# A Portable Rehabilitation Device for the Hand

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# A Portable Rehabilitation Device for the Hand

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*Abstract*—**This paper presents the design of a direct driven under-actuated portable hand exoskeleton for rehabilitation. The design of the proposed Hand EXOskeleton SYStem (HEXOSYS) was driven by multi-objective optimisation strategy and inspiration from the human hand. The optimisation algorithm resulted in the choice of optimum link lengths of the device. The optimisation criteria are based on dexterity, isotropy and exertion of perpendicular forces on the finger digits. Furthermore, a series of experiments on the human hand using appropriate sensory instrumentation guided the selection of actuators thereby resulting in a rehabilitation device which is compatible with the human hand force capabilities. The provision of force as well as position feedback gives quantitative feedback to the therapist and would imply a more efficient rehabilitation process. The first prototype of the device has been designed and realized.**

## I. Introduction

AFTER hand injuries or strokes, rehabilitation therapy may be required to allow the hand to recover its strength and functionality. These therapy procedures are usually executed manually by physiotherapists or occasionally using simple passive assistive devices. There is an increasing feeling that alternative therapies using robotic hand exoskeletons or assistive devices could have considerable potential in improving the medical outcomes.

Many robotic systems specifically intended for hand rehabilitation have been reported in the literature. HANDEXOS designed at SSSA Italy is a 4 Degree Of Freedom (DOF)/finger underactuated system allowing the full range of motion for the fingers [1]. The wearable handling support system proposed by researchers at Tsukuba University permits tuning of the compliance using a bioelectric based switching control [2]. A 4 DOF exoskeleton built in Beihang University [3] uses cables as a transmission media. The rehabilitation device realized by researchers in TU Berlin [4] can actuate 4 DOFs of a finger by means of linkage mechanism. The system developed at Northwestern University [5] intended for rehabilitation of an index finger and provides 3 DOF. Researchers of University of Salford have proposed an exoskeleton exerciser [6] with a physiotherapy VR system where a patient performs physical and occupational therapy by interacting with a number of virtually simulated exercises. Other examples include exoskeletons developed by Gifu University [7] and Harbin Institute [8]. The former has 18 DOF and can be driven to actuate the impaired hand by the patient's healthy hand while the later is a portable Continuous Passive machine (CPM) which exerts perpendicular forces on the finger.

Looking on the abovementioned literature, it is evident that there is no existing hand rehabilitation device that encompasses following features:

- **Human hand compatibility:** The target of rehabilitation device is to assist a human, so the device should be capable of exerting and assisting daily hand motions as a normal healthy human hand does. Trying to match the human hand capabilities results in a device with a natural Range Of Motion (ROM) and force levels beyond.
- **Optimisation:** The design of such a system requires a multi-objective optimisation procedure which should account for all the device performance parameters.
- **Direct driven:** The kind of direct transmission is essential to avoid the continuous control of cable tensioning and problems of having intrinsic friction which are apparent deficiencies in devices that use cable transmissions. The direct transmission also offers other advantages in terms of force bandwidth and stiffness range.
- **Back-drivability and provision of bidirectional force:** Being aimed for rehabilitation, the device should essentially have these capabilities.
- **Portability:** A portable device can also have great potential as an assistive or prosthetic device.

## II. Design Concept

The design procedure of an exoskeleton includes proper choice of number of DOF, link lengths, type of actuators and sensors to provide the required functionality with adequate ergonomics. The desired requirements are reported in [9].

The proposed conceptual mechanism of one finger of Hand EXOskeleton SYStem (HEXOSYS) is shown in Fig. 1. It is a three links planar under-actuated mechanism having single attachment point. A single actuation unit used to power the device is located at the base of the proximal joint of the exoskeleton. Advantages of this type of system include the good ergonomics, low mechatronic complexity, portability and easy doming and removal. The negative impact on force feedback capability as a result of under-actuation has been reduced with the proper design optimisation which maximizes the vertical component of applied force.

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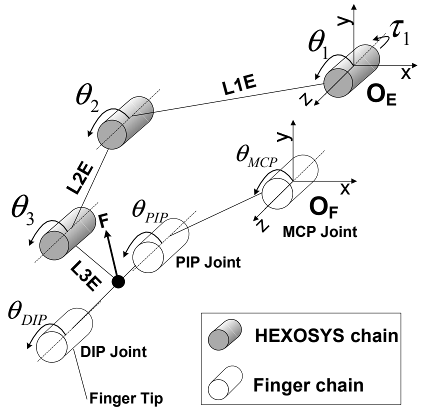



Fig. 1. Kinematic representation of HEXOSYS

## III. DEVICE OPTIMISATION

The first two links lengths of HEXOSYS have been selected as a result of optimisation algorithm while the length of the distal link (L3E) which serves as a connection link between the finger and the end-effector has been set to the minimum possible allowed by the mechanical integration (1cm).

