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Design of a Haptic Palmar Device with Thumb Flexion and Circumduction Movements for Sensorimotor Stroke Rehabilitation

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***Abstract*— To address the clinical need for high-intensity, repetitive sensorimotor hand training after stroke, we developed in a first step a novel haptic device for practicing finger movements. Because the thumb plays a fundamental role in the loss of autonomy and prehensile functions after stroke, we present here the development of a thumb module that complements our previous design. The novelties of our device are that it reduces the complexity to a minimum from a user perspective while still allowing anatomical thumb flexion/extension and circumduction movements with a highly functional range of motion. Moreover, it enables sensorimotor training thanks to its backlash-free and backdrivable actuation that allows for high-quality haptic rendering. Our device was co-created together with clinicians to incorporate clinical and anatomical requirements, and therefore, maximize its clinical relevance.**

I. INTRODUCTION

Three out of four stroke survivors experience long-term upper limb impairments that result in reduced autonomy and quality of life [1]. To regain as much of their former hand motor skills as possible, patients should undergo an intense and repetitive rehabilitation training [2], [3], which robotic devices could potentially support.

Although many hand rehabilitation devices have been developed up to date (see [4] for a review), they are not delivering the anticipated treatment outcomes [5], probably because the majority of current hand rehabilitation robots does not support patients to regain the functional movements needed to perform Activities of Daily Living (ADL). Furthermore, one of the main obstacles listed for the poor clinical acceptance of these sophisticated devices is their high complexity [6]. Most professionals are willing to spend less than 10 minutes for the patients' set-up [7].

We recently designed a novel clinical-driven haptic device that allows to train collective finger movements of the index to little finger. Our solution combines an effortless setup, sensory training, and a large range of motion in a palmar device [4]. The sensorimotor training is achieved through high-quality haptic rendering, which allows patients to not only rely on visual feedback – e.g., from a computer screen – but to also integrate somatic feedback (tactile, proprioceptive) during training [8], [9]. We employed optimization methods to meet mechanical requirements such as simple setup and the accommodation of diverse hand sizes with anatomical requirements such as the need for a large range of motion of fingers extension/flexion motion and ergonomic cylindrical grasp. Here, we present the design of a thumb module that can be used in conjunction with our palmar device to replace the previous fixed thumb support and to enhance the sensorimotor training of ADL.

Literature suggests that the thumb is essential for prehensile functions of the hand [10]. Moreover, a survey on clinical requirements for robotic hand rehabilitation that we conducted amongst clinical personnel revealed that not only finger extensions are crucial movements to be trained, but also the training of independent thumb movements is indeed of high importance [7].

The kinematics of the thumb are highly complex, and various models have been proposed to accurately represent the thumb kinematics based on anatomical observations, mostly with five degree of freedom (DoF). While Giurintano et al. [11] suggest a virtual five-link model, Chang et al. [12] introduce a virtual pronosupination axis. Yet, it is generally accepted that the two axes of the carpometacarpal (CMC) joint are non-orthogonal, non-intersecting [13] and their orientation suffers from a high inter-subject variability [12], which makes accurate modeling difficult. While anatomical considerations should be taken into account when designing devices to support thumb training, such a degree of anatomical accuracy might not be required to generate a comfortable movement in a robotic rehabilitation device. This is especially true when the aim is to develop an easy-to-use device to maximize clinical acceptance. For example, Coert et al. [14] showed that circumduction – which is a complex movement from an anatomical perspective as it includes flexion/extension and adduction/abduction of the CMC joint – can be approximated as a movement of the thumb fingertip on the surface of a cone that originates in the CMC joint. This concept has been adopted in the design of several high-degree of freedom devices, e.g., [15], [16].

Here, we present a thumb mechanism solution that is composed of two distinct movements: Flexion/extension and circumduction. The design was based on the assumption that the flexion/extension can be approximated through a circular one DoF movement, while the circumduction movement is based on the cone model from Coert et al. [14]. The parameters of our mechanical device were selected based on an optimization step that took into account four different hand sizes, from large to small. In this work, no experiments involving humans were performed and no ethical approval was required.

