FEX a Fingers Extending eXoskeleton for Rehabilitation and Regaining Mobility

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***Abstract* - Design of the automatic rehabilitation devices for fingers poses many difficulties due to the complicated structure, close vicinity and high number of degrees of freedom of the finger structure. This paper presents the design process of an exoskeleton for executing human fingers' extension movement for the rehabilitation procedures and as an active orthesis purposes. The Fingers Extending eXoskeleton (FEX) is a serial, under-actuated mechanism capable of executing fingers' extension. The proposed solution is easily adaptable to any finger length or position of the joints. FEX is based on the state-of-art Fingerspine serial system. Straightening force is transmitted from a DC motor to the exoskeleton structures with use of pulled tendons. In trial tests the device showed good usability and functionality. The final prototype is a result of almost half a year of the development process described in this paper.**

Keywords— robotic rehabilitation, hand exoskeleton, under-actuated mechanism, fingers rehabilitation, wearable system, assistive device

I. Introduction

The hand impairment and loss of dexterity may often be the result of a cortical lesion due to cerebrovascular disease or a stroke [1,2]. The stroke incident affects 0.2-0.5% of the industrialized world population annually and 1.5-3% of the population are stroke survivors [3-5]. In general, 76-88% of stroke survivors are suffering from motor deficits, out of which 70% have temporally altered arm functionality. In the same time 40% of stroke survivors suffer a persistent lack of functionality in the affected arm [4,6,7].

Rehabilitation may help regain at least some of the lost hand mobility and thus improve the general quality of life of the survivors. Everyday tasks such as eating or dressing can be re-learned thanks to hand rehabilitation programs. Effectiveness of various rehabilitation therapies can be affected by a number of interacting factors, which make it challenging especially in cases of long-term disability.

Recent research has shown that one of the advantages of robotic therapy is the possibility of an intensive motoric, tasks-based training (with a high number of task-specific movements with excessive number of movement repetition of the impaired limb) [8]. This lowers the costs of a post-stroke care minimizing the therapists' time devoted to a single patient and increases intensity of the therapy, thus making it more effective. For those who could never regain their fingers functionality, constant help is necessary to execute every-day tasks. To achieve this, exoskeletons could minimize the hand impairment effects by complementing the kinematic chain of human hand with external system.

In particular, hand exoskeleton is a mechanical structure directly connected to a hand, designed in the way that its mobility matches the mobility of the hand whereas the forces and reaction forces between those two coupled systems can be exchanged. To achieve a consistent motion and the workspace of the exoskeleton and a hand, the device has to be designed considering kinematics boundaries such as fingers mobility and degrees of freedom, having in mind the small space left for the mechanism. Designing a lightweight structure capable of tightly cooperating with human fingers and having a direct contact with a human skin is very challenging. For that reason none of the exoskeleton systems developed up to this date can be considered complementary with the human hand in its full range of motion and functionality. For the control system, force sensors and position encoders are indispensable in order to properly follow the fingers movements.

The scope of this research was therefore to develop a device that would help with executing the impaired fingers rehabilitation and at the same time would be suitable to provide mobility for people with no expectancy for the fingers functionality recovery. For this reason the Fingers Extending eXoskeleton (FEX) is proposed, which is designed to become a rehabilitation tool. At this stage of project the FEX is considered to be used with the thumb orthesis restraining movement of the thumb or with the thumb left free to move.

II. Constraints and Requirements

Rehabilitation devices are specifically designed to perform exercises for recovering lost or diminished functions of the human body. The hand rehabilitation device has to be compatible with human hand and the design process has to take into consideration all the constraints that human hand kinematics and geometry impose. Additional requirements are given by the fact that the discussed device may be considered not only as a rehabilitation tool but also as an active assistive orthesis. This brings several boundary conditions to the design:

A. *The movement made possible by the device has to cover most (if not all) of the fingers workspace including: fingers closed to form a power gap and straightened fingers (extended).*

B. *The space needed to grasp objects with a pincer or a force grasp should be unoccupied, thus no part of the device can intercede with it.*

C. *The device should assist in actuation of the fingers at a time or independently.*

D. *In case of index, ring, middle and small fingers mobility in all three joints – metacarpral (MCP), proximal interphalangeal (PIP) and distal interphalangeal (DIP) – should be covered. Range of actuated motion should allow a user to open the hand without entering hyperextension and close fingers to form a power grasp of a small object.*

E. *Stroke survivors usually have more problems with opening rather than with closing the fingers, thus the device should assist in the first place with opening movement.*

F. *Pain management both during mounting the device to the fingers and while forcing fingers to open is important and the possible pain should be minimized.*

G. *The assistive function of the device requires it to operate fingers with speeds enabling them to grasp slowly moving objects of our normal environment. This requirement is highly subjective and clinical tests should give better idea.*

H. *Forces that are exerted to the fingers should be high enough to pull the fingers up to the straight position even when fully opposed by cramped muscles.*

I. *The dimensions of the whole system have to allow patients to execute the rehabilitation at home so that the treatment is not disruptive to their daily activities and patient's travel to the rehabilitation center costs are minimized.*

J. *The device should be a plug and play system possible to work with a personal computer and be powered with batteries or from a personal computer (or a laptop).*

Fingers' movements at an early stage of the rehabilitation process may be executed with full support from the robotic system, whereas at the latter stages of the rehabilitation better results may be achieved if the system will only enhance human movements and help in achieving joint's full range of motion. Therefore the system should allow for an active position control of the finger as well as be operational in semi-active mode what enhance rehabilitation process outcome. In order to maximize effects of the rehabilitation, exercises should be accompanied with visual feedback software programmed for personal computers. Such solution will decrease the level of rehabilitation process boredom. Exercises may therefore be accompanied by goal-oriented rehabilitation games with difficulty based upon the progress of rehabilitation and level of success rate in games.

