Biomimetic Hand Exotendon Device (BiomHED) for Functional Hand Rehabilitation in Stroke

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Abstract— **Significant functional impairment of the hand is commonly observed among stroke survivors. In order to restore the functional use of the affected hand, we developed a biomimetic device that assists in generating functional movements of the hand. The device is actuated by exotendons that replicate the kinetic functional of the hand muscle-tendons, therefore it can reproduce the spatial finger joint coordination patterns of the functional manual tasks (e.g., power grip and pinch) with a reduced number of actuators. The system includes a thumb actuation mechanism, whose action is coordinated with finger exotendons to perform various manual tasks, thereby restoring the functional use of the hand. This paper presents the design of the device and the preliminary data of the functional movement generation by the system.**

Keywords—hand rehabilitation, tendon driven device, exotendon, functional movement

I. Introduction

Stroke is a leading cause of serious, long-term disability in the United States. While many stroke victims eventually regain use of their lower extremities, upper limb recovery is slow and often limited [1,2]. The functional impairment of the hand and upper extremity can significantly degrade the quality of life of those affected [3].

A number of assistive devices have recently been developed in an attempt to restore hand functions for the neurologically impaired patients. Many of these devices were designed to explicitly assist in hand opening [4,5] as significant impairment in finger extension typically emerges after the brain lesion [6]. Some devices are designed to provide assistance of both finger extension and flexion, which include Rutgers Master II [7], Hand Mentor (Kinetic Muscles, Tempe, AZ), HWARD [8], and HEXORR [9]; however, the complexity of the motions achieved by these systems is generally limited since one dimensional actuation is applied to each digit (or to the entire hand), thereby resulting in a fixed inter-joint spatiotemporal coordination pattern. Some of these devices, i.e., HWARD and HEXORR, are designed to perform functional tasks (e.g., grasping) by executing a pre-determined pattern of coupled movements within- and between-digits.

Other recent exoskeletons with more complex structures are capable of controlling individual finger joint movements [10-12]. Peripheral mechanical structures of these devices, however, tend to be bulky in order to attain complex actuation mechanisms. The complexity of the controller may significantly increase to achieve desired coordination patterns of multiple degrees-of-freedom (DOFs). Apparently, there exists an inherent trade-off between the functionality of the device and its structural simplicity.

In order to overcome the aforementioned limitations and to build a multi-functional device with a compact structure, the exotendon system developed in this study is based on a 'bio-inspired' design approach, as the proposed device is intended to replicate the musculotendon structure of the human hand. The human fingers are capable of generating complex movement patterns, for which the anatomical complexity of the peripheral structure itself plays a critical role in its neuromuscular control [13]. Most finger tendons are multi-articular, therefore each individual tendon typically generates coordinated patterns of joint moments [14,15], and functional tasks are achieved via task-specific coordination of the relevant muscles [16,17]. As a result, a significant level of covariation between joint angles is often observed during functional hand movements, indicating 'synergistic' control of the excessive DOF of the system; as a result, a significant degree of dimensionality reduction has been identified in hand postures [18] or movements [19]. Such reduced dimensionality is essential to effectively control the complex hand musculature to perform functional tasks.

Therefore, in this study, we developed a hand exotendon device, Biomimetic Hand Exotendon Device or BiomHED, which is based on a bio-inspired design, in order to achieve effective hand rehabilitation after stroke. The device is designed to generate functional movements by actuating 'exotendons' that replicate the anatomical structure of the major extrinsic and intrinsic muscle-tendons of the hand. Accordingly, each exotendon assumes the kinetic function of the corresponding muscle-tendon, and the independent and/or synergistic actuation of the exotendons will enable functional use of the hand by generating spatiotemporal coordination patterns of the finger joints specific to manual tasks (e.g., [20]). In this paper, we describe the design of the BiomHED and present the results of the pilot study that test its efficacy to produce functional hand movements. The joint coordination patterns generated by individual exotendon loadings were first examined, which were then used to reproduce the movement patterns observed during functional tasks.

