A COMPACT 2-DOFS ACTUATED WRIST FOR IMPROVING DEXTERITY OF UPPER LIMB PROSTHETICS

N. Boccardo[*,1,2,†], M. Canepa[*,1,2,†], S. Stedman[1], L. Lombardi[1], A. Marinelli[1,†], D. Di Domenico[1,3,†], R. Galviati [1], E. Gruppioni[4,†], L. De Michieli[1,†] and M. Laffranchi[1,†]

1 Istituto Italiano di Tecnologia, Genova, Italy
2 Open University Affiliated Research Centre at Istituto Italiano di Tecnologia (ARC@IIT)
3 Department of Electrical, Electronics and Communications, Politecnico di Torino, Italy
4 INAIL Prosthetic Centre, Vigorso di Budrio, Italy
† IEEE Member
** These authors equally contributed to this manuscript*

ABSTRACT

This study tackles the challenges of developing an upper limb prosthetic system that accurately replicate the complexity of the human counterpart. Upper limb prostheses still present high abandonment rates, due to poor control intuitiveness and lack of dexterity. To address these issues, we introduce an anthropomorphic wrist prosthesis featuring active flexion-extension and pronation-supination capabilities, seamlessly integrated with the poly-articulated hand Hannes, with the goal of augmenting the dexterity and overall functionality in trans-radial and trans-humeral prostheses. Notably, the high dexterity and controllability observed when operated by amputees, using pattern recognition algorithms, based on a low-density EMG arrangement in a standard prosthetic socket, paves the way for future investigations and potential applications in home environment.

INTRODUCTION

The loss of the upper limb significantly impacts life quality for amputees, affecting manipulation and interaction abilities: in particular, the absence of wrist mobility forces amputees to perform unnatural movements, adding stress to shoulder and back during Activities of Daily Living (ADLs) [1]. Despite the importance of wrist mobility in naturally orienting the hand during grasping activities, there is a lack of multi-degrees of freedom actuated prosthetic wrists in the literature, with few commercial options offering limited active dexterity. To fill this gap, we developed and hereafter we present an innovative 2-DoFs prosthetic wrist, from both mechatronic and control perspectives [2]. The design aims at mimicking the ability of the intact human wrist during ADLs, in combination with our underactuated prosthetic hand Hannes [3]. The control exploits pattern recognition (PR) techniques to enhance both naturalness and intuitiveness of the multi-DoF prosthetic device. We provide a comprehensive overview of the project, starting with system requirements and then detailing the mechanical and control design. The experimental results and potential impact of the device in prosthetic applications are discussed, along with suggestions for future developments.

MATERIALS AND METHODS

The development of a prosthetic wrist device with 2 DoFs, incorporating flexion-extension (FE) and pronation-supination (PS), followed a user-centred design approach. We initially aimed at extracting the functional requirements, in terms of range of motion, torque, speed, robustness, anthropomorphism, weight, total length, and control latency. However, literature lacks valid estimates about wrist torque and speed during healthy subjects ADLs. Therefore, we conceived an experimental method to extract this information statistically. To estimate maximum power consumption requirements, we derived an average of 411 hand movements per day and set a worst-case of 1:1 ratio between hand and wrist movement from our previous clinical evaluation with Hannes [4]. Given the requirements, we designed a serial and modular mechanical architecture, creating two separate FE and PS wrist mechanism, with space to accommodate a standard Ottobock quick disconnect mechanism with electrical slipring, to transfer power and communicate to the hand. This modular design allows flexibility and compatibility with the existing prosthetic system, adapting to various amputation types and lengths. The FE wrist is designed with anthropomorphism in mind, minimizing misalignment between mechanical and anatomical rotation axes. Non-backdrivability is prioritized to prevent excessive battery consumption under static loads: this is achieved via a 3-stage gearbox, with an initial 4:1 planetary stage, an intermediate 2.1:1 spur gear and a final 40:1 worm gear (Figure 1A). This compact design achieves