Designing a system complementary to the human hand is impossible without defining proper dimensions of generic human fingers and their mobility. From the kinematics point of view, the length of each phalange defines the distance between joints or, as in the case of distal phalanges, between the DIP and the tip of a finger (Table.1). Referring to the small, ring, middle and index fingers, length of metacarpals is not important since those are assumed not to have a relative motion in respect to the palm.

The FEX device provides control over the flexion/extension in MCP, PIP and DIP joints in case of index, middle, ring and small fingers. The thumb is considered to be constrained with an orthesis or a splint. Range of motions of all three joints for index, middle, ring and little fingers are presented in the Table.2.

Maximum forces that may be applied by each phalange while power grasp is executed are presented in Table.3 as the first value, whilst the second value represents fingers in zero configuration with straightened fingers.

According to [10] speed of rotation of PIP joint is 10rad/s for "natural speed" movement and 3-6rad/s for the MCP and PIP joints in "slow" motion. The "normal" fingers movement velocity is about three times slower than maximum – in 10s about 8 times fingers can be closed and opened, resulting in MCP and PIP joints velocities of approx.3rad/s and DIP joint velocity of approx. 2rad/s.

III. Existing solutions

The rehabilitation robotic system can be considered as an external manipulator with end-effector workspace suitable to cover the human hand fingers' workspace. Such a system is usually either a hand exoskeleton, mounted on the human's palm like University of Tokyo Hand (Fig.1, a), Percro Hand (Fig.1, b), Berlin University Hand (Fig.1, c), mounted to the forearm like Milan University Hand (Fig.1, d), Amadeo (Fig.1, e) or a system constrained to the external reference frame like Gifu University Hand (Fig.1, f) .

Specific applications of the exoskeletons demands specific architectures. According to the application of the exoskeleton, there may be different numbers of Degrees of Freedom (DoF) for one single finger, DoFs can be rotational, translational, both of them coupled or finally different numbers of fingers can be included in the system to form the whole hand. Some exoskeletons control the motion of each finger, other a whole group of fingers with use of 1 DoF or 2 DoFs by coupling the motion of DIP, PIP and MCP joints whereas some other devices control the hand with up to 20 DoFs having 4 DoFs per finger.

The University of Tokyo Hand (Fig.1, a) - the system contains of a hand rehabilitation machine that moves the index finger of the injured hand and a data glove that is connected to the healthy hand and feeds the input data for controlling the rehabilitation machine. This device controls the movement of one finger through a mechanism with 2 DoFs, where the mobility of the DIP and PIP joints is coupled by means of 3 four-bar mechanisms. This solution though suffers from a necessity to attach the all three segments to the phalanges

what entails that system has to be tightly strapped to the human's finger.

The Percro Hand (Fig.1, b) is a 2-finger device with 3 DoFs for the index finger (with coupled DIP and PIP joints movement) and 3 DoFs for the thumb. In this system a six-bars mechanism is used, which is composed of two connected parallelograms. There is no attachment to the intermediate and proximal phalanges resulting in vast workspace of the fingers. The mechanism is very big though and motors utilized are too bulky to consider the system applicable for all fingers.

The Berlin University Hand (Fig.1, c) is a system that controls 20 DoFs of the human hand motion (4 DoFs for each finger). The exoskeleton moves the finger by means of 3 four-bar mechanisms, with the same conceptual scheme shown in case of University of Tokyo finger exoskeleton.

The Milan University Hand (Fig.1, d) exploits EMG signals to control the movement of fingers with support of two DoFs – one flexion of index, middle, ring and little fingers coupled together and one flexion of a thumb. System is underactuated and the pulling cables and springs are attached to the last phalange of fingers. This solution suffers though from a complicated attachment to the hand making it difficult for people with hand muscle problems to put it on.

The Amadeo (Fig.1, e) is a commercially available product for fingers rehabilitation. It has got 5 DoFs and provides under-actuated motion to all five fingers thanks to a passive rotational joint placed between fingertip and an entity moving laterally. Interface between human hand and the machine is realized thanks to elastic bands or plasters. Wrist is restrained from the movements by a velcro strap. Fingers' workspace is not completely covered though and no adduction/abduction movements is possible.

The Gifu University Hand (Fig.1, f) is a device which supports the movement of all fingers and assists the movement of the wrist. It controls 18 DoFs of the human hand motion. Each of the index, middle, ring and little fingers have 3 DoFs, whereas the thumb and the wrist has 4 DoFs and 2 DoFs respectively. The exoskeleton assists the flexion/extension of MCP and PIP joints by means of 2 four-bar mechanisms actuated by 2 servo motors and assist the abduction/ adduction of MCP joint by another servo motor. In this case the DIP is left without an actuation what can be considered a way to simplify the mechanism. Significant drawback if considered as a rehabilitation device is that it requires the patient to wear a glove which is attached to the robot. This is a significant limitation for.

IV. The device concept

The FEX was initially considered to be a wearable glove with attached structure forcing fingers to straighten up. Based on the project constraints it was decided, that the current version of the device should refer to the index, middle, ring and little fingers, whereas the thumb is restrained from the movements with use of an orthosis. The design approach came from state of the art advanced grippers for humanoid robots and prosthesis, in particular from the exploitation of the cable-driven under-actuated mechanisms for grasping. A series of connected differential mechanisms is the basis of an under-actuated mechanism; when considered as a grasper, the under actuated mechanism leads to an adaptive self-configurating end-effector in a way that its grasping kinematics and workspace are similar to human's. The idea itself of connecting differential mechanisms to produce multiple output adaptive system is however not new and should be attributed to Hirose in [17] and [18]. In case of robotic grippers, each under-actuated finger is kinematically under-constrained and dynamically unstable; however, when it closes on an object, the finger obtains the missing external constraints and configure its shape on the object. As the result, in case of a hand with at least three under-actuated fingers an automatic grasp around the object is performed with a proper preshaping, thus increased stability [19].

