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HANDEXOS: towards an exoskeleton device for the rehabilitation of the hand

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***Abstract*—This paper introduces a novel exoskeleton device (HANDEXOS) for the rehabilitation of the hand for post-stroke patients.**

The nature of the impaired hand can be summarized in a limited extension, abduction and adduction leaving the fingers in a flexed position, so the exoskeleton goal is to train a safe extension motion from the typical closed position of the impaired hand.

The mechanical design of HANDEXOS offers the possibility to overcome the exoskeleton limits often related to the general high level of complexity of the structure, mechanism and actuation. We describe the mechanical design of the index finger module, the dynamic model and some preliminary experimental results.

I. Introduction

Stroke is the leading cause of morbidity and mortality for both adult men and women in Europe Union countries and medical and social care consume considerable healthcare resources [1] in terms of both health care costs (hospital care, nursing, and home assistance) and indirect costs due to inactivity that increase the burden both for families and society [2]. Therefore, in the recent past, potentialities of robot-mediated therapy have been exploited in order to try to partially solve such problems.

A study to evaluate the needs of chronic stroke patients was performed recently [3] and its results show that the most desired function to recover is the hand ability because of the need to perform again the Activities of Daily Living (ADL).

The main impairments of an hemiparetic hand are: weakness of specific muscles, abnormal muscle tone (spasticity), lack of mobility, abnormal muscular synergies, loss of interjoint coordination, reduced Range Of Movement (ROM), reduced finger independency and closed position [4]. In order to recover such impairments, a useful device for the rehabilitation of the hand should independently assist the motion of each finger through dedicated finger exercises, training a safe and controlled extension of each joint in order to improve their

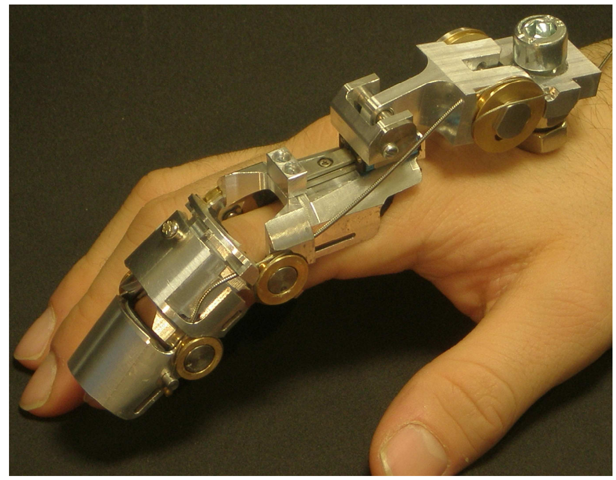

Fig. 1. Overview of the HANDEXOS index finger module.

ROM. From this point of view exoskeletons better suite for execution of the correct rehabilitative motor practice because of their functional advantages: the human machine interface is extended to the entire hand so that the trajectories of all the exoskeleton's joints are as much as possible coincident to that of the natural limb in the operational space and in the joint space allowing an accurate and repeatable finger motion joint by joint. So we are developing a novel exoskeleton device for the rehabilitation of the hand, HANDEXOS, with a first focus on independently practising the 5 fingers in order to return not only flexibility and coordination but also the ability to perform more complex movement patterns related to ADL tasks. More in detail, its design has been conceived in order to enable the activation of all the degrees of freedom (DOFs) of the human finger with a natural ROM and to achieve requirements as low encumbrance, light weight, comfort and good wearability.

This paper is organized as follows. Section II describes the mechanical design of HANDEXOS and the main features of the first prototype. The finger dynamic model is then presented in Section III, whereas some very preliminary experimental tests are reported in Section IV.