The optimisation algorithm is based on multiple factors. These factors include Global Isotropy Index (GII) [10], Perpendicular Force Impact (PIF), kinematics mapping, physical angle constraints and worst case collision avoidance. The flow chart of the optimisation procedure is shown in Fig. 2. The angle range throughout the complete flexion-extension cycle has been given by developed anatomical finger model. This ensures the coverage of complete operational range of a human hand. The finger model has been discussed in [11]. The forward kinematics of the finger chain then calculates the position of exoskeleton attachment point (expressed in the finger frame $\mathbf{O_F}$). A homogeneous transformation maps this position in the HEXOSYS frame $\mathbf{O_E}$ (see Fig. 1). The next step is to choose and iterate a set of reasonable link lengths (4-8 cm). The inverse kinematics in the exoskeleton chain results in the required device angles to reach the attachment point. If a certain set of device link lengths satisfies the worst case collision avoidance condition, then further optimisation analysis (GII and PIF) is carried out.

The PIF is a measure of 'how much' of the exerted force is perpendicular to the finger phalanges. Using this factor the exoskeleton link lengths have been optimised to maximize the perpendicular forces during grasping. Another optimisation criterion is GII which gives worst case workspace dexterity and isotropy throughout the workspace [10]. It is a normalized performance measure which assigns a value of unity to perfect isotropy and a value of zero to singular behavior. Plots of PIF and GII as a function of exoskeleton link lengths are illustrated in Fig. 3.

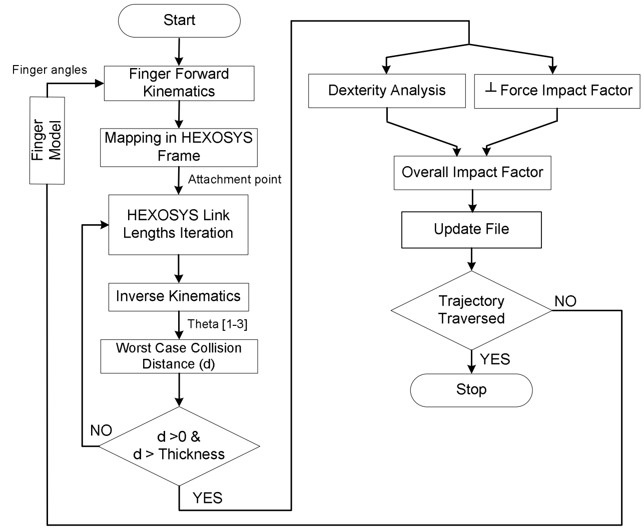
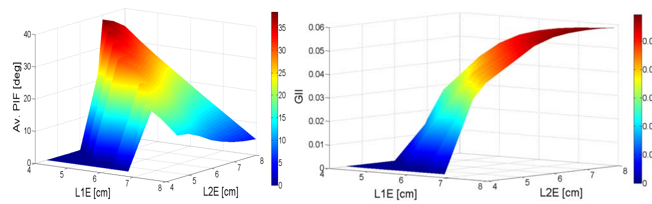



Fig. 2. Flowchart of HEXOSYS Optimisation algorithm




(a) (b)

Fig. 3. Surface plots of (a) average PIF and (b) GII as a function of exoskeleton link lengths

An Overall Impact Factor (OIF) has been then calculated by assigning equal priority to PIF and GII. OIF results as a function of exoskeleton link lengths are shown in Fig. 4. This plot shows that OIF is maximized in the region where proximal and middle exoskeleton link lengths are 8cm and 5cm respectively.

