S and F/E movements ( $\pm 75^\circ$ ) (Boone & Azen, 1979). Consequently, the structure of the human wrist was considered to be reasonably approximated to a serial RR mechanism.

A block diagram of the proposed module is reported in Figure 3. Similar to the human wrist, our proposed prosthetic counterpart is composed of two submodules serially connected to each other: one for the active P/S

allowing the user to set hand's orientation and one for the passive elastic F/E ensuring a compliant behavior to the prosthesis during object manipulation.

Finally, the wrist prosthesis is connected to the socket on one side and to the hand prosthesis on the other side.

Since the proposed wrist aims to be integrated with different hand prostheses, two biomechatronic hands were considered for the design process: the IH2 Azzurra (Prensilia s.r.l.; Prensilia, n.d.) represents research prototypes, and the Robo-Limb (Touch Bionics; Össur, n.d.) represents a typical commercial hand.

### 2.1 | Design requirements for the P/S submodule

In this section, the design requirements for the design of the P/S submodule will be presented in detail.

To meet the biomechanical structure of the wrist, the P/S motion has to be approximated as a pure rotation and the output shaft of the actuator has to be connected to the F/E sub-module: this will ensure the development of an anthropomorphic serial RR mechanism.

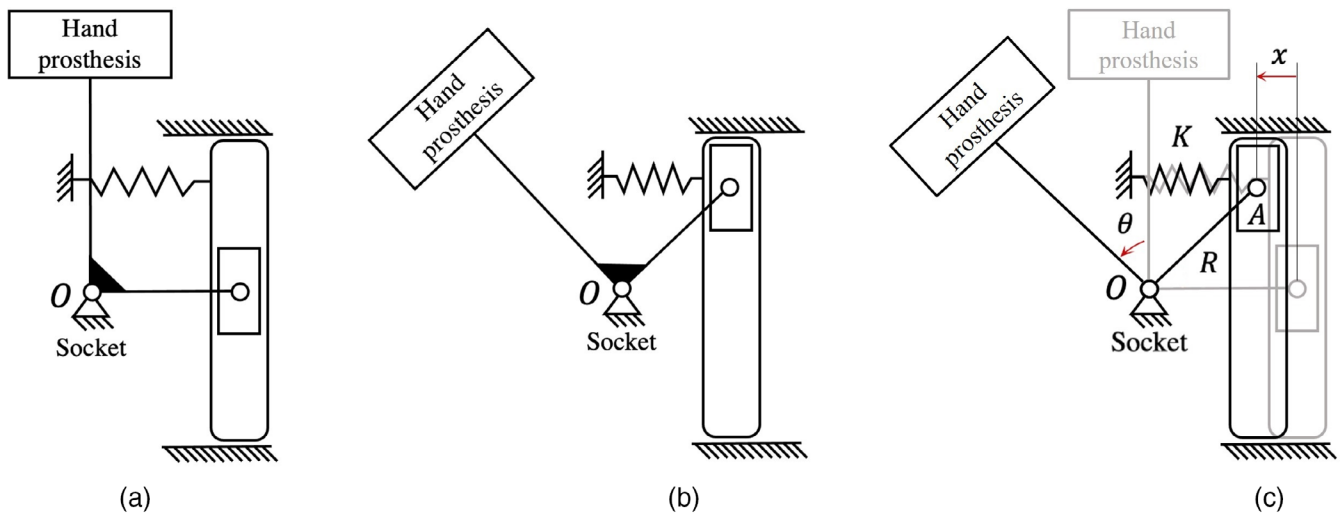
As already introduced in the previous section, the P/S occurs within the forearm, as the radius crosses over the ulna in a twisting motion. For this reason, the actuator has to be inserted into a custom-made socket for transradial amputees with circular section and average dimensions and it has to meet morphological constraints: length and diameter lower than 100 and 50 mm, respectively. Moreover, the overall mass of the submodule (actuator + socket) has to be less than 1.12 kg. This constraint was specified taking into account anthropometric data of a healthy man of 70 kg ( $M_{\text{forearm}} = 0.016 M_{\text{body}}$ , where  $M_{\text{forearm}}$  and  $M_{\text{body}}$  indicate the mass of the forearm and the body, respectively; Winter, 2009).

In accordance with physiological values, the ROM has to be  $\pm 90^\circ$  (Boone & Azen, 1979).