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II. Material and Methods

A. Device Design

1) Function of finger muscle-tendons - selection of target tendons: The index finger is comprised of three joints: metacarpophalangeal (MCP), proximal interphalangeal (PIP), and distal interphalangeal (DIP) joints. Motion about the joints is controlled by seven muscle-tendons, including extensor digitorum communis (EDC), extensor indicis proprius (EIP), flexor digitorum superficialis(FDS), flexor digitorum profundus (FDP), first dorsal interosseous (FDI), first palmar interosseous (FPI), and lumbricalis (LUM). These muscles impact multiple DOF as they insert into phalanges or extensor hood, an aponeurotic sheet connecting the tendons (Fig. 1a).

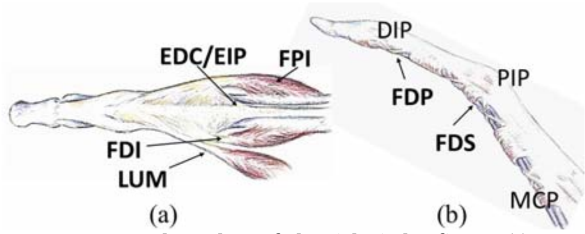

Fig. 1. Seven muscle-tendons of the right index finger: (a) extensor hood; dorsal view (b) flexor tendons; lateral view

We intend to reproduce the function of the following muscle-tendons: EDC, FDP, FDI/LUM, and FPI, as their functional importance during finger movements and fingertip force generation in grip tasks has been identified by electromyographical [16,21], cadaveric [14,22] and *in vivo* muscle stimulation studies [15]. Major functions of these muscle-tendons are: concurrent extension (EDC) and concurrent flexion of all joints (FDP), MCP flexion with small DIP/PIP extension (FDI/LUM, FPI), MCP abduction (FDI/LUM), and MCP adduction (FPI) [14,22].

2) Design of the Biomimetic Hand Exotendon Device: The BIOMHED employs four 'exotendons' for each finger, which approximately replicate the function of five major muscle-tendons: EDC, FDP, FDI/LUM, FPI. The exotendons are connected to the servo motors that provide appropriate tensions, and the motors are located on the forearm in order to avoid adding additional bulky structure to the hand.

The four cables, i.e., exotendons, assume similar paths with five major muscle-tendons of the finger (Fig. 2). The first cable (ET_1) runs on the dorsal side of each finger and creates concurrent extension of all three joints as the EDC tendon does. The second (ET_2) runs on the palmar side of each finger, thereby creating concurrent flexion of all joints (i.e., FDP). The third and fourth cables ($ET_{3/4}$) originate from the dorsal aspect of the DIP joint and run laterally, i.e., ET_3 on the radial side and ET_4 on the ulnar side, towards the palmar aspect of the MCP joint, then merge into one cable proximal to the MCP joint. ET_3 and ET_4 are loaded concurrently, thus their MCP abduction moments are cancelled; therefore, concurrent loading of ET_3 and ET_4 generates small extension DIP/PIP moments and a larger MCP flexion moment, similar to the function of FDI, FPI, and LUM [14].

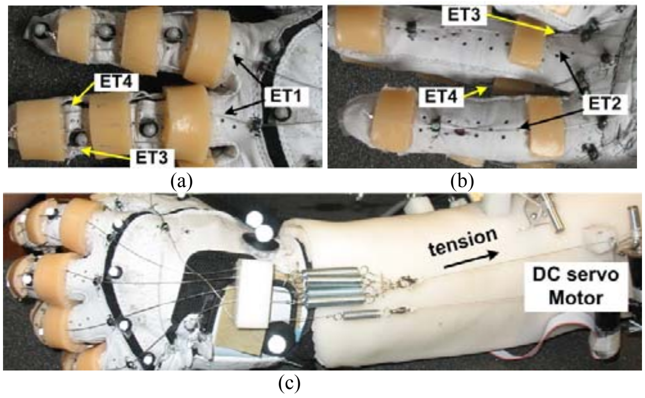

Fig. 2. Biomimetic hand exotendon device (BIOMHED): (a) dorsal view (b) palmar view (c) actuating mechanism