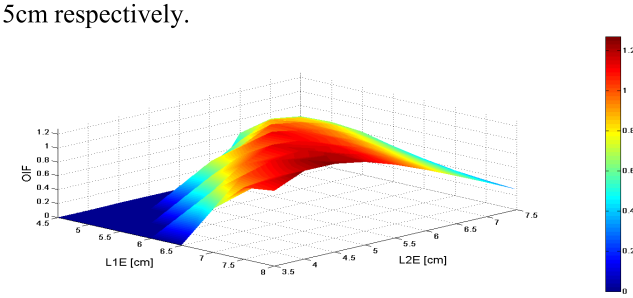



Fig. 4. OIF as a function of exoskeleton link lengths

## IV. DESIGN REQUIREMENTS

After having link length of the proposed device, the next step is to find the actuator specifications that ultimately make the device human hand compatible. An analysis of the most frequent daily life activities of the human hand has been carried to collect the necessary data for deriving the design requirements relevant to the system functionality. These requirements can be the necessary average or maximum exerted force levels and grip range of force. These ultimately can be mapped to lower level requirements such as actuation torque levels. To measure various parameters in the daily life activities, the subject's hand was sensorized using various devices including force sensors and load cell. Three healthy subjects each having small, medium and big hands participated in these experiments.

The first experiment aimed to record the force levels required to accomplish some usual grasping activities. The subjects were asked to grasp and manipulate the objects in the same way as they interact with them in their daily lives. The commercial FingerTPS™ (Tactile Pressure Sensors) have been used to measure the force exerted by the finger tips. Fig. 5 and 6 show the force profiles of two of such activities.

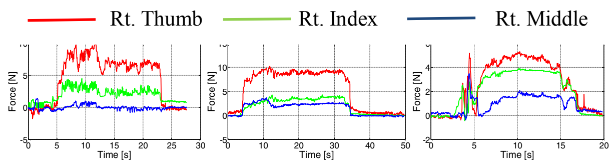


Fig. 5. Interacting a small object (writing with pencil) by a (a) Small (b) Medium (c) Big hand

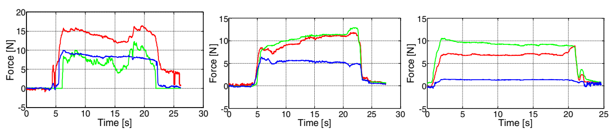


Fig. 6. Taking a big object (cup) by a (a) Small (b) Medium (c) Big hand

In our daily life usual activities, quite often we require comparatively higher force levels than those mentioned above. This motivated us to conduct second round of experiments to measure maximum force levels exerted by the fingers. These maximum levels give more realistic idea of the device actuator requirements. We have used ATI™ Nano25 load cell in this experiment. Fig. 7 shows the results in case of an index finger.

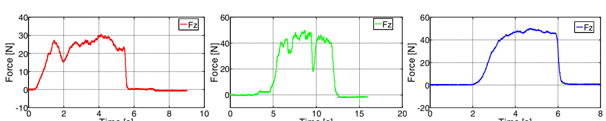


Fig. 7. Index finger maximum force levels in case of (a) Small (b) Medium (c) Big hand

The third experiment was intended to identify the force required to prevent slippage while sustaining an object of certain weight. In the first phase of this experiment, the weights can be seen by the subjects. However, there are times when we can grip objects without seeing them. This motivated us to have same experiment without visual feedback. A set-up consisting of a Futek™ LMD500 hand-gripper static force sensor together with a National Instruments (NI) DAQ board (USB6211) has been used in this experiment. Fig. 8 shows corresponding results.

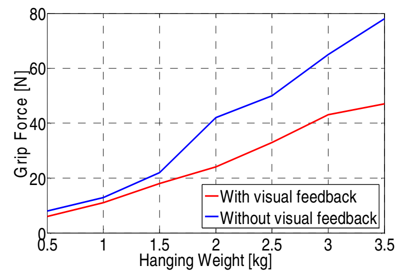


Fig.8. Grip range of forces

## V. Device Design

The device design followed the proposed 3-links direct driven under-actuated serial mechanism (Fig. 1) having a single attachment point with the finger phalanges and is conceived as the palm-free design. The single motor used for each of the finger actuates the proximal link, while the middle and distal links work as force transmission elements. The motors are capable of rotating around the vertical axis on ball bearings thereby allowing the finger abduction. The CAD model of the HEXOSYS prototype is illustrated in Fig. 9.