Moreover, the submodule has to be able to support the mass of the F/E submodule, of the hand prosthesis and of an external load. The maximum load was settled to 3 kg in accordance with ISO 11228-3:2007 concerning the handling of low loads (ISO 11228-3: 2007, 2010). Finally, the nominal angular speed has to be 2.0 rad/s, in accordance with physiological values (Lacquaniti & Soechting, 1982) and similar existing pronation devices (10S17 Ottobock, n.d.; Kyberd et al., 2011; Bajaj & Dollar, 2018).

### 2.2 | Design requirements for the F/E submodule

In this section, the design requirements for the F/E submodule will be described in detail.



**FIGURE 4** Representation of the working principle of the wrist F/E compliant sub-module: (a) neutral position; (b) Flexed position; (c) Neutral (light gray) and flexed (black) positions overlapped.  $\theta$  is the wrist F/E angle;  $x$  is the spring deflection;  $R$  is the distance between the center of rotation of the wrist  $O$  and the center of the rotary joint on the slider  $A$ ;  $K$  is the equivalent stiffness of a springs pack of  $n$  parallel springs. Rotation and translation due to Scotch-Yoke mechanism are highlighted in red

To meet the biomechanical structure of the wrist, similarly to what presented for the P/S case, the F/E motion has been approximated as a pure rotation.

Since the proposed wrist aims to be modular and it can be integrated with different hand prostheses, such as the Robo-Limb (Össur, n.d.), the F/E submodule has to have a circular section.

To comply with anthropometric constraints, the sub-module diameter and height have to be lower than 50 and 45 mm, respectively. These requirements were defined in accordance with the aforementioned custom-made socket for transradial amputees, commercial wrists (Bajaj et al., 2015, 2019), and hand prostheses (Össur, n.d.). Moreover, the mass has to be lower than 90 g to be consistent with available commercial devices (Bajaj et al., 2015, 2019).

### 3 | COMPLIANT MECHANISM FOR THE F/E SUBMODULE

The core component of the proposed F/E submodule is based on a compliant mechanism patented by the authors (Carpino et al., n.d.).

The solution adopts a Scotch-Yoke mechanism that converts the joint F/E rotation into a linear motion to deform compression springs. Although the Scotch-Yoke mechanism has been employed in a wide range of applications, such as gravity-balancers (Nguyen & Shieh, 2019; Shieh & Chou, 2015; Arakelian et al., 2016) and movement propulsors (Yu et al., 2009), to the best of our knowledge, it has never been used for upper limb prosthetics.

Figure 4 shows a schematic representation of the working principle of the proposed F/E submodule, highlighting its neutral and flexed positions. The socket is considered as the mechanical frame and the prosthetic hand rotates around the wrist joint rotation center  $O$ . The rotation of the prosthetic hand forces the motion of the slider within the linear guide and, in turn, the compression of the spring. The spring elastic force is hence translated into an equivalent wrist elastic centering torque. The presence of the springs enables the elastic return of the module to the rest position and, therefore, the realignment of the main axis of the prosthetic hand to the axis of the wrist/arm.

In Figure 4c,  $\theta$  indicates the F/E angle,  $R$  indicates the distance between the center of rotation of the wrist  $O$  and the center of the rotary joint on the linear slider  $A$ ,  $K$  is the stiffness of a spring schematically equivalent to  $n$  springs with stiffness  $k$  possibly arranged in parallel in the final construction ( $K = nk$ ).

The spring deflection can be expressed as:

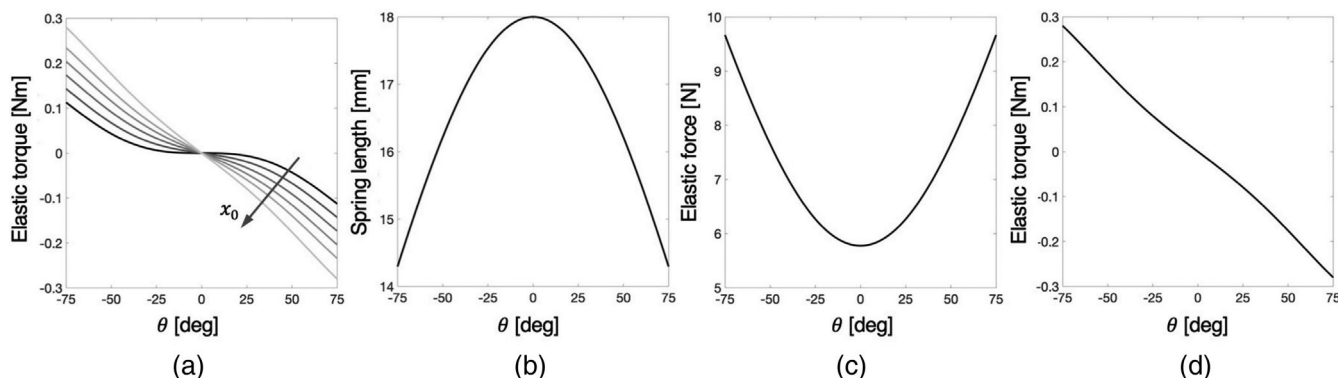
$$x = x_0 + R - R\cos\theta \quad (1)$$

where  $x_0$  is a precompression due to the spring mounting.

