A 2-Degree-of-Freedom Quasi-Passive Prosthetic Wrist With Two Levels of Compliance

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***Abstract*—Restoring the function of a missing hand is still a grand challenge for bioengineers. We witnessed significant recent advances in the development of myoelectric hand prostheses and their controllers. Conversely, the wrist joint is generally overlooked in prosthetics, despite playing a fundamental role in orienting the hand in space. Indeed, it may account for several degrees of freedom of the hand in reducing compensatory movements. We acknowledge that an active, three-degree-of-freedom prosthetic wrist is not a viable option for a self-contained prosthesis, therefore we merged in one design two opposed passive behaviors. The proposed wrist can automatically transition between a compliant mode, which exhibits relatively low stiffness allowing for passive motions around two rotational axes (wrist flexion/extension and radial/ulnar deviation), and a stiff mode, which grants stability during manipulation. To switch mode, no additional control input - hence cognitive burden - from the user is needed: it occurs synchronously with the prosthetic hand opening and closing motion, such that the wrist is compliant during reaching and stiff during manipulation. Our device proved reliable on the test bench and useful in a pilot test with an amputee volunteer, motivating further developments and more extensive testing to prove its effectiveness.**

***Index Terms*—Compliant joints and mechanisms, dexterous manipulation, prosthetics and exoskeletons.**

I. Introduction

CLOSING a hand brings a detrimental impact in the quality of life of those affected, for its pivotal role in our everyday life. Restoring the function of this missing limb in a close-to-natural manner represents therefore a major, yet unsolved, open goal of bioengineering research. Existing myoelectric prostheses suffer from several limitations that have hindered their widespread: these limitations range from less-than-ideal Human-Machine Interfaces (HMI) to imperfect grasping and manipulation abilities [1], [2]. Despite these intrinsic limitations, or possibly motivated by them, the scientific interest in this research topic almost triplicated in the last 10 years [2], while new prosthetic components (artificial hands and control systems) became commercially available [3], [4], [5], or are approaching the market, such as the prosthetic hands Mia [6], Hannes [7], and SoftHand Pro-H [8]; and the control systems Complete Control and Myo Plus [5]. Nonetheless, these extraordinary advancements overlooked the peculiar biomechanical function of the wrist in a manipulation task. In fact, with its three degrees of freedom (DoF), namely flexion/extension (FE), radial/ulnar deviation (RUD), and pronation/supination (PS), the wrist is responsible for the orientation of the hand in space, substantially contributing to all grasping and manipulation actions. Notwithstanding this suggestion, and the evidence brought by the Sven Hand, i.e., the first myoelectric prosthesis with a 2-DoF wrist, back in the 60s [9], only few research labs focused on biomechanical studies involving the wrist [10], [11], [12], [13] or in the design of new artificial wrists [14], [15], [16], [17], [18], [19], [20], [21], [22], [23] (see [24], [25] for exhaustive reviews). Among these, our group suggested that few controllable DoFs in the wrist account for several DoFs in the hand, in terms of functionality and compensatory movement prevention, hence supporting the idea of a focus shift from the hand to the wrist [10].

The ideal prosthetic wrist is easy to describe, borrowing from the human anatomy and from the handbook of engineers' wish-list. It should exhibit three independent DoFs, be compact, robust and seamlessly controlled synchronously with the hand. Unfortunately constraints in both the HMI and in the mechatronic technology – the main one being the lack of actuators with enough power density to be fitted in the size available – prevent this ideal wrist to be a viable option, so far [24].

Historically, myoelectric prosthetic wrists feature a single active (i.e., motorized) or passive (i.e., manual) DoF that enables PS of the hand [10], [24]. While this choice likely represents the best engineering tradeoff between mobility/dexterity, weight, and robustness, prostheses equipped with such wrists, limit the individual in performing a wide range of tasks useful in the daily living, due to their simple kinematics. In addition, since

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This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the Ethics Board of the Scuola Superiore Sant'Anna, Approval No. 2/2017, and performed in line with the Declaration of Helsinki.

