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Principal Orientations of the Wrist During ADLs: Towards the Design of a Synergetic Wrist Prosthesis

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Abstract. To design an underactuated wrist prosthesis, a preliminary study has been conducted to identify the relationship between the Degrees of Freedom (DoFs) of the wrist during the execution of tasks of daily living. After the identification of the principal orientations of the wrist describing the tasks, polynomial functions were used to define a synergetic relationship between the DoFs. The latter can be implemented in a prosthetic wrist featuring one actuator to obtain motion along three DoFs, with the purpose of reducing compensatory movements.

1 Introduction

Prostheses are designed to replace lost body parts, however, the rate of their abandonment is considerable among amputees due to the lack of sufficient function [1]. Recent advances in upper limb prostheses are characterized by a strong focus on highly dexterous, multi-fingered prosthetic hands, whereas only few powered wrists have been proposed [2]. However, it was suggested that it is the wrist dexterity that is missing and necessary in current upper limb prostheses, rather than hand dexterity [3]. This is especially true when considering the *compensatory movements* of the proximal joints, required to compensate for the lack of DoFs, which can be strongly reduced when using multi-articulated prosthetic wrists [3]. The need of compact and lightweight powered wrists is thus evident, however, developing it proved not a trivial task, mostly because of the large size and weight of the electric motors required for its actuation.

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The neuroscientific concept of synergies offers a powerful tool to minimize the size, weight, and power consumption of active prosthetic wrists. Broadly defined, a synergy is “a functional property of a multi-element system performing an action, whereby many elements of the system are or can be constrained to act as a unit through a few coordination patterns to execute a task” [4]. To apply this concept, it is necessary to identify a relationship between the DoFs of the wrist such that meaningful coordinated motions result from one single controlled DoF. Studies conducted on healthy participants showed that it is possible to identify synergies between the DoFs of the wrist [5, 6]. However, an analytical relation between the functional orientations of the wrist, during activities of daily living (ADLs), has not yet been found.

The goal of this work is to lay the foundation for the design of a prosthetic wrist mechanism able to produce synergetic motions along three DoFs, i.e. flexion/extension (FE), radial/ulnar deviation (RUD), and pronation/supination (PS), with one single actuator. The target for such mechanism is to feature one DoF directly driven by an actuator, while the remaining, dependent DoFs are kinematically constrained to the first one. To design this mechanism, it is necessary to investigate (i) the wrist orientations that are fundamental for the execution of ADLs, in order to identify the kinematic relation between them, and (ii) whether such relation can be reproduced by a physical mechanism.

2 Materials and Methods

To address the aforementioned issues, a study (approved by the ethical committee of the Scuola Superiore Sant’Anna, Pisa) was conducted with 10 unimpaired participants (4 males, 20–35 years old, all right handed) which wore a set of 4 Inertial Measuring Units – IMUs – (PIVOT, Turing Sense, USA) on their dominant hand, elbow, shoulder and back in order to measure the orientation of their body segments. The participants were asked to sit at a table and to perform two repetitions of a set of 21 tasks representatives of ADLs (cf. Table 1).

Table 1. ADL tasks

#	Self-contact tasks	#	Interaction tasks
1	Touch contralateral armpit	11	Pick coin (dominant)
2	Touch chest	12	Pick coin (non-dominant)
3	Touch contralateral temple	13	Cut with knife
4	Touch contralateral hip	14	Lift tray
#	Abstract tasks	15	Stir in cup*
5	Replace triangle	16	Pour in glass*
6	Replace small plate	17	Drink from glass*
7	Replace large plate	18	Open jar* (dominant)
8	Replace cup	19	Open jar* (non-dominant)
9	Replace cylinder	20	Turn door handle*
10	Replace ball	21	Turn key*

*dynamic tasks

The tasks were subdivided into *self-contact* (#1–4) and *interaction* tasks (#11–21), adapted from [7, 8], and *abstract* tasks (#5–10) chosen from the SHAP test [9]. Notably, some tasks were *dynamic*, i.e. they required a change in wrist orientation during their execution. Bimanual tasks (#11–12 and #18–19) were performed with both hands to capture differences when using a hand to support or to manipulate an object (notably, prosthetic hand users usually use the prosthesis in support to the contralateral unimpaired hand, less frequently the other way around) (cf. Fig. 1). For each data segment, the *Principal Orientation* (PO) was defined as the wrist orientation that the participants stably kept for the longest period of time during the execution of the ADL, whilst for the dynamic tasks two of such orientations were defined. The kinematic relation between the three DoFs was obtained as the best fit among the different POs and it was described by a system of three least-square polynomial functions $f_{PS}(p)$, $f_{FE}(p)$, $f_{RUD}(p)$.ù.