Starting from Equation (1), a virtual displacement  $x$  can be calculated as:

$$\delta x = R\sin\theta \delta\theta \quad (2)$$

Based on the principle of virtual work, the following energy balance holds:



**FIGURE 5** (a) Torque-angle characteristic varying with the precompression  $x_0$ . The value of  $x_0$  increases along the direction of the arrow: From 0 mm (black line) to 5 mm (lightest gray line). The other reported values are 1, 2, 3, and 4 mm. The selected precompression  $x_0$  is 5 mm; (b) spring length with  $x_0 = 5$  mm; (c) spring force with  $x_0 = 5$  mm; (d) torque-angle characteristic with  $x_0 = 5$  mm

$$\tau(\theta)\delta\theta + Kx\delta x = 0 \tag{3}$$

where  $\tau_0$  is the F/E elastic torque.

Substituting Equations (1) and (2) in Equation (3) and considering  $K = nk$ , leads to the relation describing the torque-angle characteristic:

$$\tau(\theta) = -nkR \left[ (x_0 + R)\sin\theta - \frac{R}{2}\sin(2\theta) \right] \tag{4}$$

The graphical representation of Equation (4) is reported in Figure 5a, in which the torque-angle characteristics are shown considering different values of the precompression  $x_0$ .

## 4 | WRIST MODULE DESIGN

In this section, the two submodules of the proposed prosthetic wrist are presented separately and then an overview of the global system is provided.

### 4.1 | P/S submodule

To obtain a module as much as possible biomechanically and functionally similar to a human wrist (see Section 2 of design requirements), the P/S submodule has to be able to rotate at 2.0 rad/s the hand during the pinch grasp of an external load of 3 kg.

Two biomechatronic hands were considered for the potential integration of our module. Since the mass, the length, and the width of IH2 Azzurra (640 g, 213 mm, and 102 mm, respectively) are greater than those of Robo-Limb (450 g, 180.2 mm, and 74.5 mm, respectively), only IH2 Azzurra was taken into account as load in the design phase of the P/S module. These assumptions mean

**TABLE 1** Design requirements and main features of the P/S submodule

Active P/S submodule		
	Design requirements	Current values
Length [mm]	<100	93
Diameter [mm]	<50	22
Mass (actuator + socket) [g]	<1,120	500
ROM [deg.]	$\pm 90$	$\pm 90$
Nominal torque [Nm]	1.5	3.4
Nominal speed [rad/s]	2.0	2.6

the actuator has to ensure a nominal torque and speed of 1.5 N m and 2.0 rad/s, respectively.

The selected electric actuator is composed of:

