Towards More Natural Transradial Bionic Limbs

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***Abstract*—Based on previous experience with prosthesis users and literature, this paper introduces three important aspects to further develop functional transradial myoelectric prostheses: stiffness modulation, grasp reliability and limb dexterity. In particular, we propose three possible solutions and discuss on the insights observed about the exploration of impedance control in prosthetic hands during Activities of Daily Living and social interaction, the introduction of an articulated palm to increase all hand parts contribution in grasping, and a compact 3 DoF myoelectric wrist capable to switch from compliant to rigid properties during pre-grasping phase to decrease compensatory movements and favour more natural body postures in prosthesis users.**

***Index Terms*—Soft-robotics, Myoelectric control, Upper-limb prostheses, Bionic Limbs**

I. Introduction

Hands play an important role in human life for prehensile, proprioceptive and communication purposes. An upper limb amputation leaves a person with limited ability to perform work and daily living activities, but also hinders social interaction and the perception of self-image. Artificial limbs are a valuable tool to restore some of these lost capabilities. However, there is still a sharp separation between available commercial devices and the real needs of prosthetic users [1]. Indeed, in [2] authors found that only 62% of amputees use a prosthetic device, usually due to the poor functionality [3].

The human-machine interface and the mechanical features of robotic devices could limit the performance and development of arms prostheses. The complex architecture of the human hand is difficult to translate in an artificial system. Consequently, some of its salient features are often sacrificed during the design process, to favour simplicity despite introducing discrepancies between the artificial prototype and its biological inspiration.

Different type of prostheses can be found on the market, from body-powered to self-powered systems, commonly controlled by two EMG channels. We find different mechanical structures that go from robust and simple hooks to poly-articulated hands that replicate more accurately some of the anthropomorphic features of human hands. Indeed, multi-fingered hands became famous in the last years. However, they commonly required switching control techniques to select one grasp pattern per time or more complex control techniques with additional sensors.

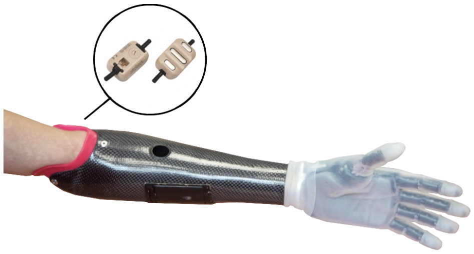

Fig. 1. The SoftHand Pro hardware: socket, two sEMG sensors and one prosthetic hand.

The SoftHand Pro (see Fig. 1), whose design is based on the concept of soft synergies [4], combines the implementation of a single motor function, inspired by the first synergy of human grasping [5], with the intrinsic softness of its 19 degrees of freedom, to adapt its grasp pattern to the case-dependent contact constraints. This results in a functional poly-articulated hand that can still be controlled with only two EMG channels. This system proposes a robust and adaptable design that represents a reduction of users' cognitive load. Even though results in [6] suggest a high potential of the prosthesis and a great users' acceptance, it is still a research device under development. In previous studies with patients we have collected important issues mentioned by users [7], observed by experimenters or highlighted during tests. These concerns are in agreement with aspects that are currently under study also in commercial prostheses. In this paper, we point out three of these aspects: stiffness modulation, grasp reliability and limb dexterity, and address in further detail our proposed solutions.

II. Stiffness modulation

The quality and safety of Human-Robot interaction, are aspects that cannot be underestimated in prosthetics, especially in upper limbs, due to the inherently interactive nature of the (artificial) hand. Impedance control, which plays a pivotal role in human movement, could be tantamount to the promotion of natural bionic interaction but maintain a strong grasps and precise pinch actions.

In the context of robotic manipulation, impedance control was introduced in [8]. It led to a revolution in how modern robots are controlled, and in what they are able to accomplish, paving the way to collaborative robotics [9]. Social Human-Robot Interaction filed gave rise to substantial research, including studies on grip force control of robotic hands interacting with humans [10]. Moreover, [11] suggests that autonomy, adaptability and touch are key requirements for social robots

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to be seen as less machine-like by humans. Human impedance-regulation skills have been transferred to robots (including hands) in the framework of teleimpedance [12].

Already in [13], the author suggested impedance control as the preferred paradigm for controlling prostheses. It could provide the amputee with an essential component of the natural adaptative capability of humans, which would be difficult to recover otherwise, due to inherent severe sensory loss. Nonetheless, experiments in [14] led to the conclusion that proportional velocity control of the joint position and high values of impedance obtain faster and more precise task execution. Some years later, [15] proved the existence of task-dependent optimal values of stiffness, a result in agreement with the literature about muscles stiffness control.

