Design of a Wearable Direct-driven Optimized Hand Exoskeleton Device

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***Abstract*—This work introduces a hand exoskeleton that allows full range of motion and can exert bi-directional forces on the finger phalanges. The link lengths and structure of the proposed mechanism have been emerged as a result of kinematics-based optimization criteria. It is an under-actuated mechanism allowing 4 DOF/finger with one active degree. The selection of the actuator has been based on human hand capabilities to accomplish common daily life activities. An initial un-actuated finger prototype has been developed to analyze the mechanism functionality and to confirm the optimization results. Results have demonstrated that the device covers the complete operational range of motion of a human hand.**

Keywords-Hand exoskeleton System, Wearable robotics, Haptic device, Optimized robotic mechanism.

I. INTRODUCTION

Thanks to revolutionary trends in multidisciplinary areas of mechatronics and computing, realistic exoskeleton devices do exist. They are devices aiming to transmit kinaesthetic feedback at the level of the finger in order to emulate the constrains imposed by grasping of virtually or remotely manipulated objects. Exoskeleton based systems combine machine power and human intelligence to enhance human operator's capabilities as well as machine intelligence. Therefore, such systems have greatly improved to acquire the performance level which has not been possible otherwise. They are always designed as an external mechanical link structure and find potential applications in various areas including haptics, Virtual Reality (VR) and rehabilitation.

As the field of haptics evolved, the application of force feedback techniques in VR has become more demanding. Haptic interfaces have proven to be extremely useful during the interaction of users within virtual environment. Exoskeleton robotic devices make use of the haptic sense to enhance the presence impression by reproducing the contact forces on the wearer hand. Thus the use of such system improves the interaction with the virtual environment and increases the dexterity of the operator with the virtual objects. Such interfaces can be classified into grounded and portable devices. Grounded devices can only simulate fixed objects because they limit the range of the operators' freedom of motion. For pseudo-natural interactions, portable haptic devices are used because they provide more flexibility in terms of operator's freedom. However they can simulate fixed forces only when employed with a grounded device.

Considering the domain of rehabilitation, theraphy procedures are usually required to regain the normal hand strength and capabilities. In past, such procedures were executed manually by physiotherapists. Occasionally simple passive assistive devices have been employed to aid in rehabilitation. However technological revolution has evolved robotic hand exoskeletons that may be used in rehabilitation to improve the medical outcome.

This paper is structured as follows: Section II explains the related work while Section III highlights brief design details including goals and device mechanism. Section IV deals with the design optimization of the proposed device while Section V introduces design requirements, Section VI presents the details of preliminary and final prototype, and finally, Section VII comments on the conclusion.

II. RELATED WORK

The development of a hand exoskeleton device is a very challenging endeavor, which has been targeted by many research professionals. A multi-phalanx hand exoskeleton consisting of four fingers that was able to exert forces on each phalanx of each finger was developed at PERCRO lab [1]. Few years later, researchers at Keio University realized a three fingers non-isomorphic device actuated by passive clutches [2]. Springer and Nicola at the University of Wisconsin have presented a 1-finger prototype utilizing a planar four-bar linkage. They analyzed the haptic effect perceived by the user [3]. A 2-finger hand exoskeleton intended for VR grasping simulation, having 3 Degree Of Freedom(DOF)/finger and 4 for the thumb has been developed by Stergiopoulos [4]. Lelieveld *et al.* proposed a 4 DOF portable wearable haptic interface with active and passive multi-point feedback for the index finger in master-slave configuration [5]. Another hand exoskeleton developed at PERCRO intended for haptic interaction in virtual environment has 3 DOF/finger and can exert controlled forces on the finger tips [6]. A under-actuated 2-

finger hand exoskeleton has been conceived by researchers at IIT. It consists of an optimized Revolute-Revolute-Revolute (RRR) mechanism and can provide force levels (45N) beyond any existing system. The main optimization criteria are Global Isotropy Index (GII) and Perpendicular Impact Force (PIF) factors. The proposed system can be used for tele-operation, VR, Human-Robot-Interaction (HRI) [7].

The present Hand EXOskeleton SYStem (HEXOSYS) is an effort to combine good salient features present individually in the existing hand exoskeleton designs: Portability, Human hand compatibility, Optimization, Direct-driven, Back-drivability, Full range of motion, Light mass, Low complexity, Provision of bi-directional force and so on. At the time of writing this paper, there is not any existing hand exoskeleton system reported in the literature that encompasses all of these mentioned features in a single device. This fact essentially puts the novelty in the proposed system. It has been designed as a general purpose system. That is why instead of concentrating on the requirements of a particular application, the device specifications have been derived from a series of experiments with the human hand, thus keeping the system beneficial for wide range of applications. Potential applications of this system include tele/virtual presence, tele/virtual manipulation and rehabilitation. Trying to match the human hand force capabilities as well as natural workspace resulted in a human hand compatible device.