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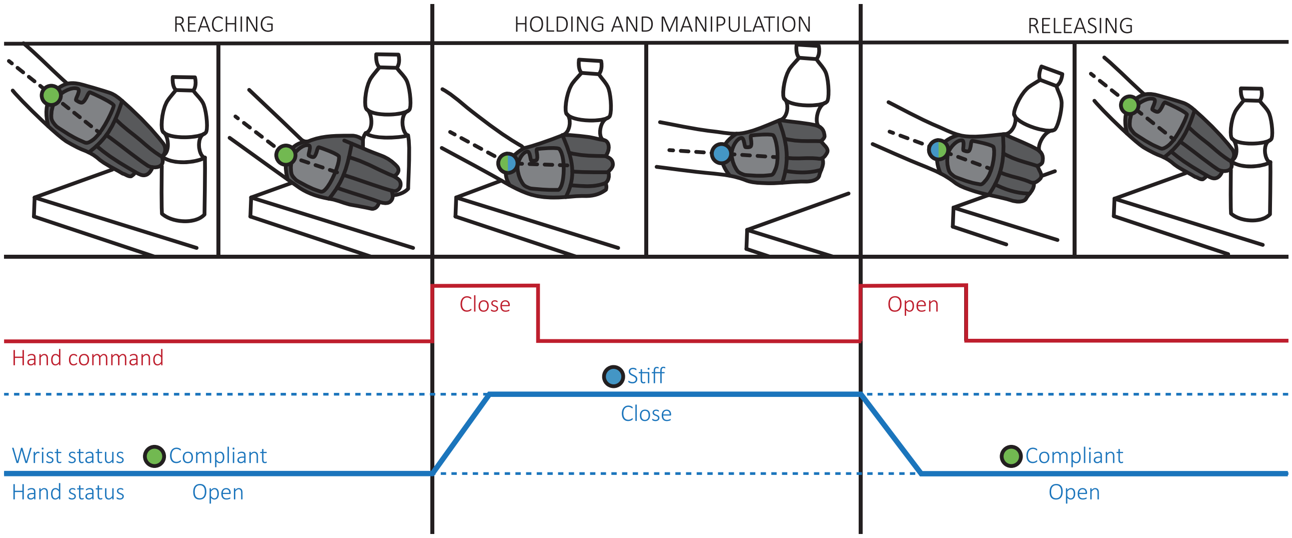

Fig. 1. Operation principle of the SHWO: the prosthetic wrist switches from compliant to stiff when the prosthetic hand receives a close command; it switches from stiff to compliant when the hand receives an open command.

individuals are proficient at compensating for the missing DoFs by changing the motions of their arms and body, and these compensatory movements often put greater forces on the anatomy, they may result in residual limb pain, secondary musculoskeletal complaints and overuse syndromes [10], [26].

To deal with these limitations, rehabilitation engineers devised different approaches for designing motorized wrists that could offer more biomimetic movements over multiple DoFs, yet using a reduced set of actuators. For example, the concept of motor synergies was recently leveraged to reduce control complexity as well as size and dimensions of prosthetic wrists [16], [18]. With the same goal in mind, wrists with passive FE and/or RUD were also developed and made commercially available. These devices can be distinguished between stiff or compliant wrists [20], [27]. Stiff wrists enable the user to manually orientate and lock the hand in a desired and firm posture, while compliant ones, can be either locked in a certain posture or unlocked, to exhibit an elastic behavior. As their name suggests compliant wrists allow for adaptation of the prosthesis by exploiting environmental constraints, while reaching the target object [28].

Taken collectively, the experimental comparisons between stiff and compliant wrists conducted so far, seem to point towards the same direction [12], [27], [28]. They suggest that a compliant wrist outperforms a stiff one during the reaching phase, as it yields to lower compensatory movements, whereas stiff wrists exhibit more natural movements during the manipulation phase of heavy objects. Hence, it was hypothesized that a transradial prosthesis would allow easier and more ecological operation if its wrist behaved compliant during the reaching and grasping phase, and stiff during the holding and manipulation phase, with the switch – from compliant to stiff – occurring in synchronous with the onset of the grasp [27].

Inspired by these findings, we sought to further develop our original intuition of a 2 DoF prosthetic wrist with switchable stiffness [14], [20]. In this work we propose the design of a prosthetic wrist prototype with two degrees of compliance, either stiff or compliant, that can be automatically switched by means of an external control input, e.g., associated to the closing/opening command to the hand. This paper presents the design rationale, the prototype as well as the evaluation of its functional performance. Besides, a case study with a participant with a below-elbow loss, provides support to the-state-of-the-art anecdotal thesis for which a prosthetic wrist with switchable stiffness reduces compensatory movements in the upper body, during common pick-and-lift tasks. This work proves the potential of a conceptually novel wrist in providing comfortable use of hand prostheses and in mitigating the insurgence of compensatory movements, ultimately preventing short- and long-term side effects.

II. Rationale and Requirements

Although representing a strong simplification of the anatomy, the design of the wrist was inspired by natural grasping behavior and aimed to allow easier and more functional operation of a trans-radial prosthesis during activities of daily living. The action of *grasping* may be segmented into reaching, grasping and holding/manipulation. During the reaching phase, the wrist (together with the more proximal joints) plays the crucial role of orienting the hand so it can properly grasp the target object [10], [29], [30]. Hence, simplifying the functional role of the wrist, and taking advantage of the well-known pros of compliant or stiff joints, we envisioned a 2-DoF wrist (FE and RUD) that could exhibit two levels of stiffness. Compliant, during reaching, in order to facilitate the alignment of the hand with respect to the object, by pushing the hand against environmental constraints (e.g., a vertical wall, a horizontal shelf, etc.) or the object itself (Fig. 1). Stiff, once the hand begins enclosing the object, to allow a safe holding and manipulation of heavy objects. With this in mind, the switch of the stiffness was assumed to be activated by the same control input used to trigger the opening/closing of the hand, in synchronous with it. We dubbed this: Synchronous Hand-Wrist Operation (SHWO).

