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A Multi-DOF Robotic Exoskeleton Interface for Hand Motion Assistance

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Abstract—**This paper outlines the design and development of a robotic exoskeleton based rehabilitation system. A portable direct-driven optimized hand exoskeleton system has been proposed. The optimization procedure primarily based on matching the exoskeleton and finger workspaces guided the system design. The selection of actuators for the proposed system has emerged as a result of experiments with users of different hand sizes. Using commercial sensors, various hand parameters, e.g. maximum and average force levels have been measured. The results of these experiments have been mapped directly to the mechanical design of the system. An under-actuated optimum mechanism has been analysed followed by the design and realization of the first prototype. The system provides both position and force feedback sensory information which can improve the outcomes of a professional rehabilitation exercise.**

I. INTRODUCTION

HANDS are central entity for the maintenance of independent living. Hand exoskeleton systems enhance the human strength by extending the sensing and manipulation capabilities of a user in a real and/or virtual environment. In rehabilitation, the primary aim of such systems is to assist physiotherapists in performing the therapies after hand injuries or strokes, thereby partially or even completely replacing the classical manual procedures. Construction of assistive systems for the benefit of humankind has always fascinated the research community. The scientific literature reports many exoskeleton-based hand rehabilitation systems.

Scientists at HongKong Polytechnic University have conceived a complete five-fingered hand with 2 DOF per finger employing Virtual Centre of Rotation (VCR) mechanism [1]. An exoskeleton system having 1 DOF has been presented by KAIST researchers considering Activities of Daily Living (ADL) training for stroke patients [2]. The main objective was to realize several types of grasp including cylindrical, lateral and pinch. A 4-bar linkage has been designed to imitate the finger tip path in grasping motion while a cable mechanism drives the movement of the thumb. Another exoskeleton aimed to restore dexterity of paralyzed hands has been developed at CMU [3]. The exoskeleton controlled by ElectroMyoGraphy (EMG) signals has two actuators controlling the index finger flexion that can be used to perform a pinching motion against a fixed thumb. Wang et al. presented a ground-based finger exoskeleton having 4 DOF [4]. The system is actuated by four actuators placed at a distance from the hand to reduce loading. The exoskeleton finger is comprised of three phalanges corresponding to the human hand anatomy. For each finger joint, two cables have been used to transmit force and motion from the actuator to the exoskeleton. Another novel hand exoskeleton exerciser comprised of four fingers having 7 active DOF has been proposed by researchers at Salford University [5]. The system has been intended to combine dexterity with a good Range Of Motion (ROM). The actuators reside on ground and the bi-directional forces are transmitted by low friction tendons. The device has been integrated within a Virtual Reality (VR) based hand therapy system, thus permitting a clinician to customise and perform hand exercises and finger motion evaluation tests. Another tendon-driven hand exoskeleton having 4 DOF per finger has been conceived by Wege et al. [6]. The system is capable of exerting bidirectional forces using a single DC motor. Researchers at SSSA, Italy have realized a novel hand exoskeleton system [7] intended to simplify the exoskeleton complexity related to its structure, mechanism and actuation while still providing full hand mobility. The natural ROM has been accomplished by keeping the number of exoskeleton's DOF similar to that of a natural hand while simplicity has been achieved by proposing a novel mechanical design. Y. Fu et al. have presented a passive hand rehabilitation system [8] actuated by two motors that can exert bidirectional forces on finger phalanges during complete flexion and extension. The developed Continuous Passive Machine (CPM) has 4 DOF/finger and uses tendons for force transmission.

The detailed review of the existing systems has revealed that there is no existing exoskeleton based rehabilitation device that encompasses following features:

- Direct-driven
- Optimized link structure
- Human hand compatible
- Full Range of Motion (ROM)
- Light mass & low volume
- Portable
- Support for variable hand size
- Possibility to accommodate up to 5 fingers
- Provision of bi-directional forces
- Palm free

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II. SYSTEM MECHANISM

A hand exoskeleton should provide the desired functionality with adequate ergonomics. In terms of mechatronic implementation, this can be achieved by appropriate choice of link lengths, number of DOF, selection of actuators and sensors, etc. Obviously, this cannot be accomplished by solutions employing a large number of actuation units trying to power most of the finger phalanges. This will certainly result in uncomfortable and cumbersome devices not suitable for repetitive periods of operations.