II. Methods and Mechanical Design

A. Biomechanical modeling

A wearable robotic system is physically coupled with the

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human hand, so an exoskeleton design has to be based on the human model in terms of biomechanics. To design a wearable mechanism compliant to the human hand movement is a great challenge because of the complexity of the hand's structure. Each finger allows 4 DOFs: from the distal phalanx there are 1 DOF per DIP (Distal Interphalangeal) and PIP (Proximal Interphalangeal) joints allowing their flexion/extension and 2 DOFs per MP (Metacarpo-Phalangeal) joint allowing both its flexion/extension and abduction/abduction. The thumb, instead, allows 6 DOFs and the opposition motion that is fundamental for human dexterous manipulation. So, in addition to IP (Inter-Phalangeal) and MP joints that allow the flexion/extension of the thumb, also the CM (Carpo-Metacarpal) joint allows the flexion/extension, the abduction/adduction and the thumb opposition motions simultaneously. One of the main features of HANDEXOS is to try to enable fully mobility of the hand with a natural ROM and, for that, the number of DOFs is similar to that of the natural hand skeleton. Moreover we tried to keep the design criteria as general as possible in terms of size: average values of 51mm, 26mm and 25mm have been chosen for the index finger from the proximal to the distal phalanx, but HANDEXOS has been designed in order to partially fit over hands of different sizes through a passive and adjustable mechanism on the intermediate phalanx (Fig. 1,3).

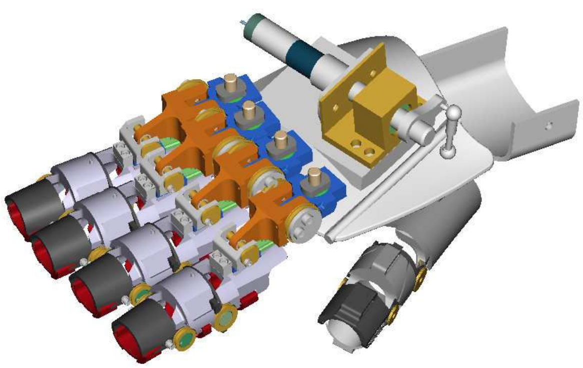

Fig. 2. HANDEXOS concept.

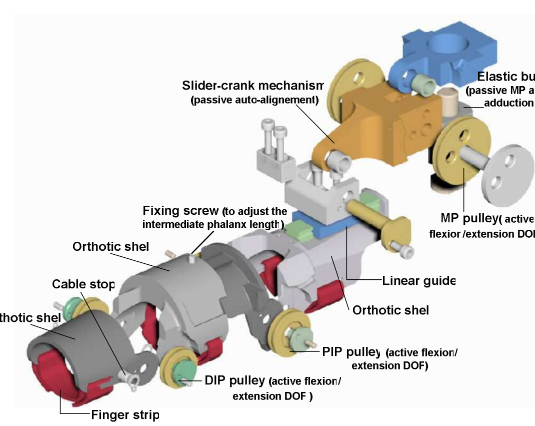

Fig.3. Finger mechanism, exploded view.

B. *Finger mechanism*

HANDEXOS is characterized by 5-fingers independent modules (Fig. 2), low encumbrance both on the lateral side of the fingers and on the upper and lower side of the hand to allow an easy wearability, light weight, comfort, low inertia, adjustable size to be adaptable to different hands and an extrinsic actuation system.

The entire mechanical design of HANDEXOS is patent-pending [5]. More in detail, the exoskeleton is composed of an external backing element applicable on the dorsum of the wearer's hand, and shell-like elements applicable on each phalanx and connected each other by translational and rotational joints (Fig. 3,4).

So, each finger is provided with three active rotational joints (flexion/extension), one passive rotational joint (abduction adduction) and one passive translational joint (kinematic coupling of the human/exoskeleton MP axes).

Six pulleys, two for each joint, are placed on both sides of HANDEXOS finger module in correspondence with the wearer's rotational joints. Such active joints are used for flexion/extension of DIP, PIP and MP joints; moreover the MP joint has been provided with a rotational passive joint obtained through elastic bushing for the abduction/adduction (Fig. 3,4). Moreover a passive translational joint acting on the proximal phalanx provides the needed kinematic compatibility between human and exoskeleton's MP rotational axes; as shown in figure 5, such passive mechanism is fundamental, indeed, to enable the MP joint to cover its entire ROM with no constraints. For the same purpose, a compliant orthesic

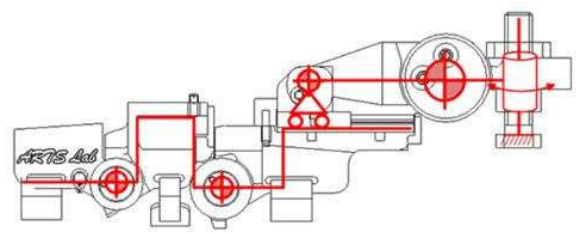

Fig. 4. Kinematics of a finger module.