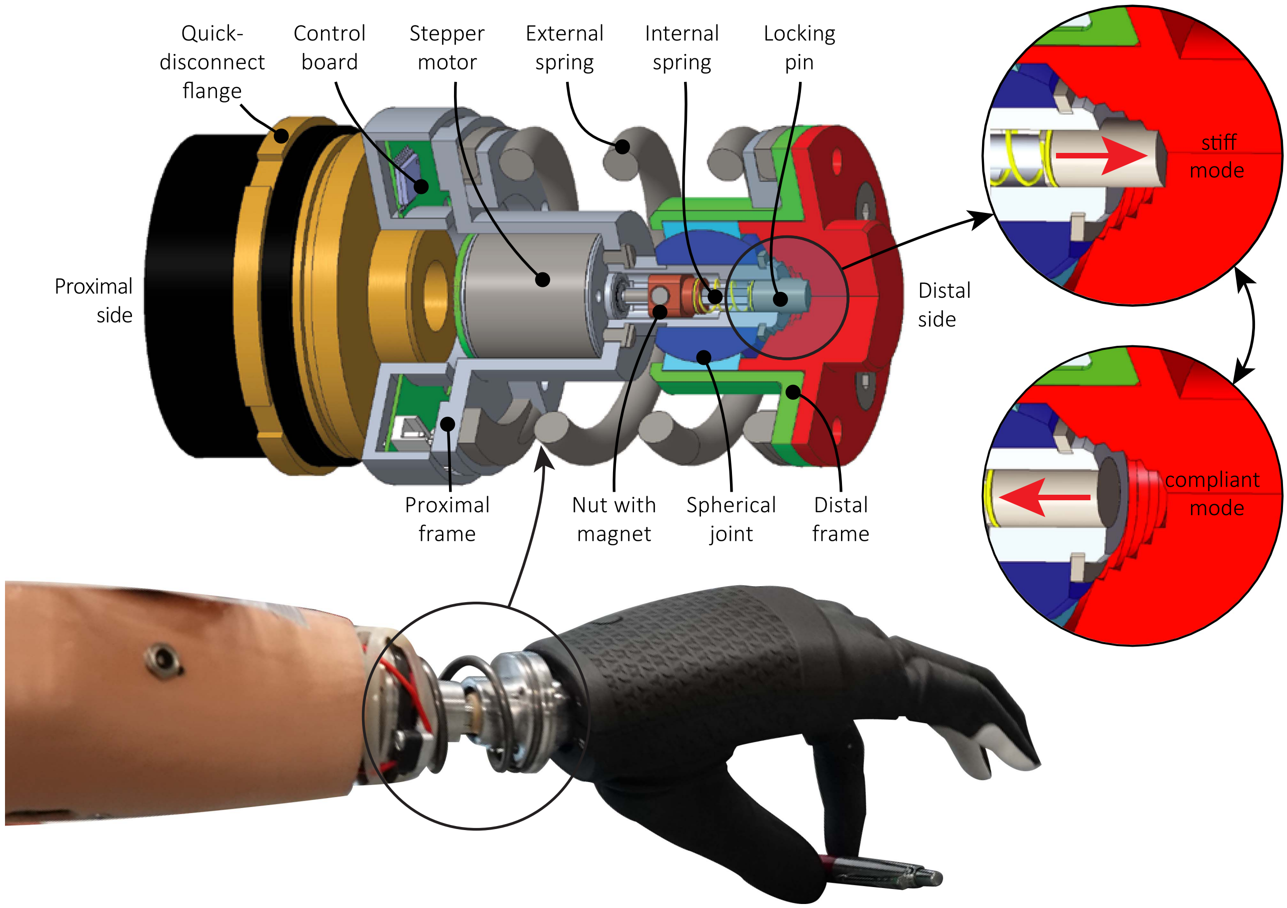

Fig. 2. Physical prototype of the proposed wrist mechanism and CAD rendering of a partial section to highlight the main components. The insets display the position of the locking pin in the two operation modes, i.e., compliant and stiff mode.

Besides those pertaining the switching operation, other functional and technical requirements relative to its DoFs, physical structure and integration with conventional myoelectric hands, guided the design of the wrist. The main constraints that steered the design were size and weight, to keep as low as possible, and taking commercial wrists as a benchmark. In their work, Bajaj and collaborators [24] thoroughly reviewed the State of the Art of wrist prostheses and provided us with the reference data for the design of our device. Tapping from these data, commercial wrists with 1 or 2 DoFs have a median diameter of 50 mm (IQR 8.25 mm), a median length of 38 mm (IQR 18.75 mm), and a median weight of 116.50 g (IQR 99 g). The range of motion of the human wrist spans within $\pm 40°$ for FE and $[+10 - 30]°$ for RUD [31], yet, since we found that a range of $\pm 30°$ for both FE and RUD could suffice to perform the majority of activities of daily living [18], we adhered to such values. As the wrist was conceived as a stand-alone add-on for standard myoelectric hands, both the mechanical and electrical interfaces were defined by the standards of commercial components. Finally, aiming to manufacture an affordable wrist we designed a device based on a reduced number of parts, and wherever possible using conventional manufacturing processes and commercial off-the-shelf components, including commercial actuators.