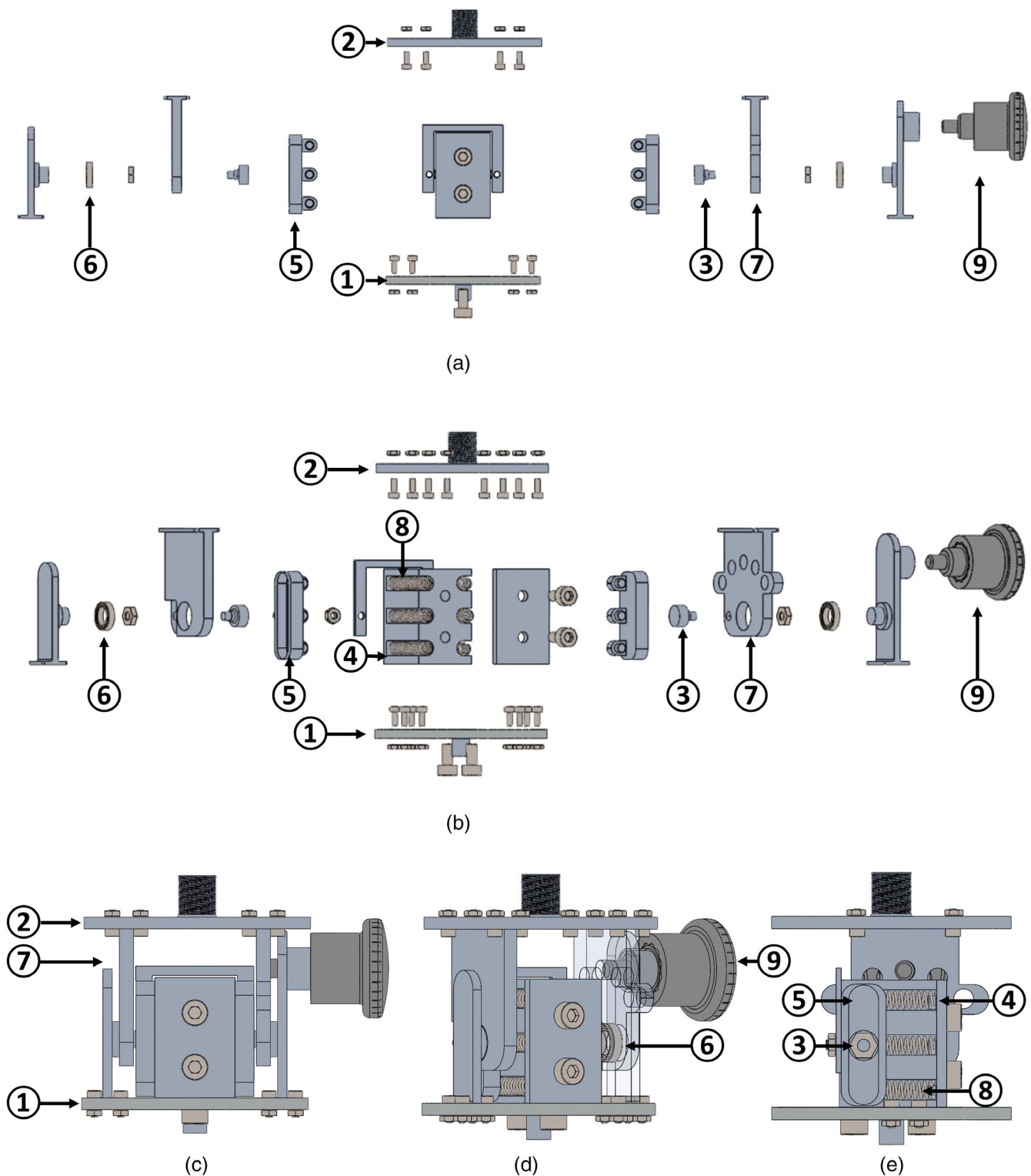
1. Planetary gearhead,  $\varnothing 22$  mm and gear ratio 590:1 (*Maxon Motor*, product code: 370807).
2. Brushless motor,  $\varnothing 22$  mm (*Maxon Motor*, product code: 323217).
3. Incremental encoder, 1,024 ppr (*Maxon Motor*, product code: 530965).
4. Wearable electronic control board EPOS4 Module 50/8 (*Maxon Motor*, product code: 504384).

The main features of the active P/S submodule compared with design requirements are summarized in Table 1.

### 4.2 | F/E submodule

#### 4.2.1 | Submodule components

Figure 6 represents the computer-aided design (CAD) of the proposed F/E submodule in exploded, frontal, 3D,