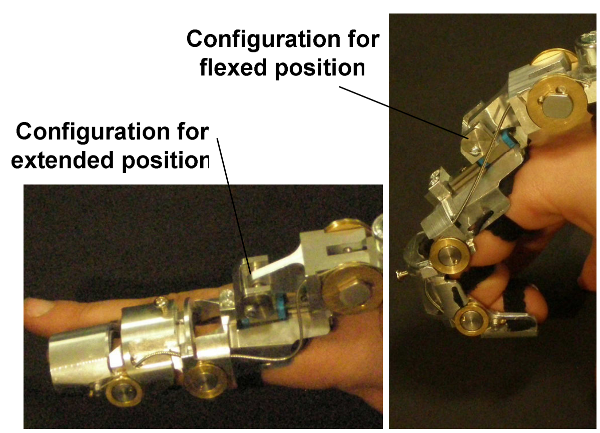

Fig.5. Auto-aligning translational joint in extended and flexed configuration.

material that fits the human finger anatomy has been placed inside each shell in order to ensure the kinematic compatibility also for PIP and DIP joints. For these two joints, indeed, the compliance of the inner material has been proved to be enough to ensure the alignment between the hand and exoskeleton rotational axes. Furthermore HANDEXOS has been designed in order to keep the palm area and each fingertip free, in order to enable the subject to interact with objects and to exploit tactile feedback. Moreover we are designing a thumb module to follow thumb opposability as it is required in dexterous object manipulation. Thumb kinematics is particularly complex because its complete motion can be described through five rotational axes: IP joint has a flexion-extension axis, whereas the MP and CM joints have a flexion-extension and an adduction-abduction axis. More precisely CM joint has a third degree of freedom that is the axial prono-supination that is not independent from the flexion-extension and adduction-abduction angles but all simultaneously operate to obtain the so called thumb opposability [6]. So, in order to simplify such kinematics, the MP adduction-abduction motion is removed, whereas the flexion-extension of the IP and MP joints will be provided. The CM joint opposability is achieved through an additional slider-crank mechanism (Fig. 2) placed on the dorsum of HANDEXOS (in order to preserve the palm area free) directly actuated by an on-board DC motor powering the thumb in order to approach the palm approximately following the thumb opposition motion.

The first HANDEXOS finger module (Fig. 1) has been made of Aluminium alloy (Ergal) and its weight is 114.9 g. It's however important to point out that more than half of such weight (64.3 g) is concentrated in the proximal slider-crank mechanism (Fig.1) and such weight will be totally discharged on the palm module (under fabrication) where the exoskeleton finger will be fixed. Finally the overall perceived weight on the index finger is very low (50.6 g).

C. *Actuation system*

One of the main design goals of HANDEXOS is the activation of each DOF of the human finger in order to enable a natural ROM. An underactuated mechanism has been used to match this requirement with low overall size and light weight. Such solution, indeed, allows to have lower number of actuators than DOFs. Another advantage coming from the underactuation choice is the possibility to passively adapt each finger to the generic shape of the grasped object (selfadaptation) because the geometric configuration of each phalanx is simply determined by the external constraints due to the particular shape of the object without the necessity to actively coordinate all the phalanges [7].