III. Design and Architecture

To comply with the desired requirements, we designed a wrist building around a 2-DoF spherical joint featuring a compression spring and a stepper-motor-based locking mechanism (Fig. 2). The wrist, based on previous design iterations proposed by the authors [14], [20], [27], exhibits a weight of 115 g (smaller than the 45th percentile of commercial wrists with 1 or 2 DoFs [24]), a diameter of 38 mm (smaller than the 1st percentile female [32] and than the 15th percentile of the commercial wrists with 1 or 2 DoFs [24]) and a length of 48.5 mm (smaller than the 80th percentile of commercial wrists with 1 or 2 DoFs [24]). In particular, the mechanism comprises a proximal frame conveniently connected to a commercial quick-disconnect flange (10S1, Ottobock, Germany) (Fig. 2) and a distal frame to be attached to the end effector (e.g., the prosthetic hand). The two frames are linked by means of a spherical joint and a compression spring. The spherical joint allows a range of motion of ± 30 degrees in FE and RUD. The spring, instead, is responsible for the compliant behavior of the wrist, with a nominal flexural stiffness of about 80 mNm/°, akin to the commercially available Multi-Flex Wrist (Motion Control, USA). Yet, the large torsional stiffness of the spring prevents rotations around the wrist axis, de facto constraining PS. When disengaged or free to move (the

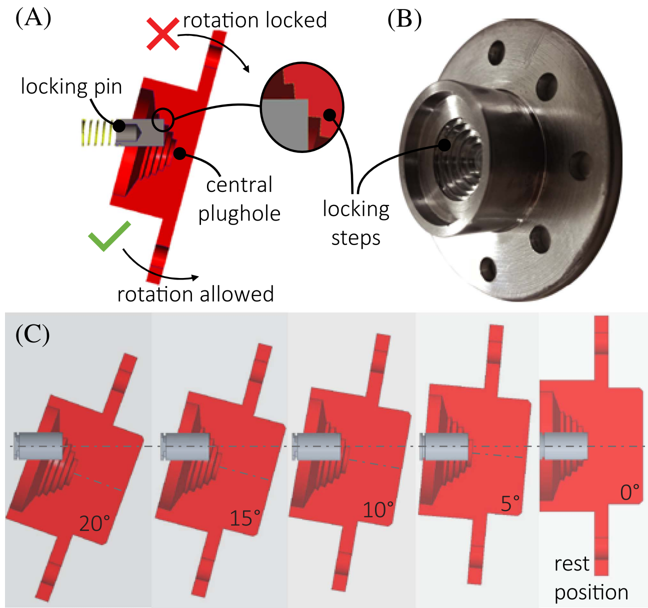

Fig. 3. A) The working principle of the hemispherical unidirectional ratchet mechanism: the locking pin engages the locking steps preventing rotation in one direction while allowing it in the other. In the rest position, the pin engages the central plughole, completely locking the writs. B) The prototypal grooved plate featuring the locking steps. C) The five locking positions of the wrist, corresponding to bending angles from 20° to 0° (i.e., the rest position) with a step of 5°.

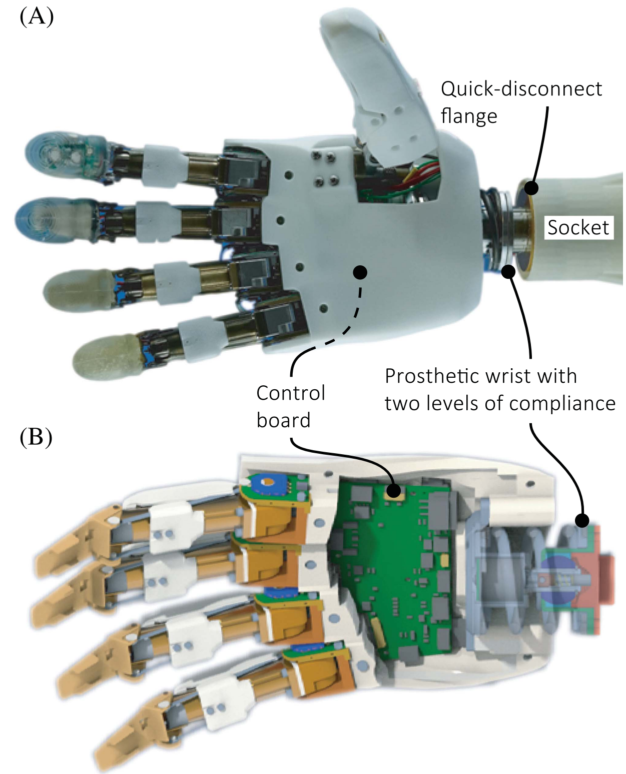

Fig. 4. Prosthetic hand prototype with the wrist integrated in the palm.

so-called compliant mode), the spherical joint can bend under tangential forces applied to the distal end of the hand prosthesis (counteracted by the spring). Conversely, when the spherical joint is blocked, it no longer offers a compliant behavior (stiff mode).