In this approach a serial under-actuated mechanism makes a great opportunity to propose a system that is easily adaptable to the human finger shape in any intermediate kinematic configuration between grasping and straighten fingers. The device concept became therefore based on a series of rigid structures called "blocks" placed on a dorsal surface of fingers all along their length; constrained by the distal block to the fingertip and by the proximal block to the palm. Other blocks are designed to come into with the finger when the subsequent phalanges go out of common plane in the grasping movement. Fingers in such a configuration play a role of an object to which the mechanism adapts gaining external references while in contact with the finger.

All blocks are conjunct in the way that adjacent blocks can separate and rotate in respect to each other only by a specific distance and angle. Fingers' straightening movement is evoked when a cable passing through all the blocks, constrained to the last block, is being pulled from the proximal side of the device by a DC motor. Such a behavior is due to the reaction forces induced between blocks and a finger as well as between adjacent blocks when compressed by the cable. On this basis, as an only symbiotic system, a finger which is connected to the exoskeleton by the most distal phalange is forced to follow the movement of the exoskeleton while the one adapts its shape to the corresponding finger beneath to minimize the reaction forces.

In this framework a design with vast space for the knuckles was proposed (Fig.2, a). This first design was structurally complicated and difficult to be assembled. It lacked proper pulling force because the cable guiding system was not rigid enough and the size of the components was not suitable to consider it applicable. Brief tests showed that a system composed of cuboid blocks as the serial components - instead of complicated shape elements as in the first prototype - do not create excessive pain on the finger being at the same time much simpler in manufacturing and assembly (Fig.2, b). It was observed that serially placed cuboid blocs have to have a limiter of the separation distance between adjacent blocks in order to equally distribute straightening force between all of the components when the finger is flexed. This was achieved by mounting a slack wire between each block. Such design lacked proper constraint to the palm and the separation limiter was not reliable. Moreover, the blocks had a tendency to rotate along the finger, slipping to its sides. The key aspect of this serial under-actuated system occurred to be a separation

limiter which had to diminish the unwilled mobility of the structure (rotation along the finger's length) and provide the equal distribution of the straightening force between all the components. To answer those necessities a chain structure was implemented in the third design (Fig.2, c). With this solution the system for each finger became restrained from rotating along longitudinal plane, while allowing the blocks to be free to rotate in sagittal plane of the hand. The chain structure was therefore designed to be passing through the center of each cuboid block creating a spine-like structure. In the final design (Fig.2, d) the spine-like structure - called a Fingerspine - installed inside the cuboid blocks was optimized to provide smooth rotation in sagittal plane movement and restrain the system from the rotation along the longitudinal axis without jamming and to big backlash.

Each cuboid block in the series is designed in the same manner (Fig.3, left). It is 4.8mm thick, 13mm tall and 12mm wide. In the center part of the block a rectangular shape aperture (Fig.3, a) is cut out to make a space for the Fingerspine - a chain running along the whole structure. A pulling cable that runs through each end every block is passed through the central aperture in the block (Fig.3, c). Fingerspine chain is constrained to each block with a shaft (Fig.3, h, d). In order to match a finger shape and maintain an equal pressure along a whole surface of the finger, a cylindrical cut was applied to the bottom edge of the block (Fig.3, e).

The Fingerspine chain structure consist of two very similar elements connected in series (Fig.3, f and g). They are 7.8mm long, 3mm thick and 6mm wide. With those dimensions was still possible to consider a conventional manufacturing process what significantly lowered the production costs. The surface k and m in Fig.3 is responsible for blocking the movement of the chain when too much shortened. Each second segment of the Fingerspine chain is connected to the respective cuboid block with a 12mm shaft (Fig.3, h) while the 6mm shaft connects chain segments together (Fig.3, j).

Every human-machine interaction system that comes into direct contact with human skin has to deal with a skin sensitivity to pressure and wear. In case of FEX, pressure is evoked to the dorsal side of the finger - especially at the joints' regions - when the finger is forced to straight up. Another place where a high pressure occur is the fingertip. For this reason a foam-textile cushion is placed between the finger and the device. Several solutions were tested in order to meet above requirements - rigid structures made of thermoplastics, aluminum, wires, plasters, glove's fingertips or material stripes (Fig.4, left, center). Best results were obtained with natural leather stripes formed into a loop (Fig.4, right). This solution resulted in least pain to the fingertip, gave significant amount of tactile perception to the fingertip and was easily adaptive to various fingertip sizes.

The system is restrained to the palm with a rigid, thermoplastics plate strapped with two velcro fastenings (Fig.4, right). This allowed maximizing the contact surface, thus minimizing the contact pressure, while not restraining movements of the fingers nor the wrist when attached firmly to the palm. Several schemes for attaching the device along the finger were verified (Fig.4, right) and the best results were achieved with the one presented on the index finger.

The final FEX device consist of a rigid, thermoplastics plate (Fig.5, a) strapped to the palm with two velcro fastenings (Fig.5, j), to which a mounting element (Fig.5, b and c) is attached in a manner that it can rotate, providing free abduction/adduction movement to the fingers. The main component of the system is the series of cuboid blocks (Fig.5, d) with a Fingerspine inside. Each finger is attached to the device with a leather strap (Fig.5, f) and a textile loop (Fig.5, g). The pulling cable - a bowden wire (Fig.5, h) - transfer pulling force from the motor unit and is passed through all of the cuboid blocks of a corresponding finger up to the last segment (Fig.5, e).