3) Actuation and Control Algorithm: The actuators that provideThe actuators that provide tensions to the exotendons are located on the forearm in order to minimize weight and volume of the device added to the finger, and not to interfere with the workspace of the fingers. Three brushed DC servo motors (Maxon Co., Switzerland) are used to apply tension to ET_1, ET_2, and $ET_{3\text{-}4}$, respectively. The exotendons are extended to thinner wires at the wrist level, which are connected to the actuators placed on the forearm brace via tension springs that help distributing forces equally to the fingers (Fig. 2c).

The motors run in 'current control' or 'torque control' mode; the tension in each cable is estimated by measuring the current at the motor. In addition, the number of revolutions of each motor is recorded for a further kinematic analysis to estimate posture and the design of a safety stop.

For given tasks and joint angles, the motion planner will estimate requited forces at each tendon which are converted into desired torques (τ_d) at the motors. The motors are then controlled to track the target torques using PID control. The joint kinematics is estimated from the motor revolution and fed back to the motion planner (Fig. 3).

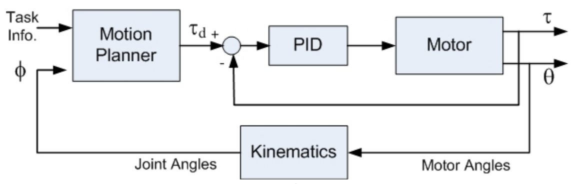

Fig. 3. Schematic diagram of the BIOMHED controller

4) Safety Consideration:

The motors are controlled not to increase torques when the joint angle reaches its pre-set limit value. The torques are monitored at 200 Hz and the system will turn off if excessive joint torque is detected or an emergency switch is pressed.

B. Experimental Protocol

Three healthy volunteers with no known neurological and orthopedic impairment and one stroke survivor (Upper extremity Fugl-Meyer score: 22/66) participated in an experiment that tests the capability of the proposed device to reproduce functional movements of the hand. All the experimental procedures were approved by the Institutional Review Boards at the MedStar Health Research Institute and the Catholic University of America, and all participants gave written consent prior to the tests.

First, the subjects were asked to perform basic manual grip tasks, i.e., power grip, palmar pinch, and tip pinch, with their dominant hands (controls) or the impaired hand (stroke) while the spatiotemporal coordination of the three joints of the index finger was recorded. In the second session, the BiomHED was put on the dominant/impaired hand of each subject, and different exotendon loading conditions were tested. In both sessions, five markers were placed on the dorsal aspects of the index finger (i.e., fingertip, DIP, PIP, MCP, and CMC joints) of each subject. A motion capture system (Vicon Motus, Oxford Metric, UK) measured the markers' three-dimensional coordinates at a sampling frequency of 120Hz.

1) Joint coordination patterns during functional hand movement: Subjects were asked to perform three basic functional tasks, i.e., power grip, tip pinch, and palmar pinch, which have significant functional importance in human manual activities. Spatiotemporal coordination pattern of the finger joints were recorded during the movements. Each task was performed three times, and the order was randomized.

2) Joint coordination patterns generated by BiomHED: The joint coordination patterns generated by the individual exotendon loadings were first examined. Each subject was instructed to wear the BiomHED and be seated comfortably on a chair, resting his/her forearm on a table placed in front of him/her. A constant force was applied to each of the exotendons and the resulting finger movements were recorded (ET_1: 10N, ET_2: 10N, $ET_{3/4}$: 5N on each of the two cables).

Based on the spatial joint coordination resulting from the individual tendon loadings, we estimated the exotendon force combination patterns required to approximate the joint coordination patterns during the three manual tasks (i.e. grips). The following three loading conditions were applied to replicate the tasks: a. Loading condition 1: 30N to ET_2, b. Loading condition 2: 10N to ET_2 and 10N to $ET_{3/4}$ (i.e., 5N to ET_3 and ET_4 each), c. Loading condition 3: 20N to ET_2. These loading conditions were designed to simulate the power grip, palmar pinch, and tip pinch, respectively.