More in detail each finger module of HANDEXOS is actuated through a Bowden cables transmission, so only one DC motor is used to extend the DIP, PIP and MP joints. Such cable transmission choice is critical especially for its intrinsic friction losses but it is necessary in order to develop a wearable system with low inertia and a remote actuation. Each finger is actuated by a cable running across idle pulleys placed in each finger joints and fixed to the distal phalanx through a cable stop. The cable is pulled through a linear slider by a DC motor placed extrinsically. The flexion of the finger is passively obtained by means of a set of three (one for each joint) antagonist cables running across the pulleys placed on the other side of the finger, connected to three extrinsic linear compression springs whose elastic torques cause the finger to flex (Fig. 6).

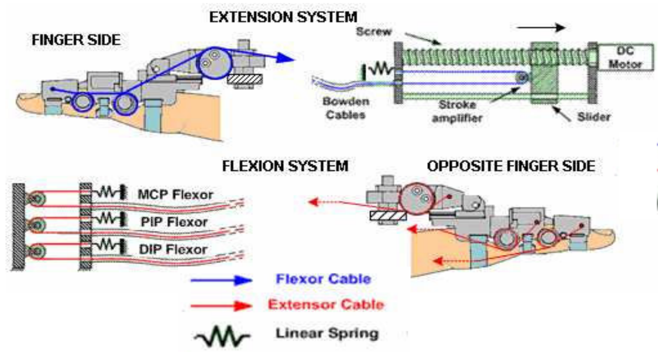

Fig.6. Underactuation with linear springs.

The underactuation solution is not the only possible actuation strategy: HANDEXOS, indeed, has been designed on purpose in order to implement different actuation/transmission solutions, from the independent joint actuation to the underactuation. So a study [8] that is beyond the scope of this paper, has been carried out in order to analyze and compare two different actuation strategies both allowed by HANDEXOS: independent joint actuation with series of non linear springs and underactuation with series of linear springs. Both the strategies have been tested through a dynamic simulator that we have implemented in LabVIEW® environment (*National Instruments LabVIEW 8.2*) including the modelling of the biomechanics of the human finger, the mechanics of HANDEXOS finger modules, the mechanics of the human/exoskeleton interface and the specific actuation/transmission system. The derived performances for both the actuation solutions are similar, but for rehabilitation purposes, the underactuation solution better suite for the low encumbrance and weight requirements.

So it is the goal of this paper to present a preliminary study on the underactuation strategy, from the dynamic modelling of an underactuated HANDEXOS finger module to some preliminary experimental results.

III. FINGER DYNAMIC MODEL

The development of the dynamic model of the HANDEXOS finger module allowed the simulation of the extension motion in the sagittal plane and the optimization of the mechanical design. More specifically, the dynamic behaviour of a standard human finger inside the exoskeleton finger module has been explored through the Lagrange model of a three-links planar manipulator [9]. The direct dynamics problem has been solved determining the joints accelerations ($\ddot{q}$) then the velocities ($\dot{q}$) and positions (q) resulting from the given joint torques (τ) and the three external forces, applied to each phalanx, representing the resistance forces due to the muscular spasticity, once the initial positions and velocities are known.

In fact spasticity, defined as a heightened velocity-dependent reflex response to stretch [10], causes a continuous contraction of the hand muscles of stroke patients that interferes with the normal hand posture. It contributes as a resistance to the extension of the fingers, so we have preliminary considered such resistant effect as three constant forces applied at the centre of mass of each phalanx with maximum values (from the proximal to the distal phalanx): F_1=10 N, F_2=6 N, F_3=3 N, as suggested by clinicians.

Because of the underactuation solution, the joints torques are coupled with each other by the same tension T through the following relations:

$$\tau_1 = \frac{r_1 T (l_1 \cos(\Theta_1) - h \sin(q_1))}{l_1 \cos(q_1)\cos(q_1 - \Theta_1)}$$

$$\tau_2 = r_2 T$$

$$\tau_3 = r_3 T$$

$$\Theta_1 = q_1 + \frac{\arcsin(-d\cos(q_1) - h)}{l_1} \qquad (1)$$

where Θ_1 (derived from the particular geometry), l_1 (0.029 m), h (0.0124 m), d (0.0139 m) and q_1 are reported in Fig. 7; whereas r_i (i=1;3 from MP to DIP joint) is the pulley radius and T the cable tension whose variation respect to time has been assumed to be of the fifth order (Fig. 8) with an initial value of 63.11 N and a final value of 147.95 N (evaluated through the static equilibrium of the distal phalanx with an initial position q_3=1.2 rad and a final position of 0 rad).

