Design of a hand exoskeleton (HANDEXOS) for the rehabilitation of the hand

A. Chiri, F. Giovacchini, S. Roccella, E. Cattin, N. Vitiello, F. Vecchi, M.C. Carrozza

***Abstract*—This paper presents a novel exoskeleton device 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 our goal is to train a complete opening movement from a strongly contracted and closed position of the impaired hand.**

The mechanical design, based on the underactuation solution, offers the possibility to overcome the exoskeleton limits deriving from the general high level of complexity of the structure mechanism and actuation.

We motivate and describe the underactuation choice. Moreover we detail the dynamic model and the analysis of the finger module.

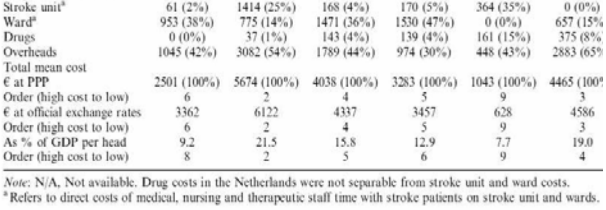
I. INTRODUCTION

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]. Recent studies showed that in Italy there are 194000 new stroke cases every year and about 30% of them survive with important motor deficits. This signifies a continuous increase in 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]. The results of a recent study about the hospital costs of care for stroke in some European countries are reported in Table 1 [1].

One of the direct consequences of this steady growth in expenses for medical care and rehabilitation is that stroke patients are receiving less therapy and going home sooner. The ensuing home rehabilitation is often self-directed with little professional or quantitative feedback [3] so often patients are forced to go to the specialized rehabilitative centres to continue their physical rehabilitation for a period that could last also several months. That is not the only problem related to the classical therapeutic practice but some other correlated negative aspects could be reported: occupational therapy is labor-intensive both for therapists and patients; classic rehabilitation is limited by subjective observations of therapists and impossibility to set reproducible measurements; impossibility to quantitatively monitor the progresses; no remote monitoring or re-evaluation of progress for a patient practising at home. In this scenario robotic devices try to overcome all the previously reported conventional therapy problems trying also to promote and accelerate functional recover of those capabilities compromised by cerebral damages, exploiting the intrinsic neural plasticity [4] through an intensive, active and repetitive movement. In fact an intense movement of an affected hand after stroke is associated with increased activation of ipsilateral motor cortical areas [5], suggesting that these motor areas in the undamaged hemisphere may adaptively compensate for damaged or disconnected regions. Therefore, in the recent past, potentialities of robot-mediated therapy have been exploited not to replace the clinician work but just to help it both to 'dose' a more accurate and repeatable therapy and both to quantitatively evaluate the outcome of the patient.

A study to evaluate the needs of chronic stroke patients was performed recently [6] and its results show that the most desired function to recover is the hand ability because of the necessity to perform again the Activities of Daily Living (ADL). But this is also one of the most difficult impairment to recover, infact just 5% of the stroke-survivors totally recover hand functionality. The main impairments of an hemiparetic hand are: weakness of specific muscles, abnormal muscle tone (spasticity), abnormal posture adjustments, lack of mobility, incorrect timing of movements, abnormal muscular synergies, loss of interjoint coordination, loss of sensation, reduced Range Of Movement (ROM), reduced finger independency, closed position and incapability to maintain a constant grip force.

In this paper we present an exoskeleton device conceived to achieve the important goal of recovering hand functionalities. In this case the human machine interface is extended to the entire hand so that the trajectories of all its 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



	Denmark	England	France	Germany	Hungary	Italy
Diagnostic procedures	443 (18%)	366 (6%)	467 (12%)	471 (14%)	69 (7%)	550 (12%
Stroke unit[a]	61 (2%)	1414 (25%)	168 (4%)	170 (5%)	364 (35%)	0 (0%)
Ward[a]	953 (38%)	775 (14%)	1471 (36%)	1530 (47%)	0 (0%)	657 (15%
Drugs	0 (0%)	37 (1%)	143 (4%)	139 (4%)	161 (15%)	375 (8%
Overheads	1045 (42%)	3082 (54%)	1789 (44%)	974 (30%)	448 (43%)	2883 (65%
Total mean cost						
€ at PPP	2501 (100%)	5674 (100%)	4038 (100%)	3283 (100%)	1043 (100%)	4465 (100
Order (high cost to low)	6	2	4	5	9	3
€ at official exchange rates	3362	6122	4337	3457	628	4586
Order (high cost to low)	6	2	4	5	9	3
As % of GDP per head	9.2	21.5	15.8	12.9	7.7	19.0
Order (high cost to low)	8	2	5	6	9	4

Note: N/A, Not available. Drug costs in the Netherlands were not separable from stroke unit and ward costs.
[a] Refers to direct costs of medical, nursing and therapeutic staff time with stroke patients on stroke unit and wards.