The switch from compliant to stiff mode and *vice-versa*, is entailed by a locking mechanism actuated by a linear stepper motor (AM1524, Faulhaber, Switzerland) in a quasi-passive fashion, i.e., the prosthesis does not provide mechanical work. A locking pin is driven by the threaded shaft of this motor, which is coupled with a custom nut. The latter is connected with the locking pin through a small-sized compression spring (stiffness 0.6 N/mm, maximum displacement 4 mm, maximum push/pull force 2.4 N), which provides a push/pull preload to the pin. The purpose of the pin is to engage locking steps in the corresponding grooved plate. To manufacture this plate, we cut a series of progressively inclined circularly extruded grooves converging to a central plughole (Fig. 3(a) and (b)). The result is a unique hemispherical unidirectional ratchet mechanism, that provides progressive locking positions from 20° to 0° of FE and/or RUD, with a step of 5°. Due to its geometrical features, the locking effect is unidirectional from the periphery (i.e., larger FE and RUD angles) towards the center (i.e., smaller FE and RUD angles, Fig. 3(c), meaning that the wrist can lock in a more bent posture but skip to a less bent one, due to weight (or external force) effects, but not vice-versa (Supplementary video S1).

When the mechanism switches to stiff mode, the locking pin is driven forward by means of the lead-screw transmission. If the wrist and hand axes are aligned (i.e., *rest position* of the wrist; Fig. 3(c) the pin latches in the plughole, directly. If the wrist is bent (as for aligning the hand to environmental constraints, like grasping a bottle on a table – Fig. 1), the pin engages with one of the peripheral steps and its internal spring provides a continuous preload force that allows the pin to progressively engage with more central steps, in the case the wrist tends to go back to the rest position. In such case, the locking pin latches the plughole as soon as they become aligned. In all cases, the wrist exhibits a stiff behavior.

A custom microcontroller-based (PIC18F26K22-I/SS, Microchip Technology, USA) electronic board controls the prosthetic wrist, by driving the stepper motor to switch the behavior from compliant to stiff and vice-versa. In the present implementation it interprets control commands sent via a serial bus, but it could be programmed to acquire and respond to two amplified EMG signals. A miniature magnet attached to the nut and a pair of Hall-effect sensors allow detecting whether the nut is in one of the two extreme positions (Fig. 2), i.e., whether the mechanism is in compliant or stiff mode. The speed of the stepper motor to transition between the two modes was set to 4 mm/s. This speed, empirically found, represented a good tradeoff between pin output torque and switching time (1.5 s). The wrist mechanism drains 3 W when transitioning between modes, and 0.05 W when idling. If the time employed by the prosthetic hand to fully enclose the manipulandum is equal or longer than the time required by the wrist to fully switch to stiff mode, its unidirectional lock allows a gradual alignment of the forearm with the hand until the pin engages the locking plughole. Conversely, if the hand closes faster than the wrist, the pin could

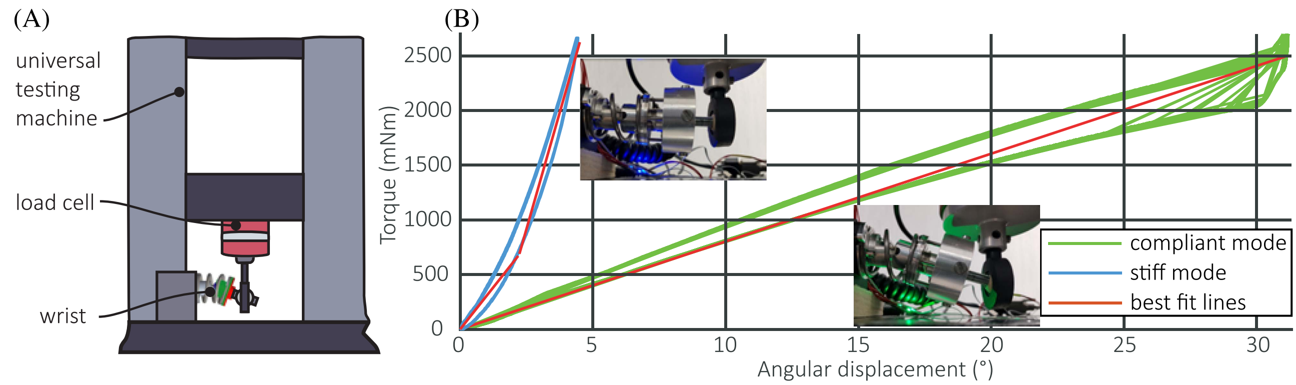

Fig. 5. A) Representation of the experimental setup for the characterization of the wrist. B) Experimental data of torque vs. angular displacement of the wrist in stiff mode (blue line) and in compliant mode (green line). Best fit lines are depicted in red.

