Four-fingered lightweight exoskeleton robotic device accommodating different hand sizes

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A wearable hand exoskeleton (EXO) device that permits exertion of bidirectional forces on finger phalanges throughout the human finger workspace is proposed. The novelty of the proposed device lies in its direct-driven, portable and optimised mechanism with the ability to adjust variable hand sizes in addition to other distinguishing features. The adjustable link lengths and structure of the device have emerged from kinematic-based optimisation criterion, which targets the natural finger workspace. The selection of actuators for the EXO is backed by the results of experiments conducted using appropriate sensory instrumentation to measure the force exertion levels of a human hand. A four-fingered prototype of the EXO is designed and fabricated. The device is then subjected to various test inputs to characterise the tracking performance. Preliminary results demonstrate that the proposed device can flex and extend the fingers following accurate trajectories.

Introduction: The fundamental rationales of a hand exoskeleton (EXO) device are to monitor the motion of the fingers/hand and to apply external forces on the phalanges. This Letter is in continuation of our research on realising novel hand EXO robotic systems [1–3]. In particular, the earlier prototype illustrated in Fig. 1 encompassed a variety of features that are non-existent in any other hand EXO system as claimed in [1]. Applications of this prototype along with experimental results for hand rehabilitation and for finger stiffness measurement are reported in [4, 5], respectively. Valuable feedback and comments received from subjects, therapists and virtual reality (VR) experts drew our attention to address the noted concerns. These include reduced dexterity and ergonomics due to device bulkiness, limited use of the device with only two fingers and its inability to accommodate different hand sizes. The improved prototype has been designed keeping in view these concerns. Table 1 presents comparative features of both prototypes.

Fig. 1 *First prototype of hand EXO device [1]*

Table 1: Features comparison of first and improved prototypes

Feature	Prototype	
	First	Improved
Direct-driven four DOF/ finger	√	√
Palm-free and full ROM	√	√
Bidirectional forces	√	√
Position and force feedback	√	√
Portability	√	√ (more)
Easy removal/donning	√	√ (more)
Support for variable sizes	X	√
Lightweight	X	√
Number of fingers	2	4
Mechanism	RRR	RR
Optimisation criteria	Global isotropy index	Human finger workspace
	Perpendicular impact force	

Conceptual design: The finger EXO is an underactuated revolute–revolute (RR) mechanism (Fig. 2) actuated with a single DC brush motor, which resides on the dorsal side of the hand providing τ_1 (see Fig. 2*a*). The finger EXO is attached to the wearer's finger at a single attachment point. In an attempt to enhance the workspace of the EXO finger comprising only two joints, the first link (L1) shown in Fig. 2*a* has been sub-divided into three segments (L1-1, L1-2 and L1-3) as illustrated in Fig. 2*b*. These segment lengths are adjustable depending on the hand size and the finger digit. Similarly, the angle between L1-1 and L1-2 (θ_{fixed}) can be varied. It, however, is fixed for a specific finger and hand size.

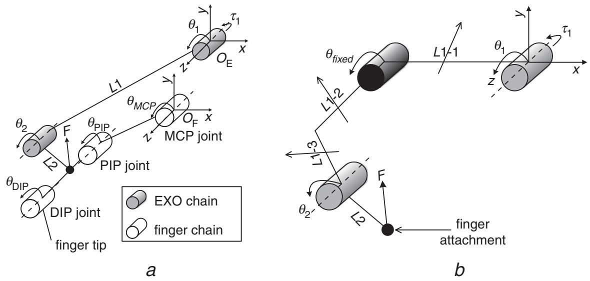


Fig. 2 *Conceptual design of improved hand EXO device*

a EXO mechanism shown with human finger
(θ_1 – active DOF and θ_2 – passive DOF)
b Modification of link 1

Requirements and optimisation: A series of experiments to investigate the force levels exertion capabilities of human hands dictated the selection of actuators for the proposed device. The maximum force levels can go up to 45 N [6]. However, most of our daily activities do not require such extremely higher levels [7]. The force profile of one such activity, measured using commercial fingertip force sensors (FingerTPS), is illustrated in Fig. 3. In another experiment using Cyber Glove, the range of motion (ROM) of a natural hand is determined to be used in the optimisation procedure. Detailed design requirements of an EXO device are mentioned in [7].

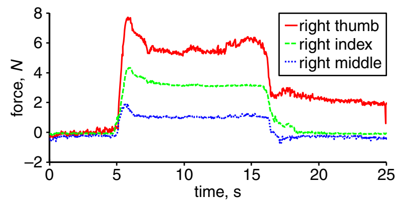


Fig. 3 *Force profile of 'using a bank card in ATM machine'*

The optimal set consisting of three segment lengths (see Fig. 2*b*) and angle (θ_{fixed}) has been determined by a kinematic-based optimisation procedure which takes the hand size {big, medium and small} and finger {thumb, index, middle and ring} as inputs and iteratively matches human finger-EXO workspaces. The workspace of a human finger has been determined based on the measured ROM. As an example, for an index finger of a small-sized hand, the optimal set {L1-1, L1-2, L1-3, θ_{fixed}} has been found to be {8 cm, 2 cm, 2 cm, 55.4°}. The corresponding workspaces are shown in Fig. 4, which confirm the ability of the optimised mechanism to completely envelope the natural ROM.