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II. METHODS

A. Requirements

We recently developed a novel clinical-driven robotic hand rehabilitation device (PRIDE), which is capable of fine haptic rendering and that supports physiological full flexion/extension of the fingers while offering an effortless setup [4]. To develop a compatible thumb module that preserves the kinematic, haptic, and ergonomic characteristics of our palmar device, a few key points had to be considered. The synthesis of our palmar device was based on our definition of four standardized hand sizes ranging from small (5th percentile women) to large (95th percentile men) according to anthropometric databases [17], [18]. Importantly, the device is designed with four size-specific exchangeable handles to avoid the need of adjusting any movable mechanical parts, and thus, ensuing an easy and fast setup. During the mechanical design synthesis, the proximodistal positions of the handles for these four specific hand sizes were determined by optimization and are, therefore, fixed. In the existing design, all hand sizes are vertically aligned at the medial border (i.e., the side of the small finger). However, for the design of the thumb module, the vertical position for each specific hand size could still be moved along an axis that lies in the transversal plane at an angle of 25° relative to the transversal axis of the hand (see Fig. 1). We leveraged this to design our new thumb module.

B. Mechanical Design

1) Thumb Flexion/Extension: As far as flexion/extension movements are concerned, the thumb fingertip movement could be tracked by a mechanism with joints coincident with the thumb anatomical joints (see e.g., [16]). However, because it has been reported that only a subrange of the available range of motion (RoM) of the thumb joints is used during functional grasps [19], we suggest using a one DoF mechanism consisting of one lever and a thumb fingertip support, hereinafter called end-effector. The rationale is that as long as the range of motion is small – as is the case in most grasping movements, e.g., during pinch or precision grasp – the spiral-shaped thumb fingertip movement during flexion/extension can be approximated by an arc.

We propose the mechanism depicted in Fig. 1 and Fig. 2 to accommodate the thumb fingertip flexion and extension movement. At a certain offset (x_c, y_c) from the thumb CMC joint, an axis of rotation is placed and the lever with length b_1 is attached. The end-effector is then placed at the end of this lever with a fixed angle β.

To allow the mechanism to work for different hand sizes, we modified our handles such that the index metacarpophalangeal joints of all hand sizes are on the same height – i.e., aligned with respect to their mediolateral position. The principle is depicted in Fig. 1. Although the CMC joints of the small and large hand are far apart, the thumb fingertip of the large hand is brought close to the thumb fingertip of the small hand just by slightly flexing its CMC joint.

The aforementioned design parameters, as well as the lengths $b_2^{(i)}$ that define the position of the contact point

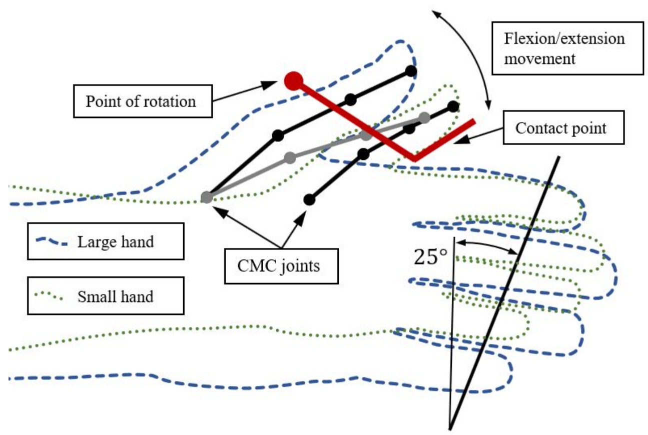

Fig. 1. Schematic overlay of small and large hand as well as the proposed mechanism. By slightly flexing the large hand thumb, the thumb fingertips of both hand sizes get sufficiently close to allow for a simple one DoF mechanism that fits all hand sizes. Note that the small hand is moved upwards along the 25° tilted line indicated at the fingertips compared to the large hand initial position design.

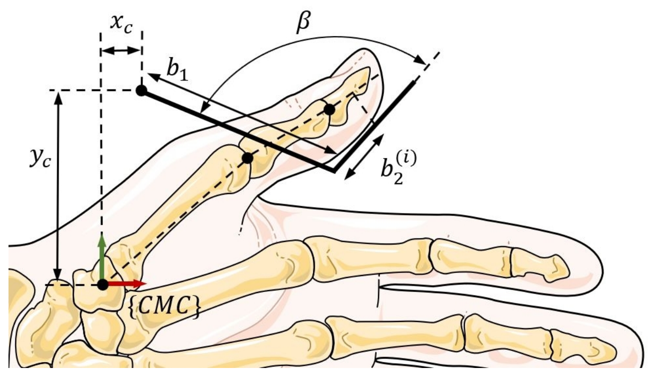

Fig. 2. Schematic representation of the proposed mechanism for thumb flexion/extension depicted for one hand size. Note that each hand size will have a specific length b_2, which results in a slightly different contact point with the end-effector. Underlying image used with permission of [20].