III. DESIGN GOALS & DEVICE MECHANISM

The human hand can be counted as one of the most difficult systems to emulate with a mechatronic device. This difficulty is mainly due to two reasons. First, is the unavailability of ample space for components placement and second is high number of DOF (4 or even more in case of thumb). These pose a great challenge in terms of design requirements. Some obvious desired characteristics of such a system are summarized below. Detailed desired requirements of such a system are reported in [7].

(i) Low mass/inertia.
(ii) Unconstrained range of motion.
(iii) Minimum complexity.
(iv) Comfort.

It is clear that the above requirements cannot be satisfied by solutions employing large number of actuation units trying to power most of the finger phalanges. Our approach to design the HEXOSYS is to use a less complicated finger exoskeleton mechanism. The conceptual mechanism proposed in this work is shown in Figure 1. The finger exoskeleton system is a two links planar under-actuated mechanism which is attached to the user finger at a single point. A single actuation unit residing at the proximal joint of the exoskeleton is used to power the device.

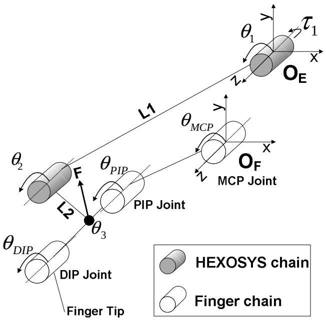


Fig. 1. Kinematic model of the proposed device

Table I lists HEXOSYS design goals and primary specifications while the DH parameters of the device are presented in Table II. Based on these, (1) states the overall transformation from end-effector to the base of exoskeleton.

TABLE I
HEXOSYS SPECIFICATIONS

MECHANICS	✓ Direct drive
	✓ Optimized link structure
	✓ Underactuated Revolute-Revolute (RR) mechanism
	✓ 4 DoF/finger (1 active)
	✓ Low complexity
ERGONOMICS	✓ Full range of motion
	✓ Light mass expected
	✓ Low volume
	✓ Variable hand sizes
	✓ Portable
	✓ Palm-free
	✓ Easy removal and donning
PERFORMANCE	✓ Bi-directional forces of upto 8N
	✓ Position and force feedback
	✓ Up to 5 fingers

TABLE II
DH PARAMETERS OF THE PROPOSED DEVICE

i	α_{i-1}	a_{i-1}	d_i	θ_i
1	0	0	0	θ_1
2	0	L_1	0	θ_2
3	0	L_2	0	θ_3

$$ {}^{0}_{3}T = \begin{bmatrix} C_{123} & -S_{123} & 0 & L_1C_1 + L_2C_{12} \\ S_{123} & C_{123} & 0 & L_1S_1 + L_2S_{12} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (1) $$

where
$S_{123} = \sin(\theta_1 + \theta_2 + \theta_3)$
$C_{123} = cos(\theta_1 + \theta_2 + \theta_3)$

The mapping from velocities in joint space to Cartesian space (Jacobian matrix) is given by

$$ J = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ 1 & 1 & 1 \end{bmatrix} \qquad (2) $$

where

$a_{11} = \ -L_1S_1 - L_2S_{12}$
$a_{12} = -L_2S_{12}$
$a_{13} = \ 0$
$a_{21} = \ L_1C_1 + L_2C_{12}$
$a_{22} = L_2C_{12}$
$a_{23} = 0$

IV. DEVISE OPTIMIZATION

The kinematic performance of the proposed device is essentially a strong function of proper choice of link lengths and the link shape. This motivated us to carry out an optimization procedure during design of the HEXOSYS to find out the optimum values of exoskeleton link lengths The primary optimization criteria is kinematics, finger-exoskeleton WorkSpaces (WS) matching and worst case collision avoidance. Since the HEXOSYS is attached to the finger at the mid of the middle phalange, this point is considered for matching WS.

To increase the collision-free reachable WS of HEXOSYS, the first link (L1) shown in Figure 1 has been sub-divided into three segments (L1-1, L1-2 and L1-3) as illustrated in Figure 2.