The last segment is pulling the finger up and ends the kinematic chain of a device for each finger. This segment is responsible for lifting the weight of the fingertip (Fig.6, *Q*). In order to lift the fingertip the force F applied by the cable has to create a higher momentum than the weight of the fingertip does ($M_{Ft} > M_{Qt}$, where $M_{Ft}=F_t \cdot r$ and $M_{Qt}=Q_t \cdot r$). In the worst case the force F_t will have the lowest values for the maximum opening angle α=34.5° that is provided by the Fingerspine. In such situation force pulling the last block is calculated to be 95% of the force applied by the cable, whereas the force inducing a momentum M_{Qt} is calculated to be 29% of the force with which the finger tip resists opening. The case shown in the Fig.6 on the right includes the behavior of amid blocks. Pulling the cable evokes a force F_i' and F_i" which direction is perpendicular to the orientation of the cable right before entering the *i*-th block. Vertical elements of this force (F_{iy}' and F_{iy}") are responsible for pushing the *i*-th block downwards straightening the whole structure and hence the finger. The FEX is therefore forcing the fingers to open by pulling the fingertip and in the same time pushing the whole dorsal surface of the finger downwards. The quantity of blocks used in the system alters the angle α. In general, the smaller the angle α is, the more force is transmitted to the fingertip thanks to less friction, whilst producing less vertical force pushing the finger downward.

The final version of the FEX device provides pulling action to index, middle, ring and small fingers all together (Fig.7). A single DC motor is exerting the pulling force to all the fingers thanks to the series of connected differentials. The control system is simple and does not need any proprioceptive sensor (e.g. hall effect encoders) at the joints, since the device self-adapts itself to the patient's fingers and any correspondent flexion axis position varies accordingly.

Only end-stroke sensors have been integrated to switch the actuation direction when the FEX is fully extended (open hand) and at the maximum cable slack (close hand), with the aim of performing a continuous rehabilitation treatment without any programming action in advance. As a result, once the FEX has been worn by the patient, the rehabilitation procedure is performed automatically; the rehabilitation supervisor has only to push the start/stop button and supervise the patient while undergoing the treatment.

The system can be easily adapted to move the fingers separately, whereas the main focus of the research was the wearable mechanism rather than simple mechanism tensioning the wires. The thumb is considered to be constrained with use of orthesis in a position allowing to pick objects. Length of each series of blocks is easily adjustable for various finger lengths. In the latest design 111 blocks are used in total for all four fingers.

V. Testing

The final prototype functionality was verified with special attention given to the comfort of wearing while the fingers were forced to open. Motivation and usability of the FEX device during the preliminary was measured using the Intrinsic Motivation Inventory (IMI) and the System Usability Scale (SUS) [20-22]. The IMI is a questionnaire that provides qualitative information with several dimensions about the content and level of motivation that a participant experience during an intervention. It is scored on a seven-point Likert scale ranging from 'not at all true' to 'very true'. A neutral score on the IMI is four, and a higher score means a more positive result on motivation. The SUS is a 10-item scale giving a global view of subjective experience of usability. Questions are scored on a five-point Likert scale ranging from 'strongly agree' to 'strongly disagree'. Scores are translated to 0-100%, with a higher score meaning better usability. Interventions that score in the 90s are exceptional, scores in the 70s and 80s are promising, and with SUS scores below 50 one can be almost certain that the product or intervention will have usability difficulties in the field [23,24].

Eight voluntaries participants were included in the study: four were normal, healthy subjects, two had chronic Traumatic Brain Injury and two were chronic stroke subjects. All participants used the system for seven days. The mean training duration per week ranged from 140 to 360 minutes per week. In general, the participants enjoyed training as reflected in the mean score on the IMI of 6.2 points, with standard deviation (SD) = 0.7 points. The mean score on the SUS is 71% (SD = 15%), indicating high marginal usability with potential for application in the field. On individual level, four participants rated usability over 70%, tree between 50% and 70% and one below 50%.

The preliminary tests on hand Range of Motions (ROM) showed that no statistical differences were found in ROM between normal and pathological subject. Pathological subjects using FEX during the Activities of Daily Living (ADL) showed no statistical differences in the ROM analysis in respect to the healthy subject that performed with and without FEX (Fig.8). It is important to notice, that achieved range of motion is completely within considered range of angular motion of the fingers proposed in Table 2.

The forces that are exerted by the FEX to the fingers in order to evoke finger opening momentum were found to be high enough to open fingers of a healthy man in age 30 completely resisting the movement (Fig.9). This was tested in closed fingers configuration as well as semi-closed (approx. 30 degrees of a configuration angle between adjacent phalanges). Therefore requirements presented in Table 3. are considered met.

VI. Conclusions

Automatic rehabilitation devices are an important aspect in the development of medical assistive technology. Wearable robotic systems for hand manipulation are frontier in this field. Lots of constraints and very high dexterity of a healthy hand sets the bar high for a mechanical device which is supposed to move inoperable fingers. Exoskeletons are usually very large especially if they are designed to control many degrees of freedom. The design of a compact, portable device strong enough to open fingers is very challenging.

The Finger EXoskeleton device presented in this paper has shown a great functionality and proves that serial kinematics, under-actuated systems with properly chosen architecture can successfully satisfy the complex task requirements related to opening human fingers while leaving free space in the inner side of the palm to freely operate the hand.

Several prototypes of the subsequent device versions were manufactured and tested. Conclusions from one to another design were implemented into the final version of the FEX device resulting in a very powerful fingers extender thanks to an innovative structure made of serially connected components called Fingerspine. This solution allowed also to keep the form and design of the system small and low profile. Fingerspine is considered usable also for any other type of wearable devices where extending movement is necessary.