Table. 1. Mean cost of stroke in some European countries according to category of resource use (in Purchasing Power Parity).

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A. Chiri, F. Giovacchini, S. Roccella, E. Cattin, N. Vitello, F. Vecchi, M.C.Carrozza, are with ARTS Lab Scuola SuperioreSant'Anna, Pisa, Italy (e-mail: {a.chiri, f.giovacchini, s.roccella, e.cattin, n.vitiello, f.vecchi }@arts.sssup.it, {carrozza}@sssup.it).

repeatable finger motion joint by joint. From the state of the art exoskeleton devices show limits often due to the high level of complexity of the structure, mechanism and actuation, the weight, the unsafe coupling with the human hand, and the low aesthetic acceptability.

So this paper presents the design and development of an exoskeleton robotic device for post-stroke rehabilitation of the hand conceived to combine a good usability, aesthetics, safety and comfort with innovative technologies. The paper is structured as follows: section II briefly presents some aspects of the underactuation solution and a description of the mechanical design; section III presents the implementation of the dynamic model of the finger module and the preliminary simulation results, and section IV briefly discusses the ongoing work.

II. DESIGN OF HANDEXOS

A. *Underactuation solution*

In stroke patients the ability to extend the fingers, in order to perform grasping and releasing functions, is slow and difficult to recover. It is also one of the most important functions to perform again Activities of Daily Living. Several operative machines have been developed to help patients to train opening and closing movements of the hand also simulating interaction with daily living objects, but the advantage of our exoskeleton is the possibility to train each finger independently through dedicated finger exercises. One of the designing goals of HANDEXOS is the activation of all the degrees of freedom of the human finger in order to allow a natural range of motion. To match this request with a low encumbrance and light weight necessity, the underactuation solution [7] has been adopted in order to have lower number of actuators than degrees of freedom. More in detail we have designed the exoskeleton so that each finger is activated by one only motor. An important advantage coming from this solution is the possibility to passively adapt each finger to the generic shape of the grasped object because the geometric configuration of each phalange is simply determined by the external constraints due to the particular shape of the object without the necessity to actively coordinate all the phalanges. In fact in rehabilitation the simultaneous joints activation to exercise particular grasp functions is preferred to singular joints activation because of its rehabilitative effectiveness.

As a consequence of the underactuation solution a therapy session by using HANDEXOS could be planned so that patients can interact with real objects of ADL tasks such as a glass, a bottle or a pen (exploiting the free palm area of HANDEXOS) maximizing motor recovery through intense motor exercises based on voluntary movements, set in a context of daily activity life.

B. *Mechanical design*

HANDEXOS will be characterized by 5-fingers independent modules (Fig 1), good wearability, comfort, low encumbrance, light weight, low inertia and a remote actuation and control system.

HANDEXOS is composed of orthotic shell structures connected by translational and rotational joints. Passive translational joints are used in phalange joints for auto-fitting and ensuring kinematics compatibility with the human fingers. Rotational joints are used for flexion/extension in Distal Inter Phalangeal (DIP) and Proximal Inter Phalangeal (PIP) joints and in Metacarpo Phalangeal (MP) joints for abduction/adduction and flexion/extension (Fig 2).

In DIP and PIP joints the joint axes correspondence is obtained through a material that fits the human finger anatomy placed inside the shell. In the case of MP joint there is an auto-aligning passive joint (abduction/adduction) obtained through elastic bushing and there is an auto-fitting (flexion/extension) joint obtained through a slider-crank mechanism.