engage one of the concentric steps past the plughole, resulting in a suboptimal locking configuration (see Supplementary video S1). It is worth remarking that even in a suboptimal locking configuration, the wrist locks any rotation directed from the center to peripheral angles, and the user can safely manipulate the object.

The wrist proved compact enough to be integrated into the palm of a robotic/prosthetic hand with powered digits (similar to the i-Limb hand) (Fig. 4), which we report for illustrational purposes. In this prototype, the center of the wrist joint was placed at the base of the palm in order to match the human anatomy. Consequently, the mechanism is flipped with respect to the configuration of Fig. 2, without any impact on its functionality.

IV. Operation and Function

The actual flexural stiffness offered by the manufactured wrist, in both modes, was assessed using a universal testing machine (5965, Instron, USA). To this aim, the proximal side of the device was secured to the bottom plate of the machine with a custom fixture, while the distal side was connected to the movable crosshead through a load cell (2580-1KN, Instron, USA) and a spherical joint, so that the vertical displacement of the crosshead could bend the mechanism (Fig. 5(a)). In each of the 200 test cycles, we linearly applied and removed a load (0 to 41 N) at a constant speed (5 mm/s), 65 mm apart from the center of the wrist, roughly corresponding to a maximum load of 4 kg in the center of the palm to simulate a realistic usage condition.

In compliant mode, the wrist exhibited a mostly linear flexural stiffness of ~80 mNm/°deg with a hysteresis of 16%, a non-linearity of 12%, and a non-repeatability of 5% w.r.t. the full-scale value (Fig. 5(b)). Hence, the experimental result confirmed the nominal value indicated by the spring manufacturer, and that the other mechanical components did not significantly interfere with it. In stiff mode the device could slightly bend for about 4.5° deg (likely due to the structural stiffness of the assembly) before locking. We inferred a dual behavior: in the first half of the bend, it displayed a relatively low level of compliance (~307 mNm/°deg), while its stiffness raised to ~851 mNm/°deg (theoretically infinite stiffness) for angles greater than 2.2° deg. In this configuration, the hysteresis proved 10%, the non-linearity 12%, and the non-repeatability 5% (Fig. 5(b)).

A. Pilot Functional Test

To get greater insights about the actual use of the device as a prosthetic wrist, we enrolled a participant with transradial amputation, to beta test it. Written informed consent was provided by the participant prior to the beginning of the experiment, according to the Declaration of Helsinki. The study was approved by the ethics board of the Scuola Superiore Sant'Anna (approval number 2/2017). The participant, a myoelectric hand regular user (male, 37 years old), was fitted with a research prosthesis including a custom socket, the wrist prototype assembled to an experimental multi-fingered hand (Mia Hand, Prensilia Srl, Italy) [6] and a battery. The socket included two surface EMG sensors (MyoBock `13E200`, Ottobock, Germany) on antagonist muscles (wrist flexors/extensors) and a commercial quick-disconnect flange (9S266, Ottobock, Germany) for connection with the wrist. The multi-fingered hand acquired the signals picked up by the EMG sensors, implemented a state-of-art two-state amplitude modulated control [33] and could control the wrist as well, as per the SHWO principle. Accordingly, when the hand initiated a closing movement, the wrist was driven in stiff mode; vice-versa, when the hand initiated an opening movement, the wrist was driven in compliant mode. After fitting, the participant was simply asked to familiarize with the prosthesis by picking and manipulating objects from the SHAP box (Southampton Hand Assessment Procedure), and to provide verbal feedback about the wrist. The latter was used both following the SHWO principle and fixed in stiff mode to collect comparative cues with respect to standard (stiff) wrists.

The participant proved able to master the prosthesis with either wrist modalities (SHWO or fixed stiff) in a noticeably brief time (Supplementary video S1). We extracted and analyzed the trunk bending, shoulder rotation, elbow flexion, and shoulder elevation/depression motions, from the video recorded during the session, by means of a state-of-the-art marker-less automated method [34]. We were able to track the participant's kinematics using only 208 manually labelled frames to train the algorithm, which is based on transfer learning with deep neural networks.