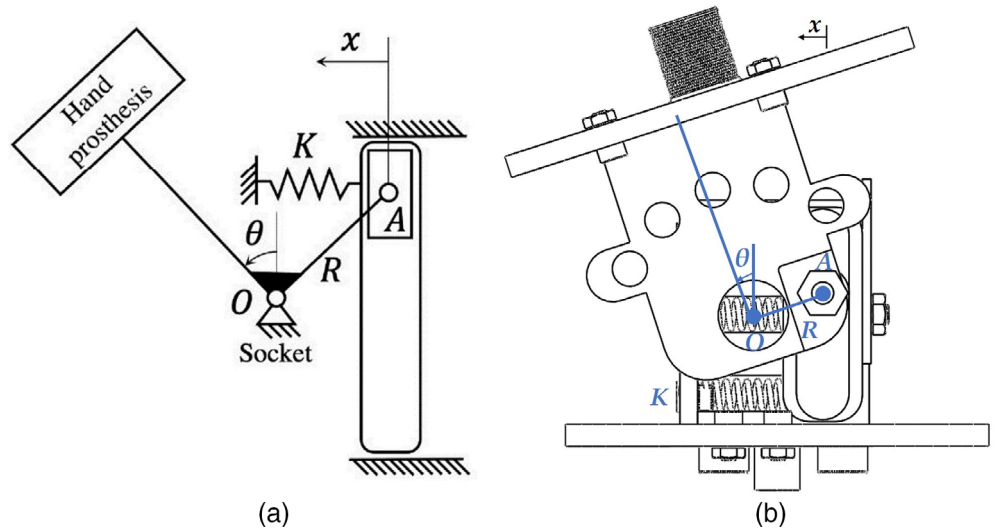


**FIGURE 6** Exploded (a, b), frontal (c), 3D (d), and lateral (e) views of the proposed F/E sub-module. The labeled components are (1) lower base connected to the P/S sub-module; (2) upper base connected to the prosthetic hand; (3) roller; (4) linear guide; (5) translating crossbeam; (6) radial ball bearings; (7) wheels; (8) linear compression springs; and (9) spring-loaded positioning piston

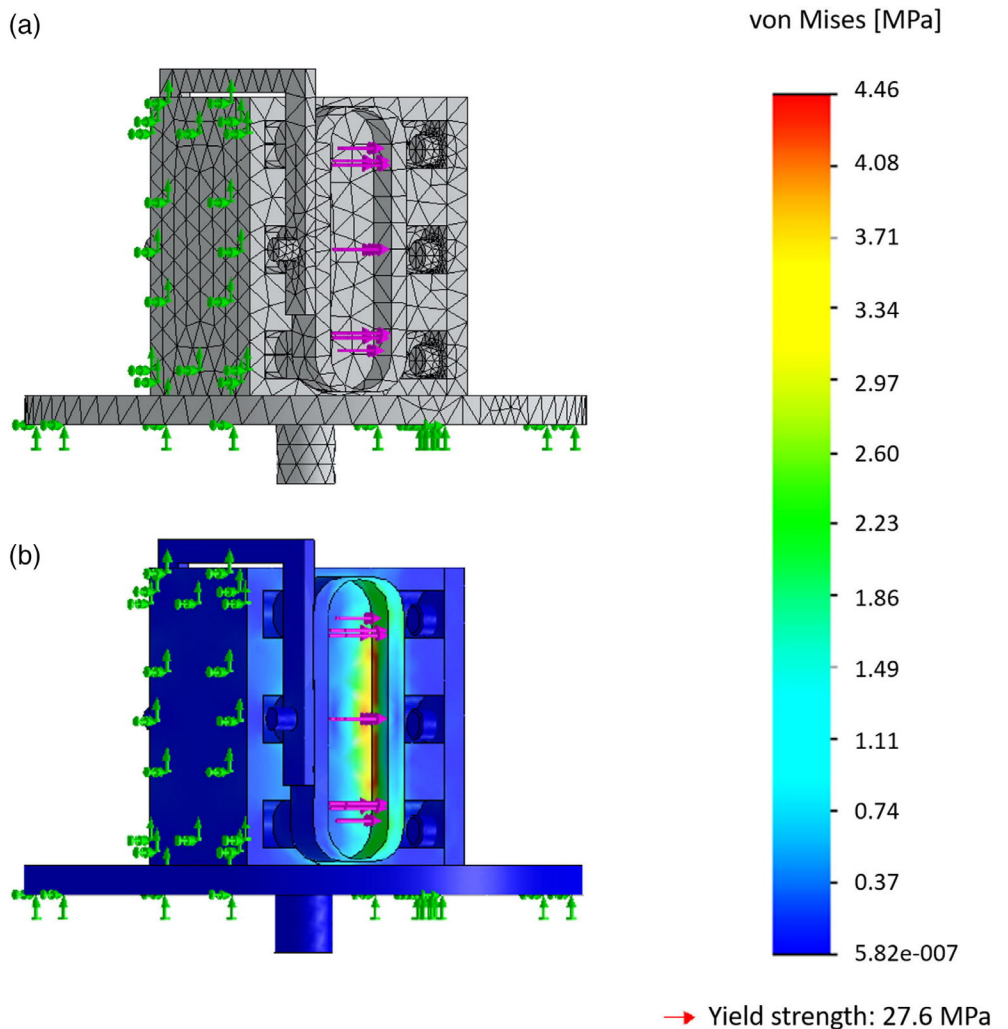
and lateral views. It consists of lower and upper bases (components 1 and 2 in Figure 6) for the connection of the wrist with P/S submodule and the hand, respectively.