The equations of motion of the finger module (considering the effect of gravity and friction) can be written in a compact matrix form which represents the joint-space dynamic model as:

$$B(q)\ddot{q} + C(q,\dot{q})\dot{q} - F_v\dot{q} + g(q) = -\tau + Kr^2(q_0 - q) + J_1^T(q)H_1(q) + J_2^T(q)H_2(q) + J_3^T(q)H_3(q) \qquad (2)$$

where:

- $q, \dot{q}, \ddot{q}$ are the (3x1) joint position, velocity and acceleration vectors, respectively;
- $B(q)$ is the (3x3) joint inertia matrix;
- $C(q,\dot{q})$ is the (3x3) matrix of centrifugal and Coriolis torques;
- F_v is the (3x3) matrix of viscous friction coefficients;

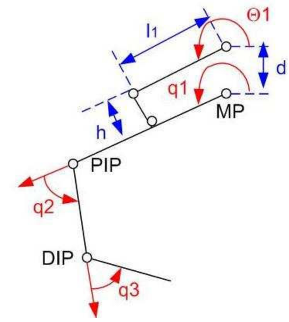

Fig.7. HANDEXOS finger scheme.

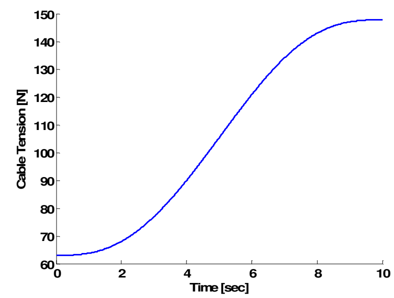

Fig. 8. Cable tension.

- g is the (3x1) gravity vector;
- τ is the (3x1) vector of the actuation torques;
- K is the (3x1) vector of spring stiffness coefficients;
- r is the (3x1) vector of the pulley radii;
- q_0 is the (3x1) vector of the spring rest positions;
- J_i is the (6x3) matrix of geometric Jacobian evaluated in the resistant force application points;
- H_i is the (6x1) vector of forces and moments exerted by the resistant forces on each link.

In equation 2, the contribution of spasticity is considered through $J^T_i(q)H_i(q)$ derived from the *virtual work principle* [9] that allows the determination of the relationship between the generalized forces applied to the joints and the generalized forces applied to the links.

Simulation analysis has been carried out to iteratively optimize the mechanical design in order to best fit the behaviour of the human finger with the desired trajectories deriving from an healthy hand extension motion. So several simulation trials with different mechanical parameters have been tested in order to iteratively define an accurate set of parameters for the prototype, finally resulted in the following values: $q_3 \in$ [0, 1.2] rad is the range of variation of the distal joint; K = [9370 9270 13960]^T N/m are the spring stiffness coefficients whose values have been chosen from the catalogue in order to be close to the values calculated with the simulation; r_1=9x10^{-3}m, r_2=6x10^{-3}m, r_3=5x10^{-3}m are the pulley radii and q_0 = [3.6 2 2]^T rad are the spring rest position. Preliminary simulations results for a slow (10 seconds) extension task, together with the required motor torque are below.

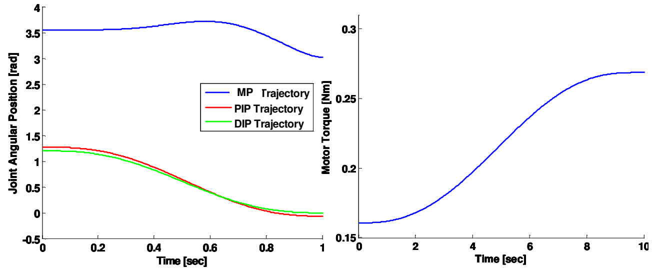

Fig. 9. Joints trajectories and motor torque.