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 adopted actuation solution is an active and controlled extension of the fingers and a return in the closed position through passive springs. More specifically, each finger is underactuated through a Bowden cables transmission, so only one DC motor is used to extend the DIP, PIP and MP joints. Each finger is actuated by a cable running across idle pulleys placed in each finger joints and fixed to the distal phalanx. This configuration is similar to that of the *Extensor Digitorum*

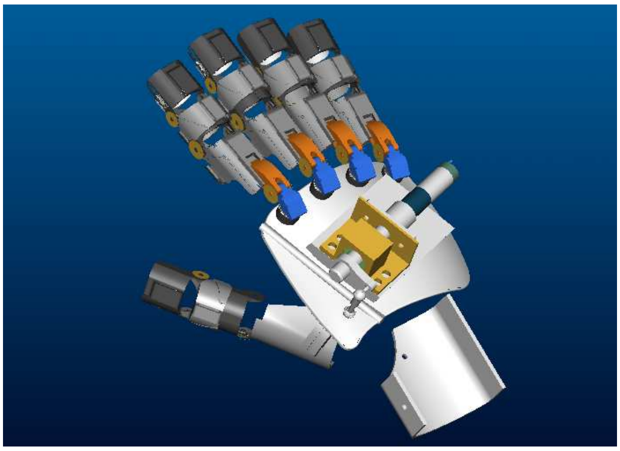
Fig. 1. Design of HANDEXOS.

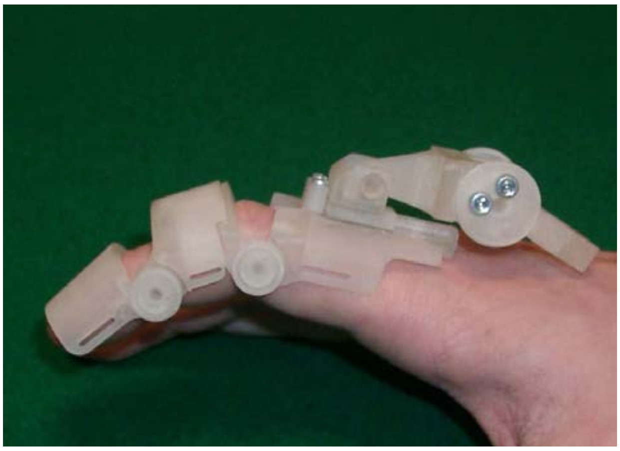
Fig. 2. Mock-up of the finger module (first prototype).

Profundus in the human hand.

The cable is pulled through a linear slider by a DC motor placed far from the device. The flexion of the finger is passively obtained by means of a set of three (one for each joint) antagonist cables running across idle pulleys placed on the other side of the finger, connected to three remote compression springs whose elastic torques cause the finger to flex.

In order to control the thumb opposition an additional mechanism on the dorsum of the patient hand is under development.

III. FINGER DINAMIC MODEL

The development of the dynamic model of the HANDEXOS finger module allows the simulation of the motion and the optimization of the mechanical design. More specifically, the dynamic behavior of a standard human finger inside the exoskeleton finger module has been explored through the Lagrange model of a three-link planar manipulator [8].

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 phalange, representing the resistance forces due to the muscular spasticity, once the initial positions and velocities are known.

Post stroke patients are affected by a continuous contraction of the hand muscles (spasticity) that interferes with a normal hand posture. It's important to consider such effect because it contributes as a resistant effect to the opening of the hand; according to clinician suggestions we have considered this effect in terms of three different constant forces applied at the centre of mass of each phalange with preliminary values (from the proximal to the distal phalange) : F_1=10 N, F_2=6 N, F_3=3N (Fig. 3).

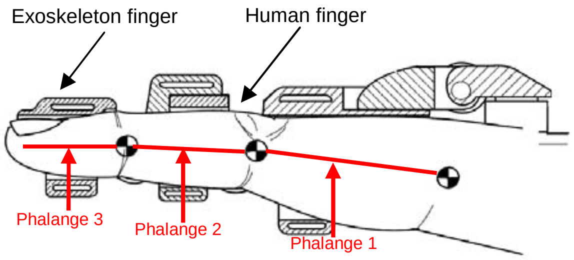

Fig. 3. Finger scheme.

Thanks to underactuation the joints torques are coupled each other through these relations:

$$\begin{aligned}\tau_1 &= r_1 T\\ \tau_2 &= r_2 T\\ \tau_3 &= r_3 T\end{aligned} \tag{1}$$

where r is the pulley radius and T the cable tension whose variation respect to time has been assumed to be of the fifth order (Fig. 4) with an initial value of 116.78 N and a final value of 227.32 N (evaluated through a static analysis of an initial position of the finger with q_3=90° and a final position of 0°, according to the *Denavit-Hartenberg Convention* [8]) derived from the following static equilibrium of the distal phalange

$$T = \frac{F_3 \cdot \frac{a_3}{2} + K_3 \cdot r_3^{\,2} \cdot (q_{03} - q_3)}{r_3} \tag{2}$$

where:

- F_3 is the resistant force acting on the distal phalange;
- K_3 is the stiffness of the spring acting on the distal phalange;
- q_{03} is the spring rest position acting on the distal phalange;
- q_3 is the current DIP joint variable.