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References

[1] P. Sale, V. Lombardi, M. Franceschini, Hand robotics rehabilitation: feasibility and preliminary results of a robotic treatment in patients with hemiparesis, Stroke Res Treat. 2012;2012:820931. Epub 2012 Dec 26.

[2] M. Franceschini et.al., Clinical relevance of action observation in upper-limb stroke rehabilitation: a possible role in recovery of functional dexterity. A randomized clinical trial, Neurorehabil Neural Repair. 2012 Jun;26(5):456-62

[3] Richard A. Berger, Arnold-Peter C. Weiss, Hand Surgery, Lippincott Williams & Wilkins, 2003

[4] A. Buryanov and V. Kotiuk, Proportions of hand segments Int. J. Morphol., 28(3):755-758, 2010.

[5] J. H. Christopher, Force-reflecting anthropomorphic hand masters, Armstrong Laboratory internal report, Crew Systems Directorate Biodynamics and Biocommunications Division Human Systems Center, Air Force Materiel Command, July 1995

[6] J. W. Garrett, Anthropometry of the Hands of Female Air Force Flight Personnel, Technical Report AMRL-TR-69-26, USAF Aerospace Medical Research Laboratory, Wright-Patterson AFB OH, 1970.

[7] http://www.continuing-ed.cc/hsgoniometry/goniometrystandards.pdf

[8] P. Sale, F. Bovolenta, M. Agosti, P. Clerici, M. Franceschini, Short-term and long-term outcomes of serial robotic training for improving upper limb function in chronic stroke, Int J Rehabil Res. 2014 Mar;37(1):67-73.

[9] K. N. An, L. J. Askew, and E. Y. Chao, edited by W. Karwowski Biomechanics and Functional Assessment of Upper Extremities, Trends in Ergonomics/Human Factors III, Elsevier Science Publishers B.V. (North-Holland), pp. 573-580, 1986.

[10] W. G. Darling and K. J. Cole, Muscle Activation Patterns and Kinetics of Human Index Finger Movements, J. Neurophysiology, 63(5):1098-1108, May 1990.

[11] H. Yamaura, K. Matsushita, R. Kato, and H. Yokoi, Development of Hand Rehabilitation System for Paralysis Patient – Universal Design Using Wire-Driven Mechanism, 31st Annual International Conference of the IEEE EMBS, September 2-6, 2009, Minneapolis, Minnesota

[12] M. Fontana, M. Bergamasco, F. Salsedo, Mechanical Design and Experimental Characterization of a Novel Hand Exoskeleton, Proceedings of the AIMETA 2009, Ancona, Italy, 14-17 September 2009

[13] A. Wege, G. Hommel, Development and Control of a Hand Exoskeleton for Rehabilitation of Hand Injuries, Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, 2005, Berlin, Germany, pp. 3461–3466

[14] M. Mulas, M. Folgheraiter and G. Gini, An EMG-controlled Exoskeleton for Hand Rehabilitation, Proceedings of the IEEE 9th International Conference on Rehabilitation Robotics, June 28 - July 1, 2005, Chicago, pp. 371-374

[15] http://www.tyromotion.com/en/products/amadeo

[16] H. Kawasaki, S. Ito, Y. Ishigure,Y. Nishimoto, T. Aoki, T. Mouri, H. Sakaeda, and M. Abe, Development of a Hand Motion Assist Robot for Rehabilitation Therapy by Patient Self-MotionControl, Proceedings of the IEEE 10th International Conference on Rehabilitation Robotics, June 12-15, 2007, Noordwijk, The Netherlands, pp. 234-240

[17] S. Hirose, Connected Differential Mechanism and its Applications, Proceedings of 1985 International Conference on Advanced Robotics, pp. 319–325, Tokyo, Japan, September, 1985.

[18] S. Hirose, Biologically Inspired Robotics, Oxford University Press,translated by P. Cave and C. Goulden, 1993

[19] S. Montambault and C.M. Gosselin, Analysis of under actuated mechanical grippers, ASME Journal of Mechanical Design 123, no. 3, 367-374, 2001

[20] R. M. Ryan, Control and information in the intrapersonal sphere: An extension of cognitive evaluation theory, Journal of Personality and Social Psychology, Vol 43(3), Sep 1982, 450-461

[21] E. McAuley, T. Duncan, V. Tammen, Psychometric properties of the Intrinsic Motivation Inventory in a competitive sport setting: a confirmatory factor analysis, Res Q Exerc Sport. 1989;60(1):48-58.

[22] J. Brooke edited by P. W. Jordan, B. Weerdmeester, A. Thomas, I. L. Mclelland, SUS: A Quick and Dirty Usability Scale, Usability Evaluation in Industry. Taylor & Francis; 1996.

[23] A. Bangor, P. Kortum, J. Miller, Determining what individual SUS scores mean: Adding an adjective rating scale. Journal of usability studies. 2009;4(3):114-23.

[24] A. Bangor, P. Kortum, J. Miller, An empirical evaluation of the System Usability Scale, International Journal of Human-Computer Interaction. 2008;24(6):574-94.