82° range of motion (RoM), which is comparable to healthy subjects' requirements during ADLs. The FE mechanism has total length of 55 mm and total weight of 211 g. The PS is designed to be hollow shaft, to allow fitting of the standard slipring. It features a frameless 25 mm PMSM motor integrated with a 100:1 strain-wave reducer. The design allows the hand prosthesis to be attached and detached by the patient, whilst ensuring a robust connection between hand and socket. The resulting is an overall length of 65.1 mm and a 43 mm diameter (Figure 1D). From the control point of view, we exploited a previously developed, EMG based, Pattern Recognition control strategy, using Nonlinear-Logistic Regression (NLR), allowing users to control wrist PS, FE, and hand open and close in real-time [5, 6]. The control architecture presents two main layers: the joint selection layer, extracting from the NLR the classification of the action according to user intention and a joint control layer, computing the position references according to the RMS of EMG signal intensity. In this implementation, 6 standard dry surface EMG prosthetic sensors are used, to ensure compatibility with patient prosthetic socket.

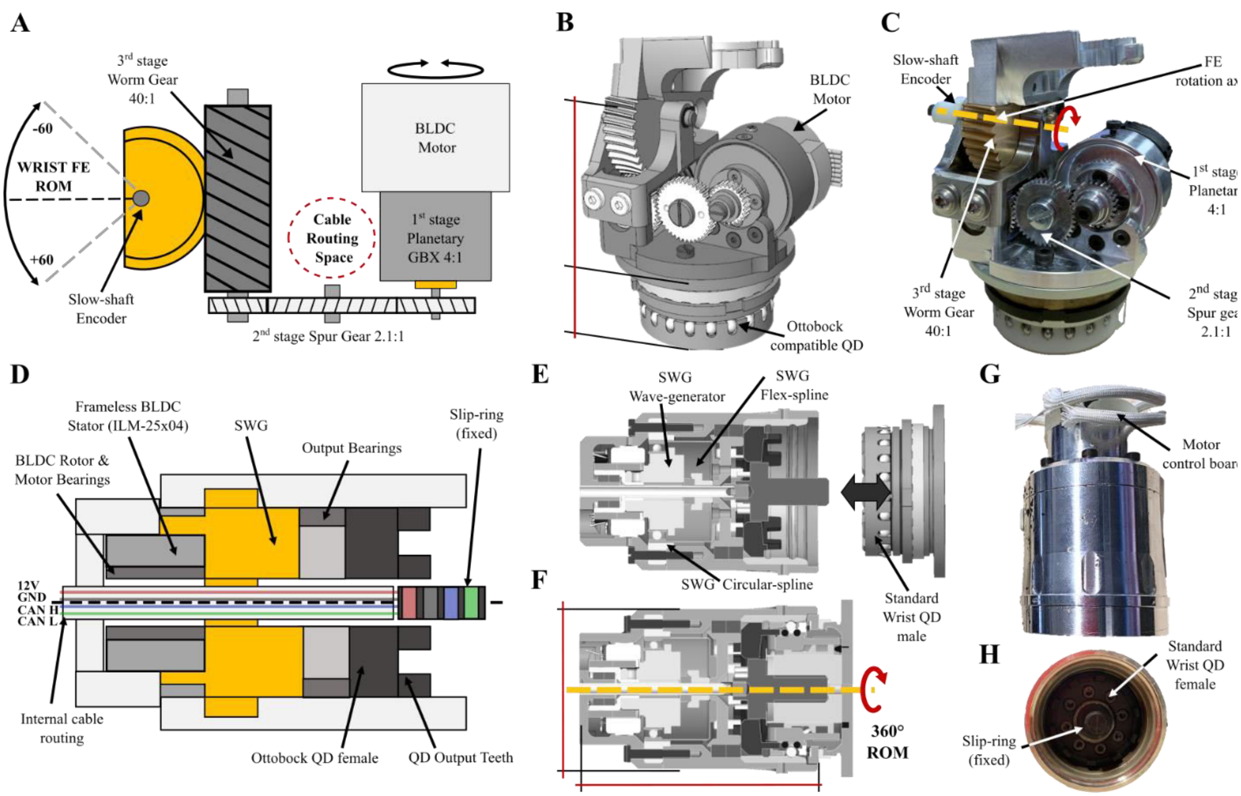

Figure 1: Wrist FE: **A)** Schematical representation of the adopted mechanism; **B)** Computer-aided design of the wrist device; **C)** Actual representation of the wrist device. Wrist PS: **D)** Schematical representation of the adopted mechanism; **E-F)** Computer-aided design of the wrist device; **G-H)** Actual representation of the wrist device.