IV. PRELIMINARY EXPERIMENTAL RESULTS

In this section we are going to describe the very preliminary experiments that we have performed with the first prototype of the exoskeleton index finger in order to firstly verify its wearability and kinematic coupling with the wearer's hand and secondly to test the underactuation solution in terms of enabled ROM.

Such preliminary experiments have been carried out respectively in passive (the wearer actuates the passive exoskeleton) and active modality while recording joints trajectories. Due to the absence of sensors on the joints of the first prototype, joint trajectories have been recorded by means of the OPTOTRAK Certus system (Fig.10) which is an infrared optical device for movement analysis.

Firstly, the joints trajectories of the index finger (without wearing HANDEXOS) have been recorded from an healthy subject while performing a natural extension task from a flexed to an extended position. Such trajectories represent both the reference for the evaluation of the performances of the device and the ideal ROM for the rehabilitative practice. Four active infrared miniaturized markers have been then placed on MP, PIP, DIP joints and on the end of the distal phalanx (Fig. 10) in order to record the angular position of each phalanx as shown in figure 11. Moreover other three active markers have been placed on a supporting base in order to refer the joint motion to a unique reference frame (Fig. 10,11). The reference joint angles over time have been then calculated from the acquired marker coordinates with an acquisition rate of 30 Hz as shown in figure 12.

Then, the same markers have been placed on the exoskeleton index module in correspondence with the MP, PIP and DIP rotational axes of the hand and on the end of the distal orthotic shell as shown in figure 13. The reference frame has been then placed on a preliminary mechanical support to maintain HANDEXOS fixed. Exploiting such set-up, the first experiment has been performed in order to evaluate the HANDEXOS wearability: an healthy subject was asked to perform a 10 seconds natural extension motion from a closed position of the hand. The acquired joints trajectories (acquisition rate of 30 Hz), are reported in figure 14. As we can see, the ROM enabled for each joint by the exoskeleton is approximately the same with the reference (Fig. 12); this means that HANDEXOS ensures the right kinematic compatibility with the wearer's finger. The slight observable differences between the trajectories reported in figure 12 and

Fig. 10. OPTOTRAK Certus system and the experimental set-up.

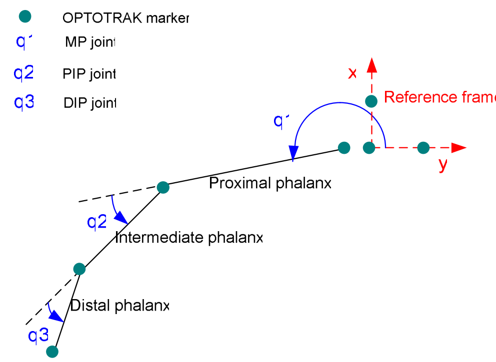

Fig. 11. Schematic drawing of the phalanges, joint angles, markers and reference frame.

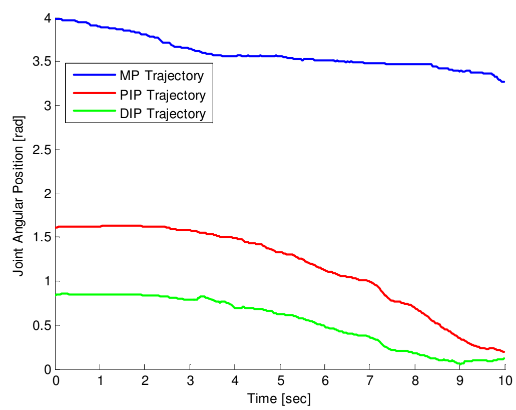

Fig. 12. OPTOTRAK recordings during an extension motion of an healthy hand without wearing HANDEXOS.