TABLE I. LENGTH OF HUMAN FINGERS' PHALANGES - AVERAGE VALUES TAKEN FROM [3] AND [4]

	Length [mm]			
Finger / Phalange	Index	Middle	Ring	Little
Metacarpals	-	-	-	-
Proximal phalanges	42,7	43,4	41,4	32,7
Intermediate phalanges	24,2	28,6	25,6	18,1
Distal phalanges	21,4	23,6	21,2	19,7

TABLE II. CCONSIDERED RANGE OF ANGULAR MOTION IN JOINTS [7]

finger	Range of movements [˚]			
	MCP		PIP	DIP
	Abduction - Adduction	Extension - Flexion	Extension - Flexion	Extension - Flexion
INDEX	-20 ÷ 20	0 ÷ 80	0 ÷ 90	0 ÷ 70
MIDDLE	-20 ÷ 20	0 ÷ 80	0 ÷ 90	0 ÷ 70
RING	-20 ÷ 20	0 ÷ 80	0 ÷ 90	0 ÷ 70
LITTLE	-20 ÷ 20	0 ÷ 80	0 ÷ 90	0 ÷ 70

TABLE III. MAXIMUM FORCES EXERTED BY HUMAN FINGERS MID-PHALANGE SURFACE WHILE POWER GRASP/ZERO CONFIGURATION [9]

	Force [N]			
Finger / Phalange	Index	Middle	Ring	Little
Proximal phalanges	42	24	15	7
Intermediate phalanges	22	40	28	20
Distal phalanges	62	68	44	31

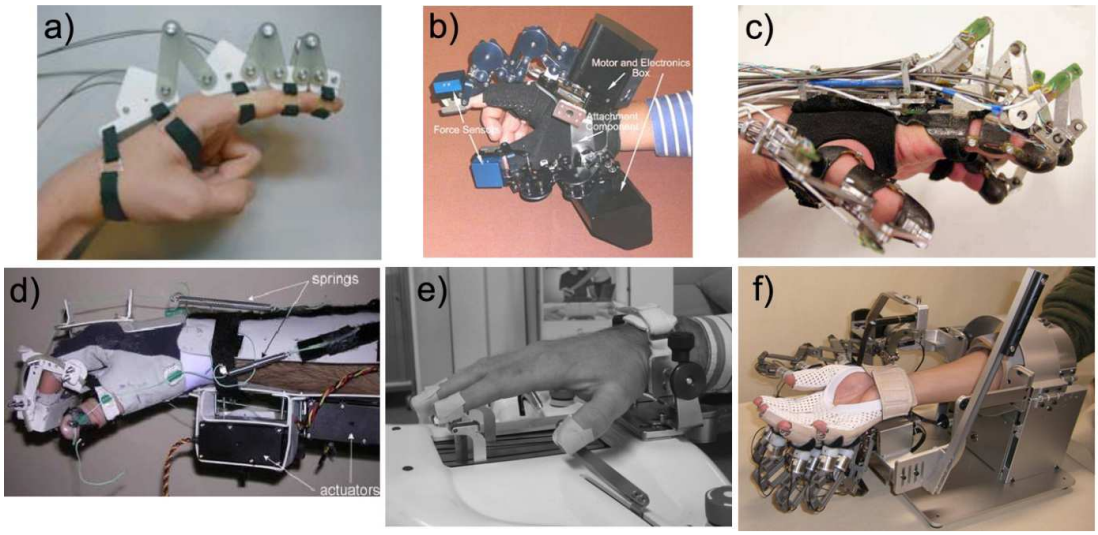

Fig.1 Various hand rehabilitation devices: a) The University of Tokyo Hand [11], b) Percro Hand [12], c) Berlin University Hand [13], d) Milan University Hand [14], e) Amadeo [15], f) Gifu University Hand [16]

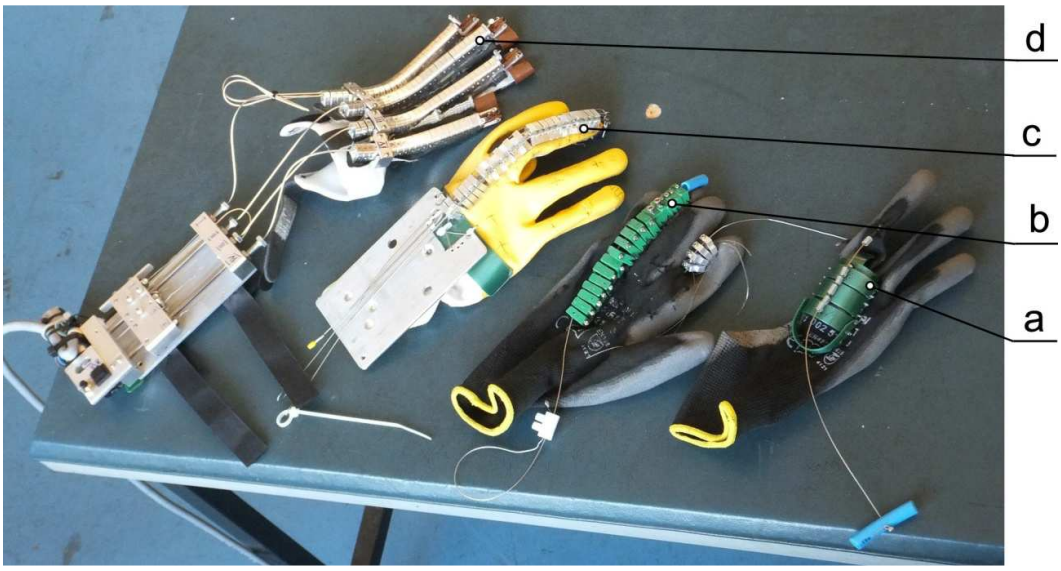

Fig.2 Consecutive FEX device designs - a) first prototype, b) and c) intermediate prototypes, d) latest design