An earlier developed Hand EXOskeleon SYStem (HEXOSYS)-I can provide force levels (45N) beyond any existing system [9]. The experiences with HEXOSYS-I enabled us to design a new light mass, less volumetric hand exoskeleton that is more ergonomic thus yielding better performance in terms of grasping and manipulation. Moreover, the newly developed exoskeleton can accommodate up to 5 fingers and supports adjustment of various hand sizes. While both the proposed hand exoskeleton systems are direct-driven and portable with the ability to exert bi-directional forces on the finger phalanges, their mechanisms, actuation systems, optimization criteria and physical features are entirely different.

The design concept of HEXOSYS-II finger is presented in Figure 1. With an underactuated mechanism, it is a two link serial Revolute Revolute (RR) manipulator which is attached to the finger at a single point. The system is powered by a single actuator residing at the base of exoskeleton's proximal joint. The finger prototype is shown in Figure 2.

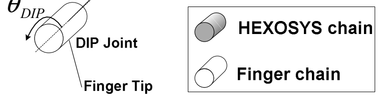


Fig. 1. HEXOSYS-II design concept

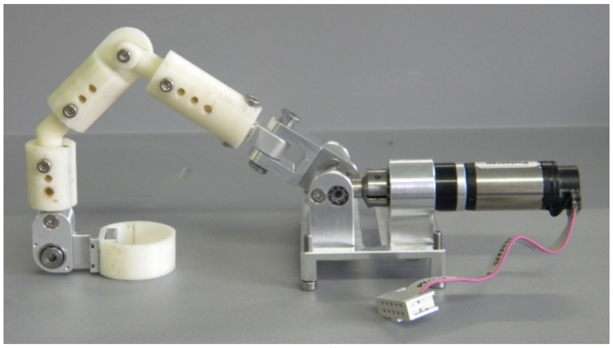


Fig. 2. HEXOSYS-II finger prototype

III. SYSTEM OPTIMIZATION

The functional behavior of an exoskeleton in the WorkSpace (WS) strongly depends on the lengths and shape of its links. This motivated us to carry a multi-parametric optimization procedure that determines the optimized link lengths. The optimization criteria primarily include finger-exoskeleton WS matching in addition to other trivial factors like kinematic mapping, worst case collision avoidance, etc. For the sake of widening the reachable exoskeleton WS without encountering the collision, the first link of length L1 (see Figure 1) has been split into sub-segments (Figure 3). The lengths of these segments are adjustable and are a function of finger and hand size. Likewise, the angle between the first two sub-segments (θ_{fixed}) is also adjustable but is fixed for a certain hand/finger. The length of the distal link (L2) 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).

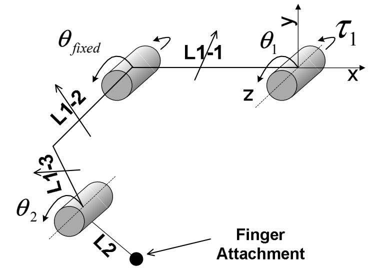


Fig. 3. Splitting the first link into three segments resulted in widening of the HEXOSYS-II workspace

The inputs to the optimization algorithm are

hand size = {small, medium, big}
finger = {index, middle, ring, thumb}

While the outputs are

lengths = {L1-1, L1-2, L1-3}
angle = {θ_{fixed}}

The optimization algorithm starts with assuming reasonable lengths of the segments. Each set of link lengths is then subjected to traverse throughout the finger WS for analysis. The finger WS has been determined using the Monte Carlo method. Random samples of the finger joint angles in the range $-10° \leq \theta_{MCP} \geq 50°$, $0° \leq \theta_{PIP} \geq 110°$ determine the points throughout the finger WS using

$$x_f = L_{1f}C\theta_{MCP} + L_{2f}C(\theta_{MCP} + \theta_{PIP}) \quad (1)$$

$$y_f = L_{1f}S\theta_{MCP} + L_{2f}S(\theta_{MCP} + \theta_{PIP}) \quad (2)$$

Where L_{1f} and L_{2f} are the lengths of proximal and middle digits of the human finger respectively while C and S refer to Cosine and Sine of the corresponding angles respectively.

