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# Automated design of a custom-made 3D printed hand rehabilitation robot

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*Abstract: A frequent consequence of stroke is limited hand function. Numerous studies have shown that repetitive passive training enhances the rehabilitation process. This contribution presents a custom-made hand rehabilitation robot, motivated by the high anthropometric variances in hand and finger anatomy. The individualized design is proposed to ensure an ergonomic interface which allows long-time wearing. To provide a cost-effective production, we present an automated design process. The individual fingers are manufactured monolithically using the selective laser sintering of polyamide. The presented device is portable and can be used for training as well as for grasping objects.*

## I. Introduction

Impairment of hand function is one of the most common effects of neurological diseases, such as stroke. In 2017, 259,594 people in Germany suffered a stroke [1], with 60% of patients having limited hand mobility [2]. Numerous studies show that intensive and repetitive training increases the neuronal plasticity of neurological patients [3]. Hand rehabilitation devices used for this application can be classified into three categories:

- *Control of end effectors:* Forces on single finger limb (e.g. Amadeo, tyromotion, Graz, Austria)
- *Driven Objects:* Expansion and contraction of held objects (e.g. Reha Digit, Reha Stim, Berlin, Germany or InMotion Hand, Bionik Laboratories, Toronto, Canada)
- *Exoskeletons:* Follow the anatomy of the hand. (e.g. Hand of Hope, Rehab Robotics, Hongkong, China or Gloreha Sinfonia, Idrogenet, Lumezzane, Italy)

Current research projects on portable or stationary hand exoskeletons can be classified by their mechanical design into soft robotic approaches using gloves and dynamic orthoses with rigid frames. First approaches of 3D printed hand exoskeletons have been investigated [e.g. 4, 5] and also a design process for individualized exoskeleton joints has been presented [6]. Due to high anthropometric variation of hands, especially in the fingers, user-specific adaptability in design is necessary to produce physiologically accurate movements. Data from the U.S. Army [7] shows that the correlation between hand length, palm length, hand breadth and hand circumference is low (coefficient of correlation < 0.5) for 6 of 12 possible combinations for men and 4 for women. This indicates that standard sizes cannot offer a perfect fit, as e.g. a small hand circumference does not correlate with a short palm length as expected for a small size. Nevertheless, a precise fitting is the key aspect to avoid discomfort, frustration by the patient and rejection of the rehabilitation program [8]. This is why the main design challenges are the limited available space, differences in hand sizes and coping with compliance of skin tissue [9].

## II. Material and methods

This project aims to develop a cheap but custom-made hand rehabilitation robot. To produce individualized devices, an automated design and manufacturing process is required.

### II.I. Kinematic model and anthropometry

The aim of the exoskeleton is to support the user's grasping motion. Therefore, two fingers – the index and the middle finger – are actuated with two joints each (see Figure 1a). The thumb and the first finger joints (metacarpophalangeal joint) are non-actuated but fixed in a functional position for grasping by elastic elements.

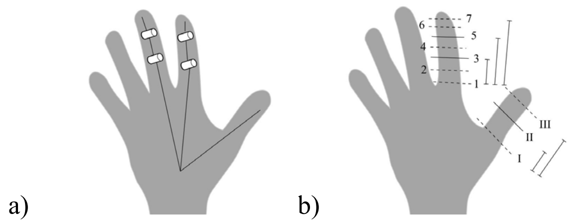


*Figure 1: (a) Kinematic model of the hand exoskeleton (distal and proximal interphalangeal joints). (b) Position of measurements defined by planes perpendicular to the finger axis.*

To ensure an optimal fit, the position of joints and finger size was measured. Therefore, planes at the knuckles and between the finger joints are defined (see Figure 1b). At each plane the finger diameter was measured parallel and perpendicular to the palm and also the distances between the proximal planes, planes of joints and distal planes (1-3, 1-6, 1-7, I-II, I-III) are measured.