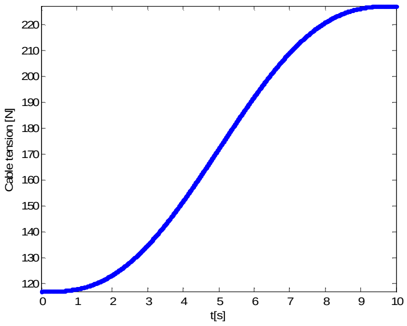

Fig. 4. Cable tension.

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

$$\begin{aligned}&B(q)\ddot{q} + C(q,\dot{q})\dot{q} - F_v\dot{q} + g(q)\\ &= -\tau + Kr^2(q_0 - q) + J_1^T(q)H_1(q) + J_2^T(q)H_2(q) + J_3^T(q)H_3(q)\end{aligned} \tag{3}$$

where:

- $q, \dot{q}, \ddot{q}$ are the (3x1) joint position (Fig. 5), 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;

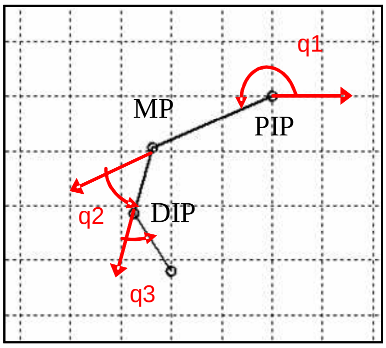

Fig. 5. Representation of the joint variables.

- F_v is the (3x3) matrix of viscous friction coefficients;
- 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 3 the contribute of spasticity is considered through $J_i^T(q)H_i(q)$ derived from the *virtual work principle* [8] that allows determination of the relationship between the generalized forces applied to the joints and the generalized forces applied to the links.

In order to develop the model of the exoskeleton finger it has been necessary to test several simulation trials with different mechanical parameters in order to iteratively define an accurate set of parameters for the prototype, finally resulted in the following values:

- $q_3 \in$ [0, pi/2] rad is the range of variation of the distal joint;
- K = [8600 10050 13940]^T N/m for spring stiffness coefficients whose values have been chosen from the catalogue in order to be close to the values calculated with the simulation;
- $r_1 = 9x10^{-3}m, r_2 = 6x10^{-3}m, r_3 = 5x10^{-3}m$ for the pulley radii;
- $q_{0i} = [\frac{3}{2}\pi, \pi, \pi]^T$ rad for spring rest position;
- $F_v = diag(-0.001,-0.001,-0.001)$ for viscous friction coefficients.

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 trajectory derived from the classical therapeutic practice.

Preliminary simulations results for a slow (10 seconds) extension task show a smooth and coordinate extension movement (Fig 6) whose initial and final position in the Cartesian plane are shown in figure 7; moreover cable tension (Fig 4) and power level reported in figure 8a and 8b, show a low power request respectively during a slow and fast (1 second) task so that a low encumbrance and light weight brushed DC motor can be used.

As described above, each finger is actuated by a DC motor moving a slider that transmits motion to the phalanges; more in detail three joints corresponding to the three phalanges are coupled in terms of dynamics through the relation 1 but also in terms of kinematics [9].

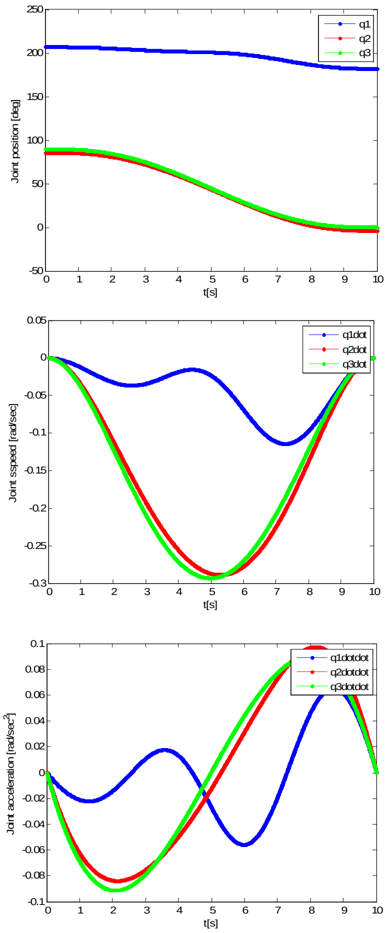

Fig. 6. Joints trajectories; joints velocities and joints accelerations.