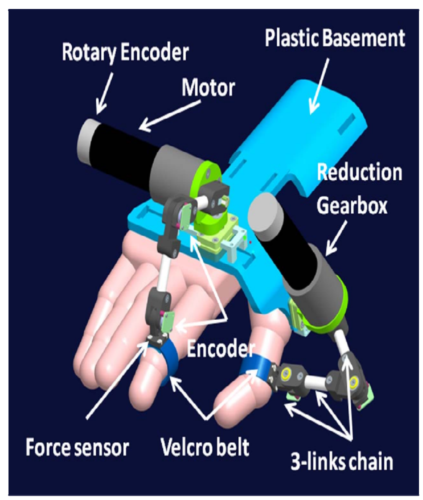
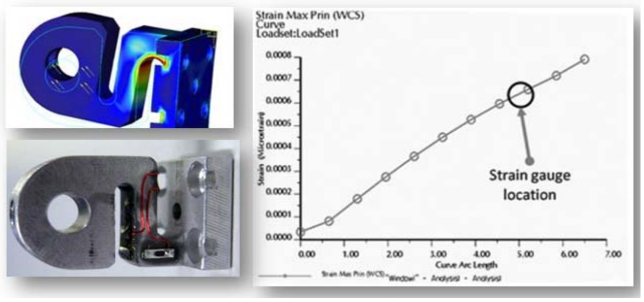


Fig. 9. HEXOSYS CAD model

The choice of actuators was based on the results of experiments on the human hand (Section IV). Two 20W Maxon RE-25 motors were chosen each with a combination of 14:1 ceramic planetary gearbox and a 1000 counts/turn optical encoder. The motors are capable of providing force levels for all activities requiring average force levels and for many activities requiring higher force levels as revealed by the motor characteristics and preliminary experimentation.

The sensory system mainly consists of two types of sensors: custom-made force sensor and position sensor. The force sensor (Fig. 10a) was integrated into the exoskeleton chain near attachment point. Both the load cells and the electronics were designed in-house for the purpose of size miniaturization. Finite element stress/strain analysis (10a and b) was used to optimise the dimensioning of the load cell structure and the selection of the strain gauge position.




(a) (b)

Fig. 10. (a) CAD and prototype of custom designed force sensor (b) Strain generated on force sensor when a load is applied to the load cell - load parameters (40N at 45° from the horizontal plane)

A DSP (56F807) based controller acting as server works with a dedicated notebook in client-server paradigm. This provides the flexibility to execute low-level as well as high-level commands. The firmware running on the board implements a closed-loop position control on the motor shaft.

The HEXOSYS prototype device together with its constituents mechatronics is shown in Fig. 11.

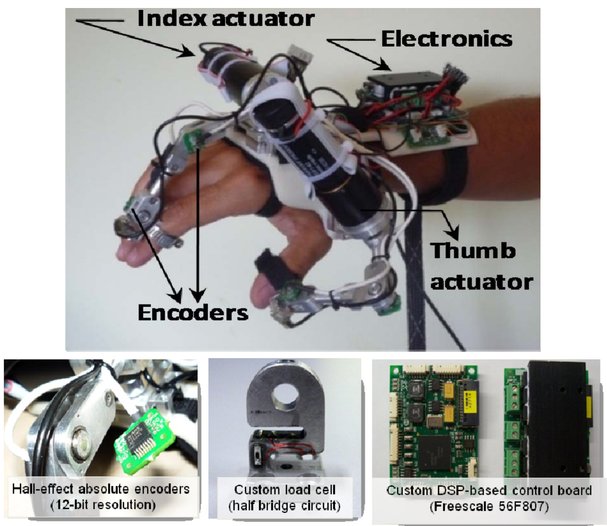



Fig. 11. The 2-fingers HEXOSYS proto-type and its mechatronic

## VI. CONCLUSION

A new portable hand rehabilitation device has been presented. The design is strongly backed by concrete computational and experimental synergies. The optimisation algorithm resulted in optimum link lengths while the experiments on human hand paved the way to choose actuators. Table I summarizes the main specifications of the proposed device. Currently the device is under in-house experimental trials. The next step essentially consists of clinical evaluation with the help of rehabilitation professionals.

The actuators for the prototype have been selected to provide high force levels. This was done to closely match the human finger force capabilities. However, targeting the average force measured levels, it is simple to replace the existing actuators with small motors reducing the overall size and weight e.g. replacing the existing motors (Maxon RE25) by Portescap 16G88-220P reduces the weight from 1Kg to 490g. This replacement results in force levels of 6N which is enough for many finger rehabilitation exercises requiring average force levels.

TABLE I
HEXOSYS MAIN PARAMETERS

| Symbol | Parameter | Value |
|---|---|---|
| DOF | Degrees of Freedom per finger | 4 (1 active) |
| $T_c$ | Actuator torque capability (stall torque) | 3.6Nm |
| $F_{max}$ | Maximum continuous force | 45N |
| $W_T$ | Total weight of the device | 1 Kg |
| $W_P$ | Weight of the device excluding actuators | 0.4 Kg |
| FSR | Force Sensor Resolution | 0.01N |

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