RESULTS

We implemented a three phases testing methodology for assessing the prosthetic device capabilities [2]. In the dynamic tests phase, we aimed at estimating the mechanical bandwidth of the wrist actuators, applying a sequence of sinusoidal speed references from 0.25 to 4.5 Hz, resulting in 1 Hz for wrist PS and 2 Hz for wrist FE at -3dB in the complete Range of Motion. We performed then an able-body kinematics assessment, to extract the wrist speed profiles from healthy subjects during ADLs. The ROM and speed profiles were compared to the prosthetic wrist capabilities, simulating loads in realistic scenarios with the prosthetic wrist, such as lifting a heavy sphere of 532 gr in flexion and extension or pouring water from a 300 g jug with 500 ml water. Results showed a maximum torque of 5.27 Nm for PS joint during the glass jug pouring task and 2.38 Nm for FE joint during lifting of a heavy sphere, which were below the maximum torque achievable by the actuators. The maximum speeds during healthy ADLs of 38.7 rpm for PS and 23.4 rpm for FE were extracted statistically from the data and compared with the maximum actuators' speeds, resulting in a superior performance of the mechanical wrist. Finally, we evaluated the PR control strategy with 10 healthy subjects and 3 mono-lateral amputees during ADLs. Written informed consent was obtained under the guidelines and approval of Bologna-Imola ethical committee (CP-PPRAS1/1-01) prior to conducting the experiments. An example of the EMG signals used to train the PR model is graphically represented in Figure 2. Preliminary results showed a good class separation and pattern discrimination, decoding the user intention and executing wrist movements in a repeatable manner at 300Hz. Since the control algorithm runs directly in the embedded control electronics, the resulting system is wearable and anthropomorphic, paving the way to the usage in a real clinical scenario. Moreover, we assessed power consumption in the worst case of 500 combined average wrist and hand movements, considering a 16 hours consecutive daily use, achieving a 56,2 % average battery usage with a small 11,1V, 2.5Ah prosthetic battery pack.

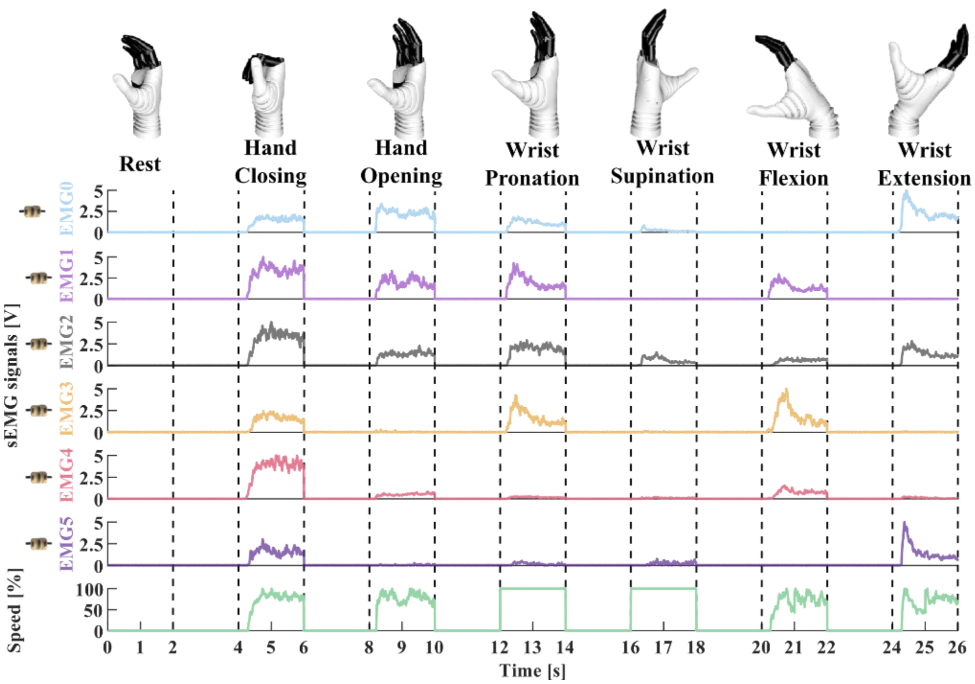

Figure 2: Representation of the 6 EMG signals used during the training of the Pattern Recognition model to control the 3 DoFs Hannes prosthetic system.