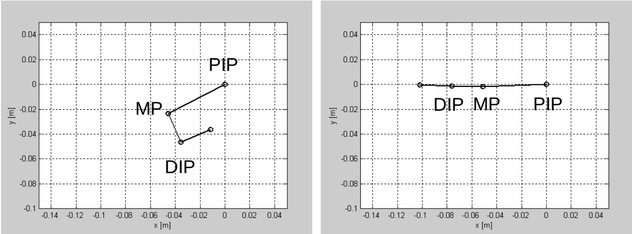

Fig. 7 Initial position of the finger in the Cartesian plane (left) and final position (right).

In particular kinematics coupling among the joints is related to the slider kinematics by the relation:

$$x_S = r_1(q_{10} - q_1) + r_2(q_{20} - q_2) + r_3(q_{30} - q_3) \qquad (4)$$
$$\ddot{x}_s = r_1 \cdot \ddot{q}_1 + r_2 \cdot \ddot{q}_2 + r_3 \cdot \ddot{q}_3$$

where:

- x_s is the slider displacement from the static equilibrium configuration (Fig 9);
- $\ddot{x}_s$ is the slider acceleration (Fig 10);
- q_{i0} = [3.61 1.50 pi/2]^T rad are the joint angles at time 0.

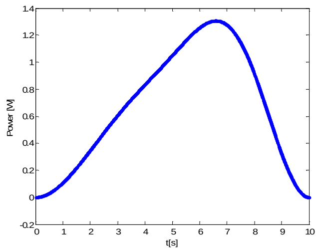

Fig. 8a Power requested to execute a slow task.

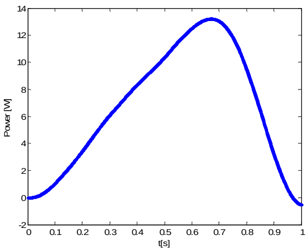

Fig. 8b Power requested to execute a fast task.

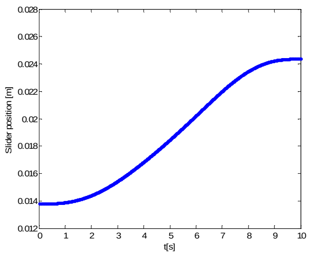

Fig. 9 Slider position (slow task).

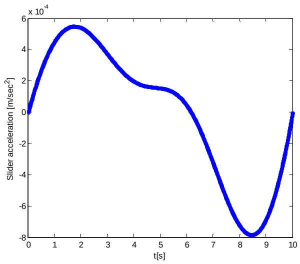

Fig. 10 Slider acceleration (slow task).

IV. CONCLUSION

This paper presents the design and development of a novel exoskeleton device for the rehabilitation of the hand whose requirements are:

- Low encumbrance
- Light weight
- Comfort
- Good wearability
- Actuation of all 5 fingers
- High participation and motivation during the rehabilitative practice.

Some of these goals have been satisfied through the underactuation solution so that all the degrees of freedom of each finger is actuated by one only motor.

The work specifically addressed the implementation of the dynamic model of an exoskeleton finger whose study has been reported in details in section III.

Moreover, in order to completely recover an impaired hand, a motion assist device should support thumb opposability. However, generally, the hand exoskeleton devices, analyzed from the current state of the art, do not adequately provide the correct thumb opposition because the human thumb has, in addition to Inter Phalangeal (IP) and Metacarpo Phalangeal (MP) joints that allow the flexion/extension of the thumb, also the Carpo Metacarpal (CM) joint that allows the flexion/extension, the abduction/adduction and thumb opposition motions simultaneously [10]. This thumb opposition is necessary for human dexterous object manipulation, but it is very difficult to assist such motion.

We are developing a thumb module that allows both flexion/extension of the IP and MP joints exploiting the same underactuation solution adopted for the other fingers and the thumb opposition forcing the CM joint to move so that the thumb approaches the palm; it is achieved through an additional mechanism set on the dorsum of the hand actuated by an additional DC motor.

Currently the HANDEXOS is under fabrication. The first prototype will be tested with post-stroke patients.

An intensive, active and repetitive practice by using HANDEXOS could maximize motor recovery and could reduce the muscular spasticity.

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