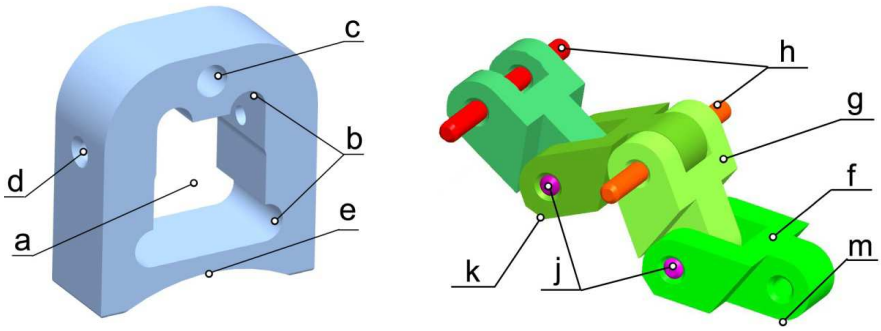

Fig.3 Subcomponents of the FEX - cuboid block (left) and the Fingerspine structure (right)

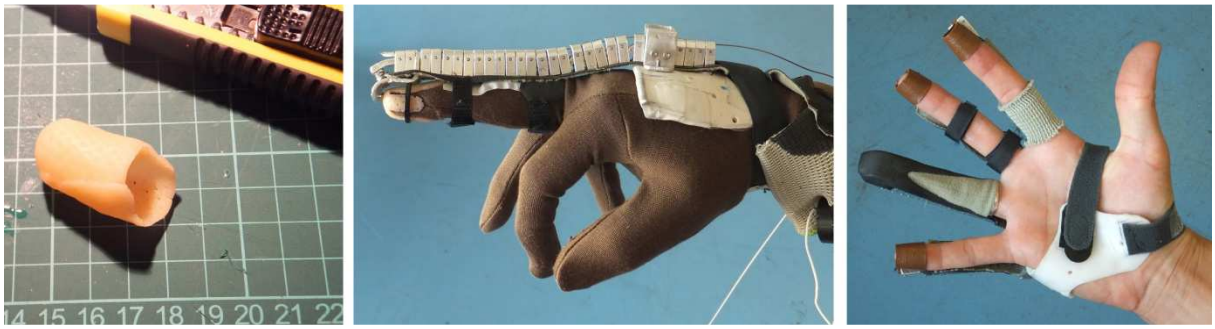

Fig.4 Finger tip cast (left), semi-rigid finger-tip mounting (center), various finger attachment schemes (right)

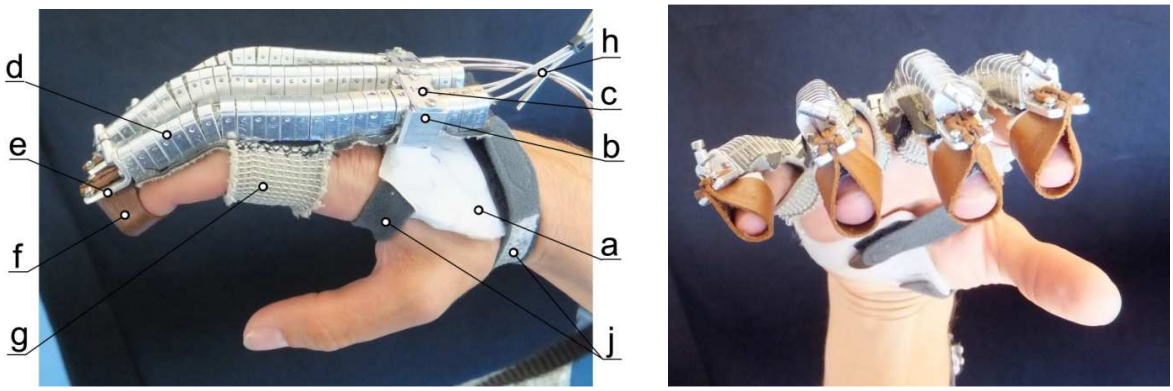

Fig.5 FEX worn on a hand - side view (left), front view (right)

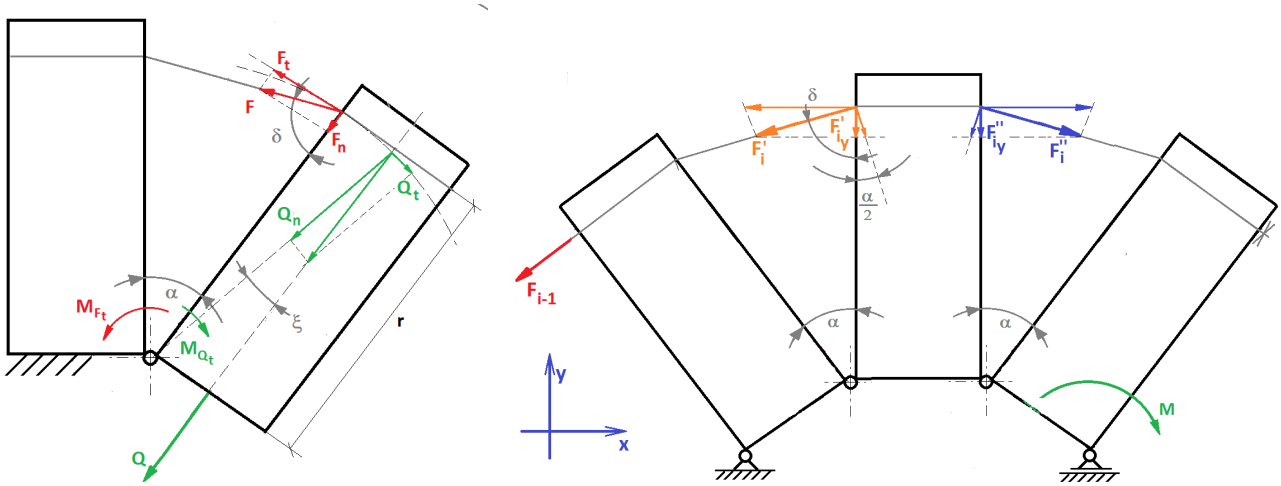

Fig.6 FEX structure working principles - last block case (left) and the amid block case (right)