To convert wrist rotation into a linear motion inducing spring compression, as described in the working principle presented in Section 2.1, the Scotch-Yoke mechanism was

**FIGURE 7** Compliant mechanism of the wrist F/E sub-module (a) and its mechanical implementation (b).  $\theta$  is the wrist F/E angle;  $x$  is the spring deflection;  $R$  is the distance between the center of rotation of the wrist  $O$  and the center of the rotary joint on the slider  $A$ ;  $K$  is the equivalent stiffness of a springs pack of  $n$  parallel springs



**FIGURE 8** (a) Boundary conditions, applied loads, and mesh based on blend curvature for FEM simulation on the most loaded components of the F/E sub-module. Green arrows indicate the fixed constraints; violet ones the applied load (30 N to the inner surface of each crossbeam). (b) Distribution of von Mises stress



mechanically implemented by using twin parallel mechanisms, in which the conceptual linear slider was constructively obtained by means of a functionally equivalent system, as highlighted in Figure 7. The

adopted solution is indeed based on a roller (component 3 in Figure 6) moving within a linear guide hollowed (component 4 in Figure 6) in a translating crossbeam (component 5 in Figure 6).

The relative F/E movement between the lower base of the module (component 1 in Figure 6), connected to the P/S submodule, and the upper base (component 2 in Figure 6), connected to the prosthetic hand, is guaranteed by two links, called hereafter *wheels* (component 7 in Figure 6), and two radial ball bearings (component 6 in Figure 6). For each twin mechanism, the roller, connected to the wheels, slides inside the crossbeam and produces a linear motion. Crossbeam translation, constrained by linear guides (component 4 in Figure 6), forces the compression of three parallel linear springs included in the same slot (component 8 in Figure 6). In total, six springs are placed in parallel and are precompressed.

A locking system is obtained by means of a spring-loaded positioning piston (component 9 in Figure 6) that can be activated by the contralateral hand. When the piston is engaged, the module is fixed in a predefined position; otherwise, when the piston is disengaged, the

module is in the compliant mode due to the action of the elastic F/E.

#### 4.2.2 | Mechanical sizing and manufacturing

The mechanical sizing and manufacturing of the prototype were carried out taking into account the design requirements listed in Section 2.2.

Since  $R$  is the distance between the center of rotation of the wrist and the center of the roller, its value influences the dimension of the section of the proposed submodule. The length of  $R$ , and consequently the values of  $n$  and  $k$ , have to be set to ensure the anthropomorphism of the wrist.  $R$  was set to 5 mm and six compressions linear springs with a stiffness  $k = 1.05$  N/mm and a free length of 23.5 mm (Sodemann product code: 11190) were selected. The equivalent stiffness due to the parallel springs is  $K = 6.3$  N/mm. The springs precompression was set to 5 mm. For a single spring, the variation of the length due to F/E movement and the elastic force is reported in Figure 5b,c, respectively. The final torque-angle characteristic, due to the selected springs precompression, is reported in Figure 5d and is very close to linearity. Because of precompression, springs are always loaded during F/E movement.

The locking system is based on an *Elesa* spring-loaded positioning piston (product code GN 717-4-M8X1-A-ST). Springs, radial ball bearing, screws, and nuts were manufactured in SAE 304 stainless steel, whereas, for the other components, a 1060 aluminum alloy was chosen.

TABLE 2 Design requirements and main features of the F/E submodule

Passive F/E submodule		
	Design requirements	Current values
Diameter [mm]	<50	48
Height [mm]	<45	40
Mass [g]	<90	65
ROM [deg.]	$\pm 75$	$\pm 75$