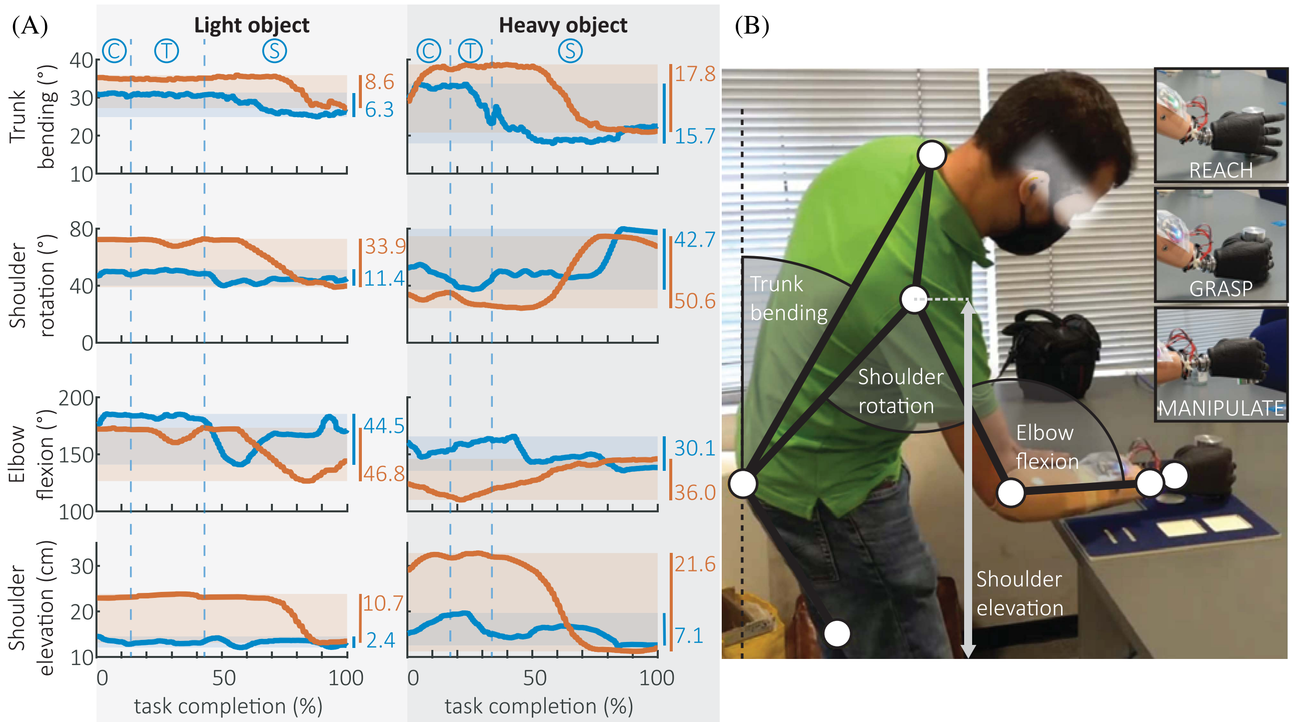

Fig. 6. A) Experimental results of the pilot test. In each plot, the kinematic data of tracked motions for each task are reported, along with their range (on the right of each plot). These data were recorded with the wrist in stiff mode (red line) and according to the synchronous hand-wrist operation (SHWO – blue line). The duration of the tasks were normalized to the task completion time. The status of the wrist in the SHWO is reported (C=compliant, T=transition, S=stiff). B) A frame of the video used to extract the kinematic features of the participant performing an experimental task: the joints and the tracked motions are depicted. In the insets: exemplar photograms of the grasping sequence performed by the amputee participant.

These frames were randomly extracted from the video recordings. This method was preferred over a traditional marker-based motion acquisition system due to its advantages in terms of portability and low set-up time, at the cost of an acceptably lower accuracy. We observed a consistent reduction of the range of movements when using the wrist under SHWO (representative case: Fig. 6, Supplementary video S1), thus suggesting the potential of the proposed device to entail more natural movements during prosthetic use.

The participant proved positive about the two levels of compliance (“I like that I can accommodate the hand without having to bend my trunk”, “While I handle an object I don’t perceive differences with my home prosthesis”) and claimed that the SHWO operation was intuitive to control/use ("I could control the wrist with no efforts”, “I did not have to think about the wrist when I used it”). However, he also advised to reduce the stiffness of the wrist in order to reduce the effort necessary to bend it. Yet, he commented not to reduce it too much in order to avoid a “floppy” and unpredictable behavior of the prosthetic hand, i.e., to stably sustain its weight without significative oscillations in the reaching phase.

V. Discussion

In this paper, we illustrated a 2-DoF, lightweight wrist prosthesis that displays a compliant behavior during the reaching phase of the grasp and a stiff behavior during the manipulation phase, operated by the same control input used to open and close the prosthetic hand. Three are the main advantages: i) the user can exploit the available environmental constraints, like a table, shelf or wall, to conform the posture of the wrist and orient the hand optimally with respect to the object prior to grasp it; ii) when the object is grasped, the user can manipulate it in a safe and predictive manner thanks to the rigid behavior of the wrist; and iii) no additional cognitive burden is required for its control.