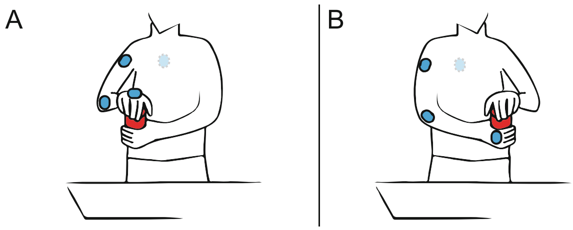

Fig. 1. Experimental setup. Dominant hand used as primary (A), or secondary hand (B) during representative tasks (#18 and #19). Blue circles indicate the placement of the IMUs.

3 Results

In particular, a set of 28 POs was obtained and three 7th order least-square polynomial functions were fitted to the data as a function of the POs numbered by descending degree of PS, indicated with p, where $1 \leq p \leq 25$ since POs of tasks #14 and #21 were considered outliers and ignored in the fitting (Fig. 2A). The kinematic relation produces a functional Range of Motion (RoM) of 103° for PS, 14° for FE and 28° for RUD. The 7th order was chosen since it minimized the partial derivative of the fitting curve with respect to PS angle (Fig. 2B). The mean error of the fitting, defined as the mean distance between the curve and the points representing the tasks, proved 5.0°. The R^2 values equaled to 0.99, 0.48, 0.66 for PS, FE and RUD respectively.

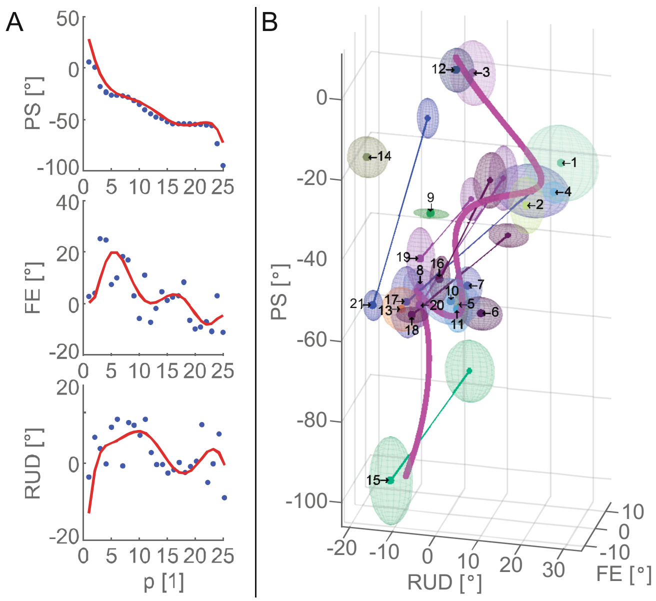

Fig. 2. (A) The three functions fitting the POs arranged by descending degree of PS (wrist prono-supination). (B) 3D representation of the mean (points) and standard deviation (colored bubbles) orientations of the wrist for each task tested (#). Dynamic tasks are represented with two points connected by a line. The synergetic relation is represented by the polynomial fit (thick solid line).

4 Discussion

A system of parametric polynomial functions describing the synergetic relation between the 3-DoFs of the wrist during ADLs was obtained for the first time. With this system the motion of FE and RUD can be described as a function of the PS. This is necessary to implement a wrist featuring one single actuator that drives PS and a mechanism to obtain the orientations of FE and RUD with respect to PS. This solution allows to optimize weight and bulk of the mechanism and we hypothesize that it also mitigates the cognitive burden of the prosthetic user, who can obtain complex 3D orientations of the wrist by actively controlling one single degree of freedom. Future work will aim at devising a physical mechanism that reproduces this analytical relationship, towards a compact and functional device. The functional RoM obtained here is considerably smaller than the data reported in [7] and [8] and tests will be performed to assess whether the wrist mechanism that reproduces this synergetic relation is effective to preserve the ability of amputees to perform common tasks with minimal occurrence of compensatory movements. Future tests will also aim at assessing whether controlling a 3-DoF mechanism with one single control input is acceptable in terms of cognitive load for prosthetic users.

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