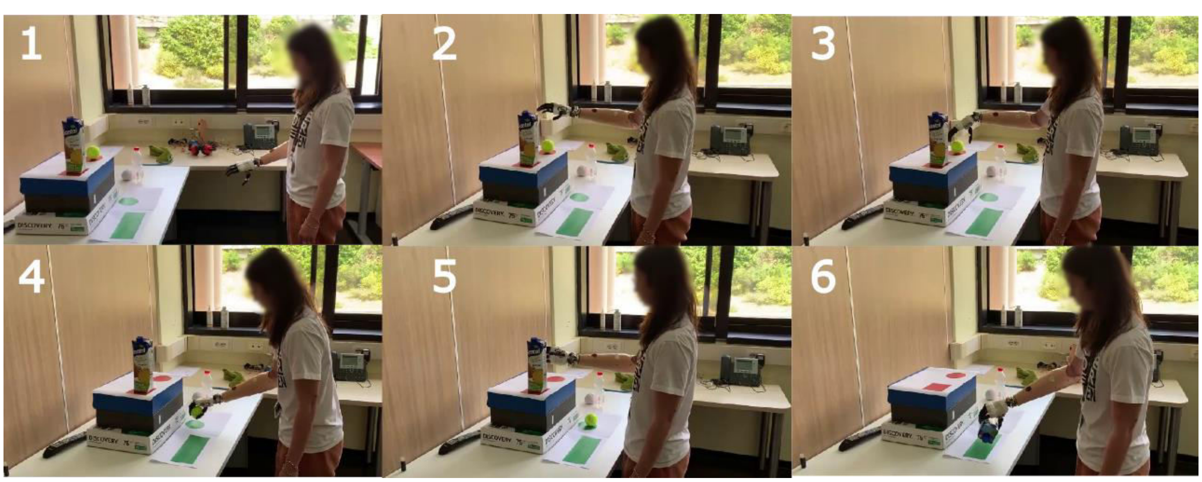

Figure 3: Time representation of a patient using the Hannes prosthesis during ADLs. Preparation of the wrist configuration to grasp an object (1), reaching the spherical object (2), adjusting the wrist FE to comfortably grasp the object (3), extend the wrist to place the object on the table (4), adjust the wrist PS to grasp a vertical object (5), adjust the wrist PS to place the object horizontally on the table (6).

DISCUSSIONS AND CONCLUSIONS

We introduced a prosthetic wrist with 2-DoFs [2], combined with the poly-articulated Hannes hand prosthesis [3], and evaluated its efficacy as a practical substitute for the natural counterpart. To achieve this goal, we conducted a variety of tests and validations: results show that this novel prosthetic system could mimic human movements and achieve satisfactory range of motions and mechatronics capabilities, providing potential benefits to patients due to an enhanced wrist dexterity. Statistical analysis confirms the 2-DoFs wrist's speed and torque performance exceeds average natural task requirements. We used the artificial wrist in combination to a machine learning based multi-DoFs control strategy, achieving low latency and a good usability, enabling an efficient control of wrist movements. Additionally, the compact prosthetic design promotes the overall anthropomorphism of the prosthesis, with a low impact on the energy budget. The promising results and performances pave the way for future studies to assess long-term use, robustness, and usability in clinical and at-home scenarios. As an example, Figure 3 illustrates a timeline depicting two distinct grasping scenarios that necessitate the utilization of the two DoFs in the wrist. The subjects in the study employed the PR model [5] to control the 3 DoFs of the prosthetic device during ADLs. In particular, the amputee was tasked with grasping and positioning both a spherical object and a vertical object using the developed prosthetic device. Notably, our observations indicated minimal compensatory movements at the shoulder level. The mechatronic system will enable usage of other advanced control strategies, including artificial intelligence, and has the potential for adaptation to trans-humeral prosthetic solutions, broadening its applicability.

ACKNOWLEDGEMENTS

This work was supported by the Istituto Nazionale Assicurazione Infortuni sul Lavoro, under grant agreements PPR AS 1/1 and PR19-PAS-P1. The Open University Affiliated Research Centre at Istituto Italiano di Tecnologia (ARC@IIT) is part of the Open University, Milton Keynes MK7 6AA, United Kingdom.

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