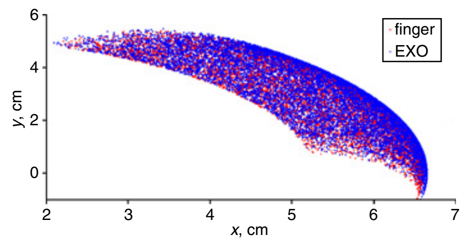


Fig. 4 *Optimisation result showing finger and EXO workspaces*

Prototyping and results: The device design is based on the optimised link structure and results of force measurement experiments. Each finger EXO (Fig. 5) mainly comprises an actuator, an optimised link structure, a pair of bevel gears and sensors. The actuator is a 5 W Portescap DC motor (16G88-220P), which actuates the proximal link of the device while the next link works as a force transmission element thus offering flexion/extension. Passive abduction/adduction is achieved by rotation along the vertical axis supported by a ball bearing. The sensory system consists of a programmable magnetic rotary encoder and a custom-developed force sensor in addition to the motor's built-in position encoder. Multiple holes in the links structure together with the nut and bolt arrangement offer adjustment in the segment lengths while the possibility to orient L1-2 with respect to L1-1 permits changing θ_{fixed}. A pair of bevel gears/EXO finger changes the motor orientation axis so as to incorporate four or even five EXO fingers.

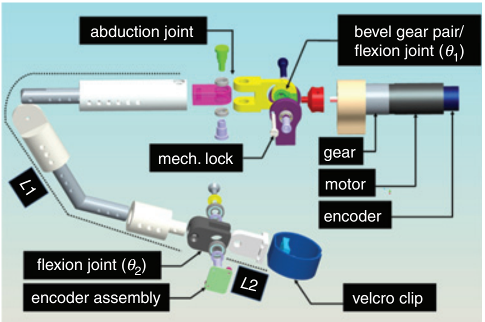
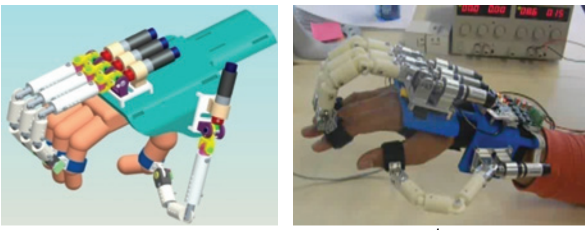


Fig. 5 *CAD model of proposed finger mechanism (exploded view)*

A four-fingered device prototype has been designed and fabricated mainly in light aluminium with custom miniature components made up of stainless steel. The EXO base and link structure are made up of ABS plastic for reduction in device weight. A Freescale processor (56F807) works with a dedicated laptop in the client–server paradigm to execute commands. A CAD view of the proposed device and the fabricated prototype are shown in Fig. 6.



a b

Fig. 6 *Proposed device*

a Three-dimensional CAD model
b Fabricated prototype

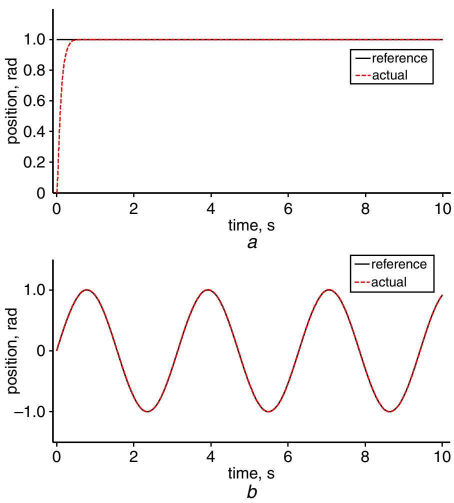


Fig. 7 *Trajectory tracking*

a Step response
b Sinusoidal response

On the basis of the desired position set as a reference and the actual position sensed from the motor encoder, a proportional, integrator and derivative-based closed-loop feedback control system is realised. Preliminary results are presented in Fig. 7 where step and sinusoidal responses depicting the capability of the device to track the desired trajectories are shown. Table 2 summarises the specifications of the device.

Table 2: EXO key specifications

Specification	Value
DOF/finger	4 (1 active)
Actuator torque capability (with gear)	0.5 Nm
Maximum continuous force	8 N
Total weight of device	460 gm
Weight of device excluding actuators	312 gm
Force sensor resolution	0.01 N
Position sensor resolution	0.0879°

Conclusion: This Letter presents the design and development details of a novel hand EXO device. Owing to its distinguishing features, the device finds potential in a wide range of application areas including, but not limited to, VR, haptics, rehabilitation, motion assistance, tele-presence and tele-existence. A series of upcoming VR and rehabilitation exercises to quantify the benefits of the proposed device in a more systematic and sophisticated way are planned.

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One or more of the Figures in this Letter are available in colour online.

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