III. Results

A. Finger Joint Coordination during Functional Tasks

The ratio of the angular displacement of the three joints showed distinct patterns across the three tasks (Table I). Within-task variability in the joint angles was the lowest for the power grip. The ratio of displacement during power grip and tip pinch tasks were similar ($\theta_{DIP} \approx \theta_{PIP} \approx \theta_{MCP}$; i.e., similar flexion angles of all three joints), while a distinct coordination pattern, i.e., small DIP/PIP flexion and large MCP flexion angle ($\theta_{DIP} \approx \theta_{PIP} < \theta_{MCP}$) was observed during the palmar pinch task.

TABLE I
MEAN (SD) ANGULAR DISPLACEMENT OF THE THREE JOINTS DURING THREE GRIP TASKS

		Tasks		
		Power grip	Palmar pinch	Tip pinch
Joint	DIP	50.0 (2.0)	15.7 (4.0)	46.0 (5.3)
	PIP	60.0 (3.5)	13.0 (7.2)	45.3 (12.9)
	MCP	58.7 (3.6)	73.0 (1.7)	59.5 (8.4)

B. Joint Angular Displacement from Exotendon Loading

The ratio of the angular displacement of the three joints resulting from each exotendon loading (Table II) in the three subjects generally agree with the kinematic function of the finger tendons that they aim to reproduce; ET_1 loading produced concurrent extension of all three joint angles (DIP < MCP < PIP), ET_2 loading resulted in concurrent flexion of all angles (DIP < PIP < MCP), and $ET_{3/4}$ loading produced extension of the DIP and PIP joints and flexion of the MCP joint, which were similar to the kinematic function of the target muscle-tendons reported in the literature [13-15]. Similar joint coordination patterns were obtained from control subjects and a stroke survivor.

TABLE II
MEAN (SD) ANGULAR DISPLACEMENT OF THE THREE JOINTS PRODUCED BY THE THREE EXOTENDON LOADING CONDITIONS

Joint	Control subjects			Stroke survivor		
	Exotendon loading			Exotendon loading		
	ET_1	ET_2	$ET_{3/4}$	ET_1	ET_2	$ET_{3/4}$
DIP	-8.0 (3.2)	3.0 (6.1)	-4.8 (3.2)	-2.5 (2.1)	7.5 (2.1)	-3.0 (1.4)
PIP	-18 (7.0)	15 (4.3)	-6.3 (4.0)	-17 (2.8)	23 (9.9)	-7.5 (3.5)
MCP	-13 (7.7)	21 (3.8)	32 (4.4)	-9 (1.4)	28 (8.5)	37 (12)

C. Reproducing Joint Coordination of Functional Tasks

We applied the three loading conditions (1-3) to reproduce the joint coordination patterns observed during the functional tasks. Each condition corresponds to the joint angular coordination patterns observed in manual tasks (e.g., Fig. 3). The loading condition 1 generated large flexion angles in all three joints, the condition 2 small flexion of the DIP/PIP joint and large flexion of MCP joint, and the condition 3 moderate amount of flexion in all three joints (Table III).

Interestingly, the summation of the exotendon forces was found to be nonlinear: the combinations of the two exotendon loadings (i.e., ET_2 and $ET_{3/4}$) did not correspond to the linear combination of the joint angle coordination from each of two exotendon loadings (see Tables II and III).