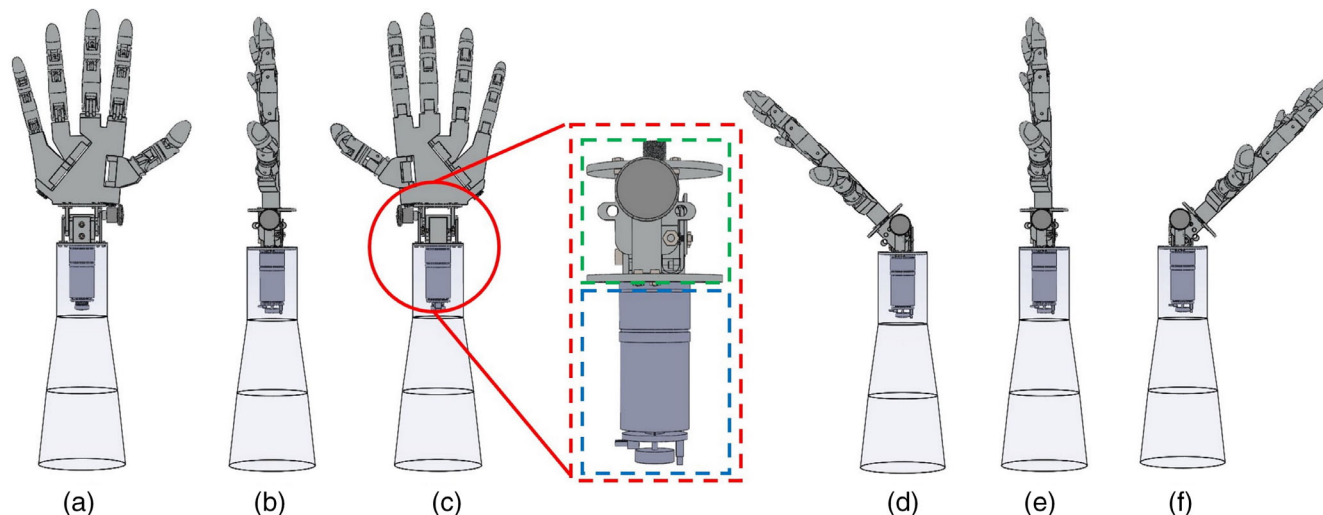
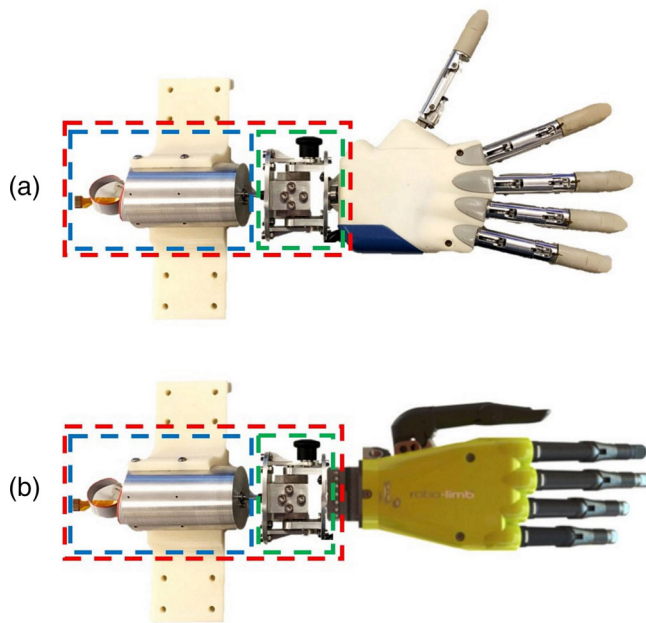


FIGURE 9 CAD model of the overall module in six different configurations. On the left, the system is reported in three different P/S angles. **B** refers to neutral position, while **A** and **C** refer to maximum prone and supine positions, respectively. On the right, the system is reported in three different F/E angles. **E** refers to neutral position, while **D** and **F** refer to maximum flexed and extended positions, respectively. A zoom of the proposed prosthetic wrist is reported in the central red box where it is possible to distinguish the P/S sub-module (blue) and the F/E sub-module (green)



**FIGURE 10** Prototype of the overall module (red box) where it is possible to distinguish the P/S sub-module (blue) and the F/E sub-module (green). The socket is not represented since the P/S sub-module is inside a bench support; the mechatronic hands are IH2 Azzurra (a) and Robo-Limb (b)

A finite element method (FEM) simulation was carried out to verify the correct sizing of the components. Two 30 N loads were applied to the inner surface of the two crossbeams that compress the springs, whereas the lower base and the slot for the springs pack were kept constrained (see Figure 8a). Load values were chosen in accordance with Figure 5b where the force acting on a single spring is maximum 9.6 N. A mesh based on blend curvature was used. Considering the yield strength of 27.6 MPa for the 1060 aluminum alloy and the maximum von Mises stress obtained from the simulation (4.46 MPa), a safety factor greater than 6 is achieved (see Figure 8b).

Table 2 reports the main features of the F/E submodule compared to the design requirements.

#### 4.2.3 | Full wrist module

The CAD drawing of the overall system (socket, 2-DoFs prosthetic wrist, and hand prosthesis) is represented in Figure 9 in six different configurations.

## 5 | DISCUSSION

Thanks to the reduced size, the P/S submodule can be embedded in the selected socket miming the actual

biomechanical structure of a human wrist since P/S motion occurs within the forearm. Indeed, the gear ratio and efficiency of the actuator allow a nominal torque of 3.4 N m (more than double than the one required) and a nominal speed of 2.6 rad/s (30% higher than strictly required) allows the user to actively preposition the hand and an external load of maximum 3 kg before a task's execution (Table 1).