The typical number of grasps that a prosthetic user performs daily is about 120 [35], hence the characterization on the test bench proved that our wrist could withstand cyclic loads that mimicked the effects of daily life manipulation activities. A more extensive test batch should be performed to assess the effects of fatigue in the long run, possibly verifying that the device can withstand 300.000 cycles, as prescribed by the ISO 22523 [36]. However, we also envision to manufacture a series of prototypes to be tested in the home setting for an extended period of time. It is worth noting that we designed our wrist prosthesis to be compatible with standard sockets (thanks to the quick-disconnect flange) and with commercial hand prostheses (that can be connected to the wrist through a custom flange). In this way we could more easily perform realistic testing with a relatively large cohort of participants, by adapting their prosthetic systems rather than providing them with prototypal hands.

From a rather preliminary study with a participant with transradial amputation, we observed that it is possible to quickly and intuitively learn how to use the wrist with minimal training. This supported the validity of the SHWO paradigm, which taps from the hypothesis formulated by Kanitz et al. [27]: a compliant wrist is needed during reaching and a stiff wrist during manipulation. Excitingly, we could measure a decrease in joint angular and displacement ranges when the participant used the wrist with the SHWO mode, with respect to the stiff wrist. In particular, the ranges of the trunk bending angle, elbow flexion angle, shoulder rotation angle, and shoulder elevation dropped when using the proposed wrist mechanism with respect to the rigid counterpart (Fig. 6(a)). Reducing the insurgency of compensatory movements in upper limb prostheses users is fundamental to alleviate the possible onset of secondary injuries and to mitigate discomfort [26]. From our results we can speculate that using the proposed wrist prosthesis may lead to this benefit, at least for a certain subset of daily living tasks. In addition, we firmly believe that the stiffness of the prosthetic wrist played an important role in the kinematics of the participant: finely tuning this parameter might further increase the performance of the device in terms of reduced compensatory motions. However, this assumption should be confirmed in future by experimental data.

While the reduction of the joint ranges associated to shoulder rotation and elevation were somehow expected [37], [38], the reduction of the elbow flexion was not [10]. It is known that compensatory elbow flexion movements are caused by the lack of PS movements of the prosthetic wrist [39]. In our case, as the wrist and socket prevented any PS movement, it is likely that the passive FE and RUD movements of the wrist were responsible for the mitigation of the elbow compensatory motions. In addition, following the advice of Deijs et al. to assess trunk movements [12], we observed a reduction of trunk bending motion. This, although very anecdotally, seem to confirm with a realistic setup and an amputee participant the evidences found by Kanitz et al. (with healthy participants) on the benefits that a compliant wrist leads in alleviating compensatory trunk motions [27]. All these evidences, however, need to be confirmed with a large cohort of participants.

The positive subjective opinions about the prosthesis and its ease of use are encouraging and motivate further developments of the proposed design. The comment on the excessive stiffness in compliant mode will be taken into account for future design iterations to reduce the fatigue in bending the wrist. For example, we could heuristically reduce the stiffness of the spring to the minimum value that maintains the hand in a relatively stable posture aligned with the forearm during reaching movements. However, we believe that this value could depend on subjective factors, e.g., the user's muscular strength and his/her personal preference in terms of desired stiffness. We could tap from the literature in order to embed an ellipsoid profile akin to the intact wrist [40].

Other than the SHWO, we envision alternative control strategies for our device. For example, coactivation of antagonist muscles could be employed to switch to the stiff mode. In this way, the physiological property of the joints (i.e., stiffening by co-contracting the agonist muscles) could be mimicked for an intuitive control, albeit this control strategy might result fatiguing for the user. Alternatively, the grasp force could be used as a control signal to switch from compliant to stiff mode: as soon as the force exerted on an object overcomes a threshold, the wrist turns stiff to support manipulation. It is worth noting that this control strategy is viable only if the prosthetic hand is instrumented with force or contact sensors, which unfortunately is rarely the case for commercial myoelectric hands. In future iterations of the device, we will consider replacing the locking steps with a continuous surface to implement the unidirectional locking mechanism. A possible implementation may exploit the wedging effect, as already extensively explored by the authors [41].

In general, we can speculate that the proposed wrist is durable enough to withstand more than one day of regular daily use, that it can be integrated in an upper limb prosthesis and be seamlessly controlled using myoelectric signals. However, as our pilot study is far from being exhaustive, we could not draw significative conclusions. Nevertheless, as we believe that these preliminary outcomes are rather encouraging, we intend to continue exploring this promising concept by running extensive tests, possibly involving multiple participants who use the device at home. This will allow us to gather significative data on the participants' compensatory movements, possibly enriched by the outcomes of clinical tests alike the SHAP, and structured questionnaires, possibly in the form of a Likert scale to better capture the performance of the device as subjectively perceived by the users. Indeed, we believe that only after adequate at-home use the participants will master the device and benefit the most from it, unlocking its true potential.

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