The concurrent action of antagonistic muscles, i.e. coactivation, defines the mechanical properties of the joint. Within the framework of standard direct control (see [16] for a review), muscle cocontraction is, in first approximation, considered as a source of noise to be discarded, or used as a switching technique in multi-grasp hands of the market. Inspired by the natural behaviour of muscles, the proposed method is capable of a simultaneous and proportional decoding of position and stiffness intentions from two surface electro-myographic sensors placed over a pair of antagonistic muscles (see Fig. 2). In [17], we explore the utility of variable stiffness in prosthetic hands when performing activities of daily living and physical social interactions. Our algorithm describes user's stiffness modulation, proportional to muscle coactivation, and closure/aperture speed, proportional to reciprocal activation through the use of a Finite State Machine, capable to discard voluntary cocontraction as a position command. To the best knowledge of the authors, this was the first experimental validation of the feasibility of mechanical impedance control in prosthetic hands, performed by an amputee. Its feasibility was validated and compared to existing control modalities while performing a set of tasks, which include one- and two-handed object manipulation, self-interaction, and social interaction with 12 able-bodied volunteers. The data recorded suggest that user's muscles adapt to the external conditions intuitively as muscles of healthy humans do. In agreement with the previous, results prove the preference of variable stiffness control for the prosthesis user due to a higher adaptive capability, while results from able-bodied subjects highlighted their preference for soft interaction, i.e. low stiffness, which is perceived more human-like and comfortable.

III. GRASP RELIABILITY

Prehension is a very developed function of the human hand, an organ capable to adapt to an object-based both on its shape and the intended use. Compared to other animal hands, one of the most apparent differences is its superior quality of opposition. While fingers play an important role, also the palmar concavity determines the ultimate hand posture and gives a fundamental contribution to provide an adequate and stable grasp [18]. In traditional anatomical definitions [19], the hollow cavity of the palm is described by three arches that run in different directions. In [18], the authors analyse the palm kinematically by describing it with three planes, and by measuring the thenar and hypothenar angles. During pre-grasping and grasping phases, the palmar and dorsal surfaces of the human hand change according to the shape of the target to increase the contact surface. Palm features enable the accommodation of large stresses associated with opposition, and result in sophisticated manipulation capabilities.

In robotics, many highly anthropomorphic hand prototypes were designed over the last century [20]. Their grasping capabilities are usually engineered through complex finger structures and sophisticate actuation mechanisms, often disregarding the palm contribution. Some systems approximate the palm concavity through a rigid curved surface, as the DLR Hand II [21], while another explores an extremely biomimetic approach [22]. Few examples propose active palms at the cost of additional actuators (e.g [23]). More recently, through the introduction of soft robotic technologies, the importance of flexible palms has been investigated in hands (e.g [24]).

Inspired by human anatomy, we propose a two degrees of freedom deformable palm, able to emulate the motions of the thenar and hypothenar muscles. Most noticeably, we adjust the synergetic under-actuation mechanism of the hand to actuate also the palm motions, with the advantage of not introducing additional motors in the system. We explored the advantages of including a flexible concave palm and analyse how this

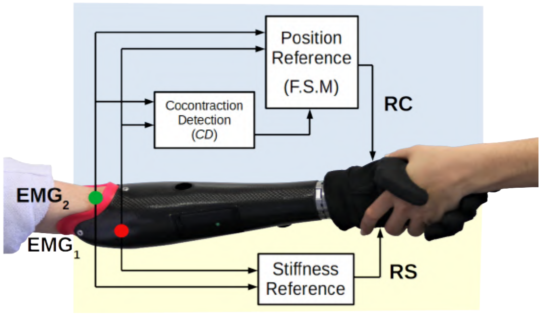

Fig. 2. Variable stiffness control provide users with the ability to both precise grasps and soft human interaction.

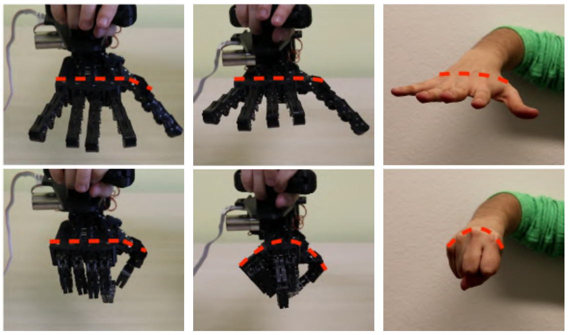
(a) Fixed palm (b) Articulated palm (c) Human palm

Fig. 3. Palm comparison among studied systems.

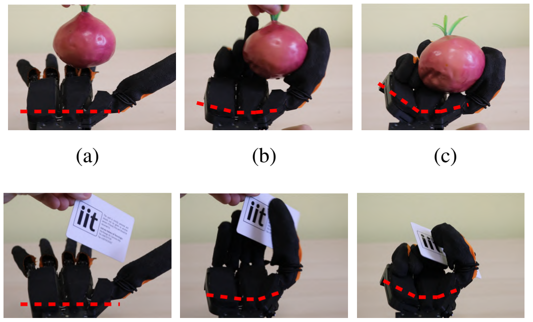
(a) (b) (c)
(d) (e) (f)

Fig. 4. Photo-sequence of the adaptive capability of the articulated palm during the grasp of different objects.

inclusion improves finger workspace and manipulability (see [25] for details). Finally, we validate its feasibility and the effect of palm motions integration in active grasping, compared to a system where palm motions are inhibited and to a human hand (see Fig. 3).