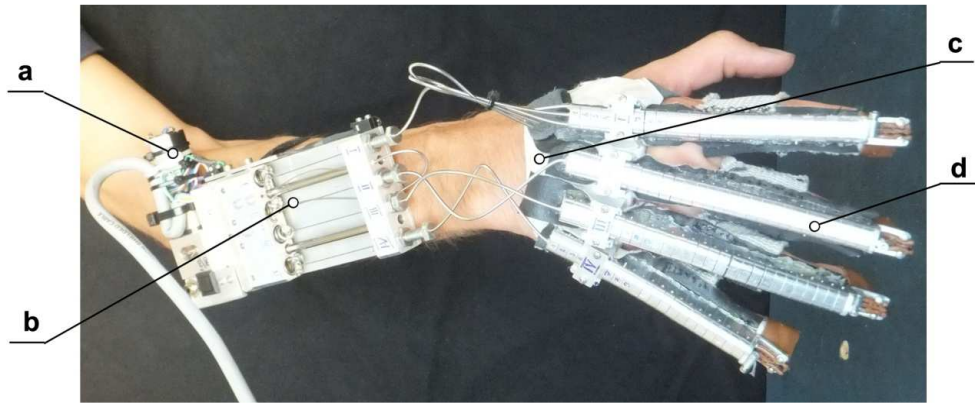

Fig.7 FEX device - a) motor, b) wires tensioning unit, c) palm mounting plate, d) pulling chains

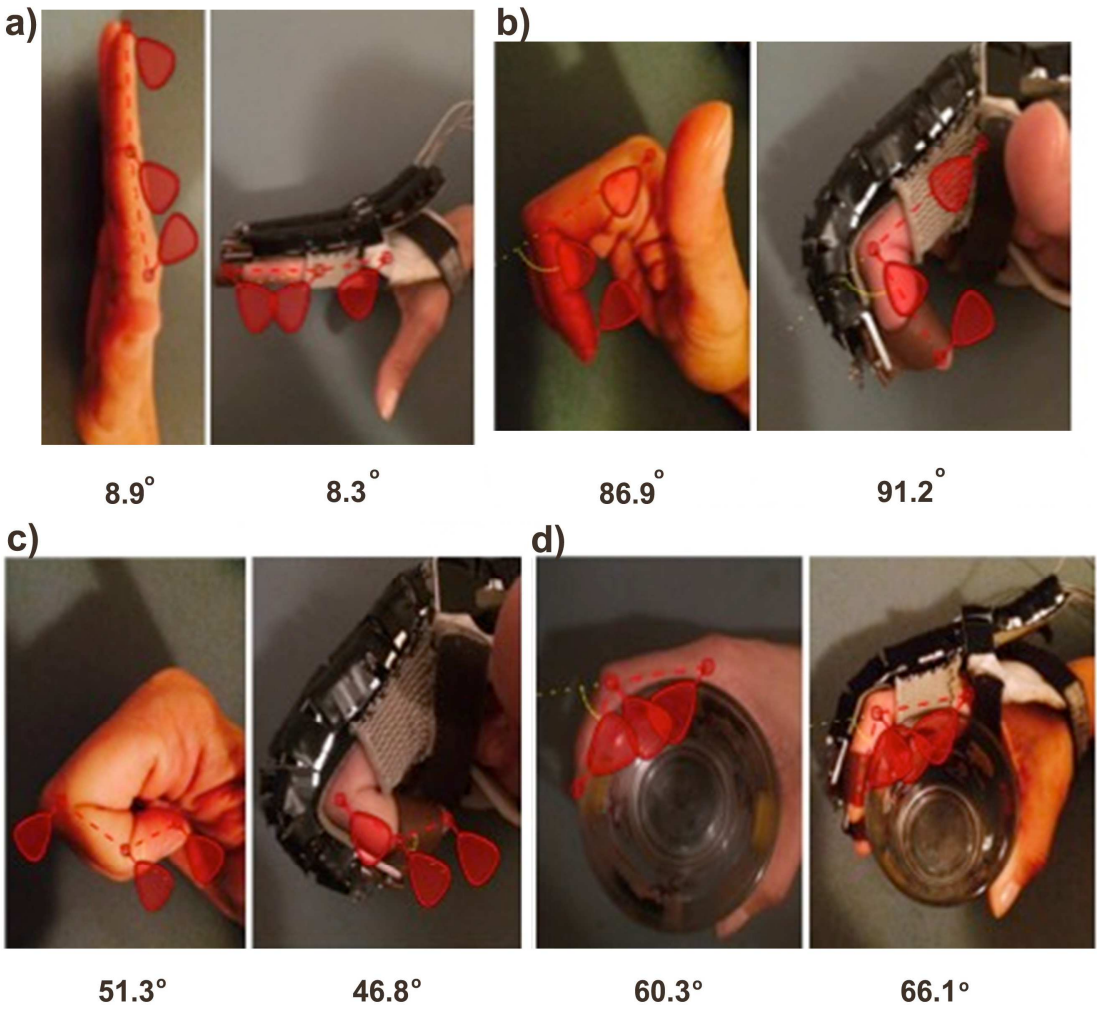

Fig.8 - Range of motions for bare fingers in comparison to fingers equipped with FEX device: a) straight fingers configuration, b) proximal interphalangeal maximum configuration angle, c) distal interphalangeal maximum configuration angle, d) exemplary power grasp.

Fig.9 - FEX device tested for being possible to wear even during very complex tasks like handshake and to be able to force open semi-closed fingers (left), FEX device with markers glued onto (right).