### II.II. Mechanical Design

The finger overtubes are individualized in circumference, joint position and length. To be able to adjust the finger structures to the varying anatomies, a monolithic flexure hinge design is chosen (see Figure 2). The parallel arranged flexure hinges can be aligned to position of the real finger joints and adjusted in stiffness and deflection angle [10]. Flexure hinges of this kind can withstand more than 10.000 cycles of deflection [10]. Each joint is realized by a chain of four flexure hinges. This allows a small movement of the rotation axis and therefore an alignment to the natural movement. The mechanical design of each joint prevents hyperextension (end stops in neutral position) and allows a flexion angle of 90°, which is sufficient regarding the range of motion of the finger joints. The movement of the finger is actuated with Bowden wires. The custom-made fingers can all be plugged into a standard actuation unit that is the same for any user.

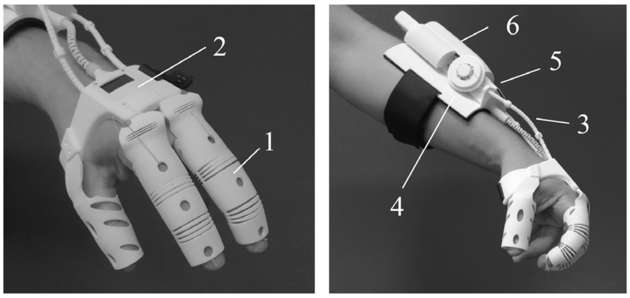


*Figure 2: Prototype of the hand rehabilitation device: Finger overtube (1), finger base unit with display (2), Bowden wire (3), pulley (4), buttons (5) and actuation unit (6).*

## II.III. Actuation and Control

As described, the focus of this work is the design of patient-individual finger structures for a rehabilitation robot, while the design of the actuation unit is kept simple. There are two operating modes: Grasping mode and training mode. Training mode repetitively opens and closes the hand. Three buttons (open, close, training) allow the patient to activate these modes. The robot also creates a WiFi access point and serves a web application via HTTP enabling the patient to control the robot using any WiFi-capable smartphone. A display which is mounted on the back of the hand shows information such as the current mode, finger position, training speed and progress. User input is processed by a microcontroller that controls bending or stretching of the fingers accordingly. For each finger, the microcontroller controls a servo motor linked to a twin cable pulley which actuates the finger via Bowden wires. When bending a finger, one Bowden wire is rolled up and the other one is rolled off. As the Bowden wires responsible for bending and stretching need to be of different lengths, the pulleys are of different radius.

## II.IV. Design and manufacturing process

The process of making custom-made hand exoskeletons is shown in Figure 3. First, the anatomy of the hand is captured by measuring according to section II.I. Then, the individual finger overtube structure is calculated and designed. A parameter-controlled model is used for this purpose. All mechanical components are then produced by selective laser sintering (SLS) with polyamide PA 2200 (EOS, Krailling, Germany), which is biocompatible according to EN ISO 10993-1. Together with the electronic components, wires and Velcro fasteners, the complete robot is assembled. The total weight of the robot carried on the arm is less than 350 grams. Additionally, the device uses batteries which can be transported in a trouser pocket or attached to a wheelchair.

**Measurement:**
Marking of joint position and planes, measurement of diameters and distances

**Calculation of the individual design:**
Parameter-controlled model of the finger structure

**Additive manufacturing:**
SLS of polyamide

F*igure 3: Process of making individual hand exoskeletons: First the hand's anatomy is measured, then the individual design is realized by a parameter-controlled model of the finger structure and finally, the exoskeleton is manufactured by SLS of polyamide.*

## III. Results and discussion

Within the scope of this work, a concept for the design of patient-individual hand rehabilitation robots is shown. The basis for this is an automated design process in combination with selective laser sintering as suitable additive manufacturing technology for the monolithic finger exoskeletons. The custom-made robotic device was manufactured for n=3 healthy individuals. All participants reported that sufficient comfort was achieved. Objects up to a water bottle with a total weight of 500 g could be grasped sufficiently. Nevertheless, during daily activities the robot's ability to grasp an object highly depends on the object surface properties. For future development different coatings of the finger structures and a positionable thumb could be investigated.

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