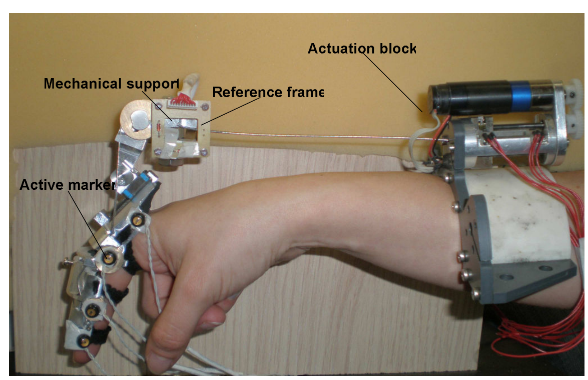

Fig. 13. Experimental set-up for exoskeleton joints trajectories recordings.

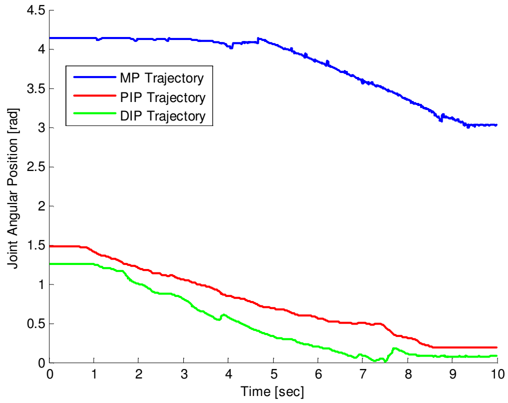

Fig. 14. OPTOTRAK recordings during an extension motion of the HANDEXOS index module in passive modality.

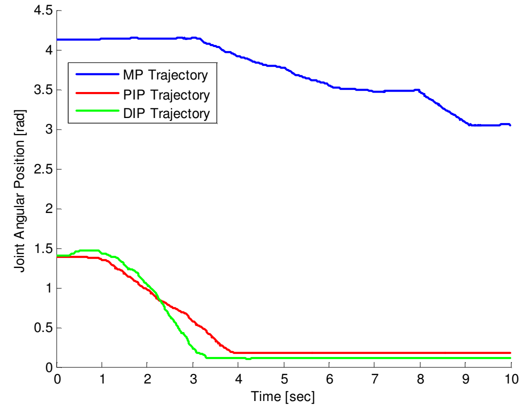

Fig. 15. OPTOTRAK recordings during an extension motion of the HANDEXOS index module in active modality.

14, very likely depend on the natural human hand variability in performing non externally controlled motor tasks as well as on the absence of the HANDEXOS palm module (Fig. 13), currently under fabrication, that will allow the human MP rotational axis to be rightly aligned with the exoskeleton one.

Then the same experimental set-up has been exploited also to perform the second experiment in order to test the underactuation solution: an healthy subject was asked to be completely passive allowing HANDEXOS to extend his finger. In this preliminary test one DC motor (Faulhaber Minimotor 1727 U006C) activated the MP, PIP and DIP joints through an extensor cable fixed on the distal orthotic shell of the exoskeleton, while flexion was not provided by the device because no flexion cables and springs were included in this preliminary experimental set-up (Fig. 13). This is the main reason why such recorded data can not be compared with those ones obtained through the dynamic model presented in the previous section. However, as we can notice in figure 15, the ROM is very similar to the previous experiments but, as a consequence of the underactuation solution and the absence of the fixed palm support to which the hand can be constrained, the proximal phalanx remained in the same position during the first part of the task, while the proximal and distal phalanges first initiate the motion. Such result, however, has no consequences in terms of wrong or uncomfortable motion.

Then we can conclude that underactuation can be a good solution both for low encumbrance requirement and to enable the desired ROM. However the first finger module needs to be tested together with the palm support in order to properly evaluate its performances.

V. Conclusion

This paper presented a preliminary study on a finger module of a novel exoskeleton device for the rehabilitation of the hand. Because of its design, HANDEXOS will allow the independent actuation of all 5 fingers, low overall size, light weight and a proper kinematic coupling with the human fingers. Moreover HANDEXOS preserves the palm area and each fingertip free so that the patient can directly interact with ADL objects while exploiting tactile feedback.

Next planned work counts to exploit the device as an interface for biomechanical assessment of a post stroke hand, with the final aim to develop a proper model of spasticity to be used to refine and test the dynamic model presented in Section III.

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