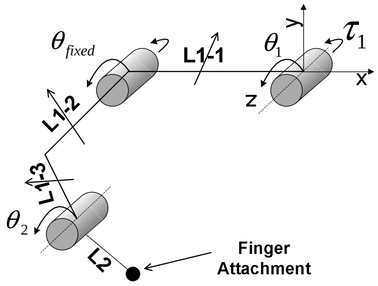
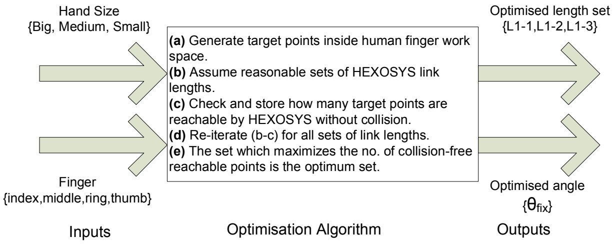


Fig. 2. First link structure of HEXOSYS ensuring collision-free workspace

These segment lengths are adjustable depending upon finger and hand size. Similarly the angle between first two sub-segments (θ_{fixed}) is also variable but is fixed for a certain finger and hand size. The objective of optimization algorithm is to find the optimum lengths of these three segments and angle (θ_{fixed}). The optimization algorithm takes the hand size and finger as inputs and gives these optimized values as an output.

HEXOSYS link lengths have been iterated through reasonable range. Each set of link lengths is then subjected to traverse through the complete finger WS for analysis. Using inverse kinematics, the set of link length is then analyzed to see how many points inside the finger WS, the exoskeleton can reach without collision. For collision detection, equidistant points (0.5cm apart) on the HEXOSYS links and the rectangular envelopes surrounding the finger centre of mass have been determined. An HEXOSYS link length set is considered as collision-free if all the points on the links reside outside the rectangular envelopes. Finally the collision-free WS is stored for comparison with the next iterated link lengths set. Figure 3 shows the overall optimization strategy of HEXOSYS.



(a) Generate target points inside human finger work space.
(b) Assume reasonable sets of HEXOSYS link lengths.
(c) Check and store how many target points are reachable by HEXOSYS without collision.
(d) Re-iterate (b-c) for all sets of link lengths.
(e) The set which maximizes the no. of collision-free reachable points is the optimum set.

Fig. 3. Optimization strategy of HEXOSYS

For a medium hand size, in case of index finger, the optimized segments have been found to be L1-1=8cm, L1-2=2cm, L1-3=2cm and θ_{fixed}=55.4°. The corresponding WS is illustrated in Figure 4.

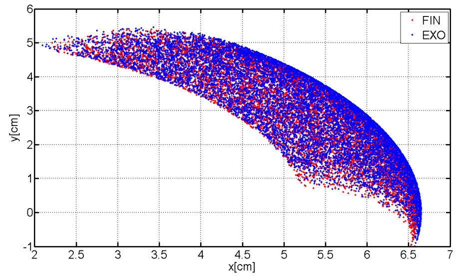
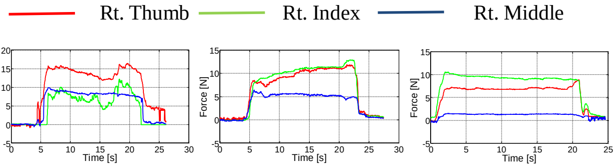


Fig. 4. Plot showing the workspaces of finger (red) and exoskeleton (blue) on optimized link lengths

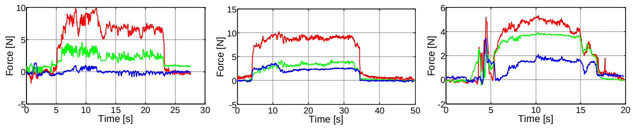
V. DESIGN REQUIREMENTS

To collect necessary data for selecting the actuator, an analysis of the most common daily life activities of the hand has been carried. Included in this analysis are the experiments to measure average or maximum exerted force levels and the required range of motion. The data collected from these experiments can then be mapped to lower level actuator requirements. Commercially available data glove, a load cell and fingertip force sensors have been used to collect data from small, medium and big hand sizes in various activities. Detailed design requirements have been mentioned in [8]. Figures 5-6 show results of force profiles corresponding to interacting with a small and comparatively big object. The results of activities requiring average force levels demonstrate that we usually need 10-15N to accomplish many of our daily life activities. Another experiment intended to measure the maximum force levels exerted by human finger revealed that the maximum levels can go up to 45N.