The set of segment lengths is analyzed to determine the number of points in the finger WS reachable by the exoskeleton without collision. For collision detection, the rectangular envelopes surrounding the human finger Centre of Mass (CoM) and equidistant points on the exoskeleton links have been determined. An exoskeleton link length set is considered as collision-free if all the points on the links reside outside the rectangular envelopes. The collision-free WS is stored for comparison with the next iterated link lengths set. When all the segment lengths are iterated, the set giving maximum correlation of the finger WS and the exoskeleton WS is considered as optimized. Figure 4 illustrates flow-chart of optimization procedure.

In case of an index finger of a medium sized hand, the optimized segment lengths as found from the algorithm are L1-1=8cm, L1-2=2cm, L1-3=2cm with $\theta_{fixed}=55.4°$. The finger WS and the exoskeleton WS corresponding to these optimized link lengths are illustrated in Figure 5. This shows that the optimized RR mechanism fully covers the natural ROM of a finger.

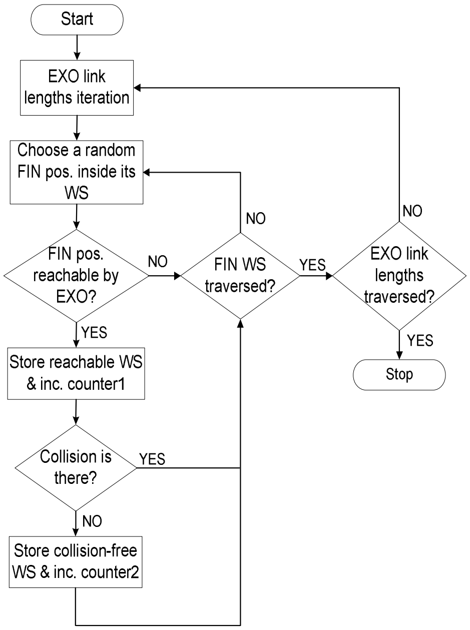


Fig. 4. Optimization algorithm

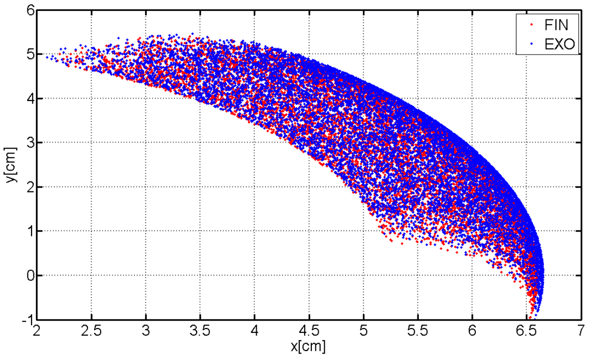
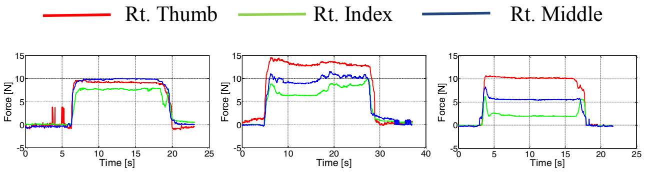


Fig. 5. Exoskeleton and finger workspaces

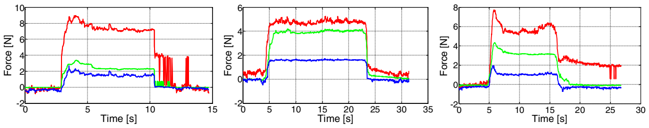
IV. SYSTEM DESIGN REQUIREMENTS

The HEXOSYS-I was targeted at maximum force capabilities of the human hand. In an attempt to reduce the system physical dimensions and thus enhancing the ergonomics, HEXOSYS-II has been aimed at exerting average force levels. These levels measured with various devices including force sensors and the load cell can be ultimately mapped to lower level requirements such as actuation torque. Three healthy subjects each having small, medium and big hands participated in the experiments. One of the experiments included recording the force levels required to accomplish some usual grasping activities. The subjects were asked to grasp and manipulate the objects in the same fashion 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. 6 and 7 show the force profiles of two activities in case of Right (Rt.) thumb, index and middle digits. Detailed design requirements have been reported in [10].



(a) (b) (c)

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



(a) (b) (c)

Fig. 7. Interacting a small object (bank card) by a (a) Small (b) Medium (c) Big hand

V. SYSTEM DESIGN

The optimized link lengths and shape presented in Section III guided the design of the HEXOSYS-II structural sub-system while the results of average force measurement experiments (Section IV) paved the way to choose actuators for the proposed system.