Grasping experiments show a closer resemblance of the soft-palm robotic hand to the human hand. Results evidence a higher adaptive capability and a larger involvement of all fingers in grasping, getting closer to a standard power grasp and a better opposition. Another important feature visible in Fig. 4, is that the palm angles are different in every condition, highlighting the capability of the hand to adapt to different shapes, favouring grasp safety, and suggesting the possible inadequacy of fixed palm angles to adapt to different objects.

IV. LIMB DEXTERITY

The lack of compact and reliable actuators and the difficulties to mimic human prehension capabilities result in a reduced set of practicable movements. Prosthesis users are often forced to alter their strategy and perform unnatural compensatory movements to increase their range of motion [26], to apply larger forces on objects and to obtain acceptable levels of smoothness, accuracy and energy efficiency [27]. Compensatory movements increase the discomfort, often resulting in residual limb pain or overuse syndromes [28].


(a) Human wrist (b) Rotational wrist (c) Lockable wrist


(d) Human wrist (e) Rotational wrist (f) Lockable wrist

Fig. 5. Comparison of different wrist systems during Activities of Daily Living. Panels (a), (b) and (c) present compliant capabilities for soft interaction with the environment, while panels (d), (e) and (f) show the usability of a rigid joint for adequate pre-grasping body posture.

In [29], the authors demonstrate that a single DOF hand with wrist flex/extension allows functions comparable to a highly performing poly-articulated hand without wrist. Moreover, [30] suggests that an adaptive wrist with both compliant and rigid behaviours could benefit the user by alternating between its adaptative capacity for the approach, and stability once the object is grasped. Nonetheless, the simple kinematics of commercial prosthetic wrists limits the individuals in performing a wide range of tasks and restore natural motor functions.

We propose a functional prosthesis that improves grasping capabilities through the addition of a simple yet useful 3 DoF myoelectric wrist joint with compliant and rigid properties. Its friction-locking capability enables the adjustment of hand configuration in pre-grasping phases and the adjustment of its stiffness through sEMG signals and only one motor. We study the proposed system and compare it with the most common active wrist - a prono/supination rotator - and to subjects' natural wrist using time-based metrics and biomechanical measures from 8 able-bodied subjects and a subject with a limb loss. The experimental protocol is based on functional movements related to reaching, grasping and transport at different heights. In addition, one prosthesis user performed purpose-oriented movements inspired by ADL with the 3 systems, focusing on the reaching phase conditions.

Results evidence the feasibility of the prototype, improved performance capabilities, and the subjects' first impression about the proposed system. Regarding the completion of ADL, Fig. 5 shows that with the lockable wrist, the user presents a more natural body posture. Fig.s 5(a), 5(b) and 5(c) highlights the usability of a softer interaction with the environment when it behaves compliant. With a rigid behaviour, we observe a safer grasp in extreme cases (Fig.s 5(d), 5(e) and 5(f)), where the stability of the object can be compromised when using the rotational wrist. Overall, ADL results suggest a decrease in the time to complete the task (usually related to cognitive load) and an increase in intuitiveness with the proposed wrist.

V. CONCLUSIONS

Artificial hands are already integrated into everyday life of prosthesis users, but little is known about their capability to interact socially and to adapt to situation-dependent requirements. We believe that the implementation of stiffness modulation would improve control naturalness of prosthetic hands, promote bionic interaction, and in turn, favour their acceptance. Results from both the prosthesis user and the 12 able-bodied subjects suggest the use of variable stiffness as a viable compromise between firm control and safe interaction [17].

With the inclusion of an articulated palm to improve grasp reliability, we observed a larger contribution of the hypothenar side of the palm and the fifth and ring fingers to support objects [25]. We observed the palm being modulated according to the shape of different objects, which seems to enlarge the design capabilities for adaptation, object support and enhance grasp stability. The use of palms could be investigated in prosthetics to study the reduction in cognitive load in more complex grasping conditions, the safety of grasping while holding and moving objects, which is a common failure in testing, and the comfort and acceptability of interaction.

Finally, this work presents a preliminary design of an innovative and compact 3 DoFs prosthetic wrist to increase limb dexterity. This solution could reduce compensatory movements and facilitate the reach of objects while promoting stability in the transport and holding phases. Results prove the interest of able-bodied subjects in active use of the system, which does not compromised their execution time Furthermore, users show preference and acceptance of the proposed system over the rotational wrist. Experiments with the prosthesis user suggest enlarged capabilities to adapt to different requirements, intuitive use and more natural body postures.

This paper build upon three important aspects needed to further develop more functional transradial myoelectric prostheses in regards to stiffness modulation, grasp reliability and limb dexterity. Encouraging results suggest that the three possible solutions proposed are aspects worth investigating to break barriers between current prostheses solutions and more useful systems that favour simplicity, intuitiveness and naturalness.

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