(a) (b) (c)

Fig. 5.Force profiles of taking a big object (cup) in case of (a) Small (b) Medium (c) Big hand sizes

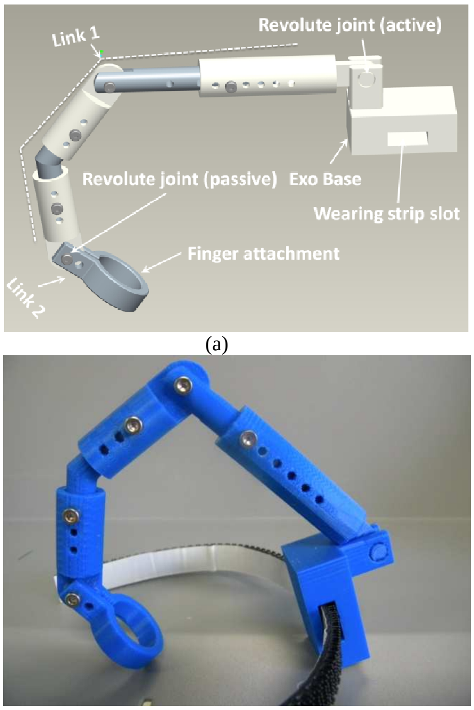


(a) (b) (c)

Fig. 6. Force profiles of interacting a small object (writing with pencil) in case of (a) Small (b) Medium (c) Big hand sizes

VI. DEVICE PROTOTYPE

Initially, an un-actuated finger prototype made up of ABS-plastic has been fabricated using a high-tech in-house 3D printer. The purpose was to verify the optimization results and analyze the behavior of the selected mechanism (RR). Both revolute joints can be moved passively without imposing any unrealistic constraints. The prototype can be easily fastened and removed from the hand using a single velcro clip. The CAD design and snapshot of this initial prototype has been illustrated in Figure 7.

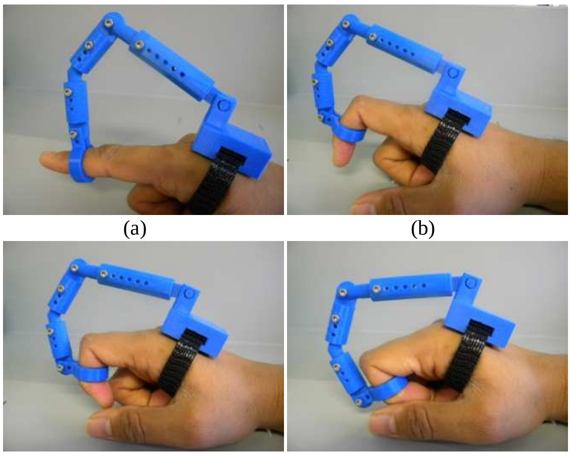


(a)

(b)

Fig. 7. The un-actuated rapid finger prototype
(a) CAD design (b) Prototype

With the initial prototype on the hand, the collision-free reachable workspace has been observed by moving the finger from complete flexion to complete extension. Figure 8(a-d) gives illustration of one complete cycle. The mechanism together with the optimized link lengths and shape provide full range of motion without any constraints as evident in Figure 8. This confirms the optimization results presented in Section III.



(a) (b)

(c) (d)

Fig. 8. Complete flexion-extension cycle depicting the full collision-free workspace coverage of an index finger

The final prototype consists mainly of an actuator (Portescap 16G88-220P) with its accessories (R16 Gear and MR2 encoder) and a pair of bevel gears (1:1). The use of bevel gears, by changing the orientation of motor axis permits the extension for neighboring hand fingers. The prototype is planned to provide position as well as force feedback. Figure 9 shows CAD view of the final prototype. The prototype provides flexion, extension as well as passive abduction.

VII. CONCLUSION

We have proposed design of a portable, direct-driven and optimized hand exoskeleton system that has the capability to provide the force levels necessary to accomplish common daily life activities. The system design has been emerged as a consequence of optimization studies to ensure that the device has complete range of motion as that of human hand. Moreover, the data collected from the series of experiments on human hands paved the way to choose actuators. Initially an un-actuated rapid prototype has been fabricated to confirm the optimization results. The final prototype captured using CAD tools is being sent for fabrication and is expected to be light weight and less volumetric.

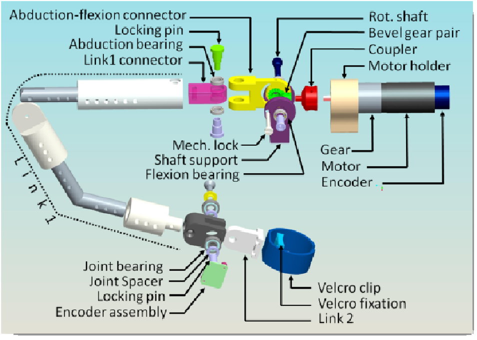


Fig. 9. CAD Design of final prototype (Exploded view)

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