TABLE III
MEAN (SD) ANGULAR DISPLACEMENT OF THE THREE JOINTS PRODUCED BY THE THREE LOADING COMBINATIONS

		Loading condition		
		1	2	3
Joint	DIP	35.8 (10.0)	15.3 (8.8)	17.5 (8.1)
	PIP	51.0 (8.3)	37.5 (9.4)	35.1 (11.2)
	MCP	72.0 (4.1)	70.0 (1.8)	47.3 (12.4)

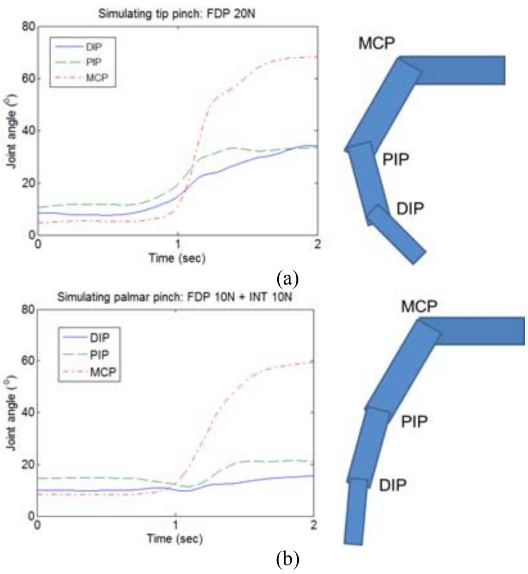

Fig. 3. Configuration manipulation: Joint angular profiles generated by the loading conditions and terminal finger posture in Subject 3 (a) Loading condition 1 (power grip): concurrent small flexion of all joints, (b) Loading condition 2 (palmar pinch): large MCP flexion with small DIP/PIP flexions. From (a) to (b): Adding ET3/4 forces while reducing ET2 force created DIP and PIP joint extension while maintaining similar amount of MCP flexion (MCP >> DIP ≈ PIP).

IV. Discussion

We presented a novel biomimetic device for the hand, BiomHED, which provides assistance in generating functional movements of the hand as an improved version from our previous work [23]. The exotendons replicate spatial coordination patterns of the finger joints similar to those generated by the major finger muscle-tendons targeted. Therefore, this device is expected to replace and/or reinforce the functions of the specific hand muscles that may be impaired as a result of neurological injuries such as stroke. Further, proper combination of proper exotendons can generate joint coordination patterns observed in different functional manual tasks (e.g., power grip and pinch), thereby extending its application to functional task-oriented training.

This study delineates the results of the finger actuation that aims to restore the task-specific spatial coordination of finger joints. In the future, the finger actuation will be coordinated with a thumb exotendon actuation to restore functional use of the hand that involves precise finger-thumb coordination; in other words, the within-digit and between-digit coordination patterns of functional tasks will be reproduced by the BiomHED system.

A future design of the system will also incorporate flexion sensors that estimate joint angles, which would be crucial in designing a feedback controller that can compensate the effects of altered neuromechanics of stroke survivors, such as increased joint stiffness and muscle hypertonicity, which may significantly impede/alter movement patterns generated by the BiomHED. The glove design will also accommodate the inter-subject variability in the segment lengths by varying geometry of the exotendons/pulleys.

References

[1] T.E.Twitchell, “The restoration of motor function following hemiplegia in man,” *Brain*, vol. 74, pp. 443-480, 1951.

[2] S.M.Lai, S.Studenski, P.W.Duncan, S.Perera, “Persisting consequences of stroke measured by the stroke impact scale,” *Stroke*, vol. 33, pp. 1840-1844, 2002.

[3] D.S.Nichols-Larsen, P.C.Clark, A.Zeringue, A.G.S.Blanton, “Factors influencing stroke survivors’ quality of life during subacute recovery,” *Stroke*, vol. 36, pp. 1480-1484, 2005.

[4] H.C.Fischer, K.Stubblefield, T.Kline, X.Luo, R.V.Kenyon, D.G.Kamper, “Hand rehabilitation following stroke: a pilot study of assisted finger extension training in a virtual environment,” *Top Stroke Rehabil*, vol. 14, pp. 1-12, 2007.

[5] J.Ochoa, Y.J.Dev Narasimhan, D.G.Kamper, “Development of a portable actuated orthotic glove to facilitate gross extension of the digits for the therapeutic training after stroke,” *Conf Proc IEEE Eng Med Biol Soc*, pp. 6918-6921, 2009.