The anthropomorphism of the passive elastic F/E submodule is ensured since its dimension is comparable with human one and also with other commercial prostheses' one (see Table 2). It can work in compliant and fixed modalities. In the first operating mode, the submodule is able to elastically return to the neutral position when no external force is applied, thus conferring adaptability of the system especially during the interaction with the environment. Conversely, in the fixed mode, the user can fix the prosthesis in five different F/E angles allowing to perform firm and stable grasps during object manipulation.

Thanks to the system's modularity, our wrist device is easily adaptable to different commercially available hand prostheses. In Figure 10, the modularity and adaptability of the wrist are verified since it can connect to IH2 Azzurra (Figure 10a) and Robo-Limb (Figure 10b) just by modifying the upper base.

## 6 | CONCLUSIONS

In the last decades, there has been great effort in the development of advanced polyarticulated prosthetic hands to replicate the functionality of the human one. In contrast, prosthetic wrists design has attracted less interest and has modestly progressed so far.

This paper presents a novel prosthetic wrist with two DoFs, that is, an active P/S and a passive elastic F/E. The two submodules (one for each DoF) are connected to reproduce in an anatomically inspired way the serial RR mechanism of a human wrist.

The actuator of the P/S submodule is placed inside the socket along its major axis and the output shaft is connected to F/E submodule. It allows the rotation of the hand and an external load of 3 kg at 2.6 rad/s.

F/E DoF can work in two different modalities: compliant and fixed. In the first operating mode, the rotational motion is converted in a linear one with the consequent compression of a spring pack through two parallel Scotch-Yoke mechanisms: in this way, the module is able to return elastically to the neutral position when unloaded. Intrinsic compliance confers adaptability during the interaction with objects. Conversely, the fixed modality is implemented by means of a piston: when it is engaged, the module is fixed in a selected position and it allows firm and stable grasps during manipulation.

Current wrist devices with double operating modes for F/E submodule are available only in integrated solutions, that is, including prosthetic hands, such as the commercially available Michelangelo hand. The system has a wrist rotator that partially fits within the body of the hand itself and a passive joint for the F/E that can be locked/unlocked in a desired position by the user. The use of integrated solutions allows the reduction of the overall system encumbrance but it limits the modularity and compatibility of wrist devices with hand prostheses (Puchhammer, 2014). On the other hand, the proposed wrist aims to be used in a stand-alone way and is designed to be compatible with prosthetic hands already available on the market still guaranteeing functional performance similar to the physiological biomechanics of human wrist.

Moreover, the proposed device makes the movement and the control of the hand prosthesis by an amputee easier and more natural. This is accomplished since the articulated wrist allows to obtain hand orientation with no trunk and shoulder's undesired compensatory movements that can potentially cause the onset of RSI or exacerbate pre-existing arthritis or injuries. The proposed wrist can indeed favor a more physiological dexterity with respect to basic fixed prostheses that induce ineffective and harmful motion of body districts not naturally involved in the reaching and grasping tasks.

As a future work, the authors aim to carry out experimental tests to verify the expected performance. From a broader point of view and as already claimed in authors' patent (Carpino et al., n.d.), the working principle on which the F/E compliant submodule is based could be potentially adapted to be used in several other applications, such as prosthetics for other body districts (e.g., lower limb) and robotic joints, belonging to systems designed for other human-robot interaction applications (e.g., assistive, rehabilitation, or surgical robotics).

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## CONFLICT OF INTEREST

Andrea Demofonti, Nevio Luigi Tagliamonte and Giulia Baldini declare they have not conflict of interests. Giorgio

Carpino, Laura Bramato and Loredana Zollo are coauthors of the patent "Robotic joint for prosthetic articulation," International Publication Number: WO 2020/031035 A1, International Publication Date: 13/02/2020, Priority Data: IT02018000007933 filed on 07/08/2018.

## AUTHOR CONTRIBUTIONS

**Andrea Demofonti:** Formal analysis (equal); methodology (equal); software (equal); visualization (equal); writing – original draft (equal); writing – review and editing (equal). **Giorgio Carpino:** Conceptualization (equal); methodology (equal); software (equal); writing – review and editing (equal). **Nevio Luigi Tagliamonte:** Methodology (equal); writing – review and editing (equal). **Giulia Baldini:** Formal analysis (equal); methodology (equal); software (equal); visualization (equal). **Laura Bramato:** Conceptualization (equal). **Loredana Zollo:** Funding acquisition (equal); supervision (equal); writing – review and editing (equal).

## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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