The exoskeleton finger consists of an actuator per finger together with its accessories, a pair of bevel gears, optimized links and sensors. An exploded CAD view of a single exoskeleton finger is illustrated in Figure 8. The actuator is a DC motor by Portescap (16G88-220P). It can provide torque up to 16mNm and has a mass of 37gm including the gear, thus making the system light weight. The actuator accessories consist of a 2 stage planetary gear-head with ratio of 30.2:1 and a Magneto-Resistive (MR) encoder with a resolution of 512 pulses per revolution. The use of bevel gears, by changing the orientation of motor axis permits the extension of exoskeleton fingers. A miter gear pair (1:1) from Boston Gear made up of stainless steel has been used in every exoskeleton finger.

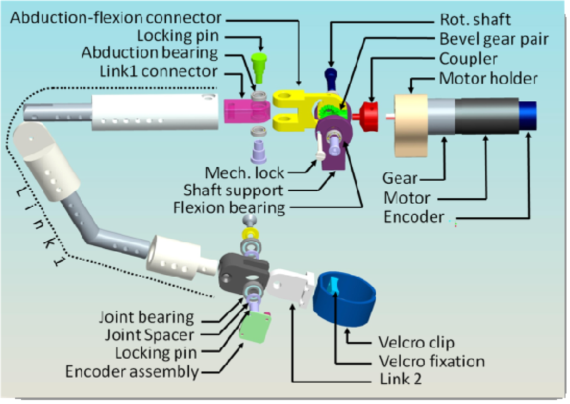


Fig. 8. HEXOSYS-II finger CAD exploded view

Two types of sensors mounted on the device measure both the device motions and interaction forces. A custom-made force sensor has been mounted immediately on the abduction-flexion connector (shown in yellow in Figure 8). The sensor based on strain gauge measures the interaction forces with the finger segment. In addition to the motor encoder, a 12-bit programmable magnetic rotary encoder available from Austriamicrosystems has been mounted on the passive revolute joint to measure the position of the 2-link joints. This permits monitoring of the exoskeleton from which the fingertip posture can also be extracted. This means that no additional instrumentation is required to track the finger motions, e.g. data-gloves. The CAD model of the complete HEXOSYS-II prototype is illustrated in Figure 9.

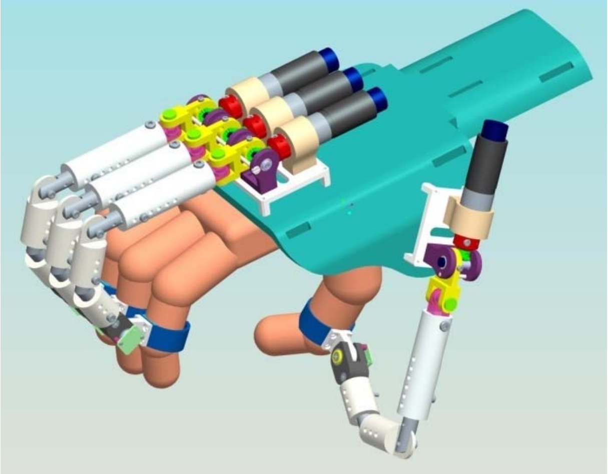


Fig. 9. HEXOSYS-II CAD model

The links and the base of the exoskeleton have been fabricated using a high-tech in-house 3D printer using ABS plastic to reduce the overall weight of the system. The custom miniature parts (e.g. pins, lockers) have been fabricated in steel while the rest of the custom parts have been made up of light aluminium. A partially assembled HEXOSYS-II finger prototype is presented in Figure 10. The base of index, middle and ring fingers is also shown in the figure. The proposed concept is capable of controlling each finger individually and provides active flexion/ extension as well as passive abduction.

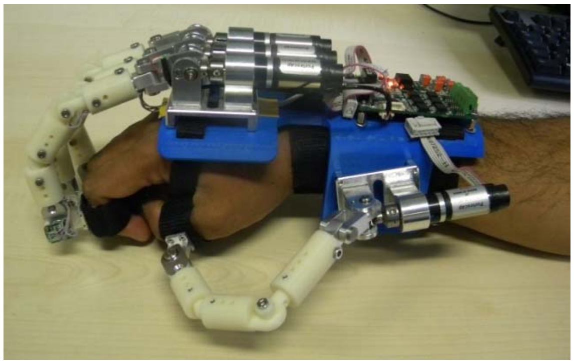


Fig. 10. HEXOSYS-II prototype

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