[6] C.A.Trombly, Stroke. In: Trombly Ed. Occupational therapy for physical dysfunction, Williams and Wilkins, pp. 454–71, 1989.

[7] M.Bouzit, G.Burdea, G.Popescu, R.Boian, “The Rutgers Master II – new design force-feedback glove,” *IEEE/ASME Trans Mechat*, vol. 7, pp. 256-263, 2002.

[8] C.D.Takahashi, L.Der-Yeghiaian, V.Le, R.Motiwala, S.C.Cramer, “Robot-based hand motor therapy after stroke,” *Brain*, 131, 425-437.

[9] C.N.Schabowsky, S.B.Godfrey, R.J.Holley, P.S.Lum, “Development and pilot testing of HEXORR: Hand EXOskeleton Rehabilitation Robot,”*J NeuroEng Rehabil*, vol. 7, 36, 2010.

[10] A.Wege, G.Hommel, “Development and control of a hand exoskeleton for rehabilitation of hand injuries,” *IEEE/RSJ IROS,* pp. 3046-3051, 2006.

[11] T.T.Worsnopp, M.A.Peshkin, J.E.Colgate, D.G.Kamper, “An actuated finger exoskeleton for hand rehabilitation following stroke,” *IEEE ICORR,* pp. 896-901, 2007.

[12] C.Jones, F.Wang, C.Osswald, X.Kang, N.Sarkar, D.G.Kamper, “Control and kinematic performance analysis of an actuated finger exoskeleton for hand rehabilitation following stroke,” *IEEE Int. Conf. Biomed. Robot. Biomechatr*, pp. 282-287, 2010.

[13] F.J.Valero-Cuevas, J.W.Yi, D.Brown, R.V.McNamara, C.Paul, H.Lipson, “The tendon network of the fingers performs anatomical computation at a macroscopic scale,” IEEE *Trans Biomed Eng*, vol. 54, pp. 1161-1166, 2007.

[14] S.W.Lee, H.Chen, J.D.Towles, D.G.Kamper, “Estimation of the effective static moment arm of the index finger extensor mechanism,” *J Biomech*, vol. 41, pp. 1567-1573, 2008

[15] S.W.Lee, D.G.Kamper, “Modeling of multiarticular muscles: importance of inclusion of tendon-pulley interaction in the finger,” *IEEE Trans Biomed Eng*, vol. 56, pp. 2253-2262, 2009

[16] M.A.Maier, M.Hepp-Reymond, “EMG activation patterns during force production in precision grip,” *Exp Brain Res*, vol. 103, pp. 108-122, 1995

[17] F.J.Valero-Cuevas, “Predictive modulation of muscle coordination pattern magnitude scales fingertip force magnitude over the voluntary range,” *J Neurophysiol*, vol. 83, pp.1469-1479, 2000

[18] E.J.Weiss, M.Flanders, “Muscular and postural synergies of the human hand,” *J Neurophysiol,* vol. 92, pp. 523-535, 2004.

[19] M.Santello, M.Flanders, J.F.Soechting, “Patterns of hand motion during grasping and the influence of sensory guidance,” *J Neurosci*, vol. 22, pp. 1426-1435.

[20] I. V. Grinyagin, E. V. Biryukova, M. A. Maier, “Kinematic and dynamic synergies of human precision-grip movements,” *J Neurophysiol*, vol. 94, pp. 2284-2294, 2005.

[21] T.E.Milner, S.S. Dhaliwal, “Activation of intrinsic and extrinsic finger muscles in relation to the fingertip force vector,” *Exp Brain Res*, vol. 146, pp. 197-204, 2002.

[22] F.J.Valero-Cuevas, F.E.Zajac, C.G.Burgar, “Large index-fingertip forces are produced by subject-independent patterns of muscle excitation,” *J Biomech*, 31, pp. 693-703, 1998.

[23] S.W. Lee, H.S. Park, “Biomimetic Approach Enables Functional Movements of Hand Post Stroke: A Pilot Study”, Gait and Clinical Movement Analysis Society, 2012