for each thumb size (i, for a total of four possible sizes), were found using an optimization approach. We employed a differential evolution global optimization algorithm to find the optimal position of the axis of rotation (x_c, y_c) and the design parameters (b_1, β, and size-specific $b_2^{(i)}$) such that the end-effector tracks the thumb fingertips movements of the four hand sizes as closely as possible. The thumb movements were computed based on a three DoF serial kinematic chain model with constant inter-joint couplings, as presented in [4]. The optimization was performed by first discretizing the thumb and end-effector paths for the four sizes in five equally spaced points each. Note that the mechanism is identical for all thumb sizes, however, the different sizes lead to distinct contact points on the end-effector, and hence to size-specific end-effector paths. The optimization consisted in minimizing a cost function with three elements: 1) the mean of the Euclidean differences of each of the thumb paths and its corresponding end-effector path; 2) the mean of the angular deviations between the end-effector and thumb, whereby 3° angular deviation was equally weighted as 1 mm Euclidean deviation; 3) because the spacing between the discretized points was also size-specific and subject to the optimization, we introduced a penalty term to enforce similar end positions (flexed thumb) of all the paths.

2) Circumduction: Similar to [15], the entire flexion/extension of our mechanism is moved on a circular path as the thumb performs a circumduction movement. Previous mechanisms based on the cone model [14] assumed that the cone axis originates in the thumb CMC joint and that it is parallel to the longitudinal axis of the index finger. However, in experiments using rapid prototyping, we found that a more comfortable circumduction movement can be realized if the cone axis is tilted forwards in the transversal plane of the hand by 20°. To realize a mechanism based on the cone model, a remote center of motion (RCM) was required to avoid any collision with the hand. We chose a parallelogram-based RCM [21] designed to occupy minimal space while still retaining enough rigidity.

The circumduction motion can be used to position the thumb prior to a grasping movement, independently of the flexion/extension of the fingers. We therefore recognized the need for a highly backdrivable actuation that would not hamper any self-initiated movements. Hence, we aimed for a capstan drive, similar to the actuation of the fingers [4].

III. RESULTS

The results of the design parameter optimization is depicted in Fig. 3. The root-mean-square (RMS) Euclidean deviation between the end-effector and the thumb fingertip paths for all four sizes was found to be 2.85 mm, with an angular deviation of 8.23°.

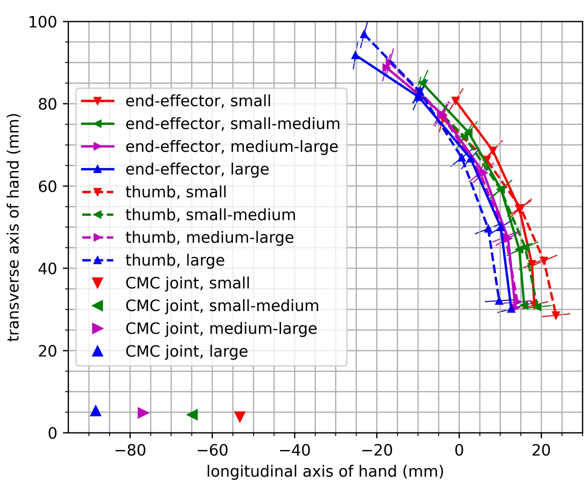

Fig. 3. Resulting optimized end-effector mechanism path and thumb fingertip path for each of the four hand sizes after optimization. The dashed lines represent the thumb paths while the solid lines denote the end-effector paths for each hand size (represented with different colors). Note that, although the mechanism is identical for all thumb sizes, the different contact positions lead to size-specific end-effector paths. The position of the CMC joints positions (given by our previous design) are represented by the filled triangles.

A new set of handles was designed that takes into account the new vertical alignment of the different hand sizes. Moreover, these handles provide an almost seamless transition between the main handle and thumb end-effector, which facilitates the setup. Structural parts of the novel thumb module were 3D-printed in carbon-reinforced poly-lactic acid (PLA), while parts with skin contact were manufactured from standard PLA.

We realized the actuation of the thumb flexion/extension with a RC servomotor (Hitec D625MW, Fig. 4) that we modified with an external position encoder (CUI AMT10E). The actuation of the circumduction RCM mechanism (Fig. 4) is achieved through a DC motor (Maxon DCX22S) that drives a 7 mm pulley which then actuates a large 190 mm pulley with a steel cable for a backlash-free and backdrivable actuation. The thumb flexion/extension actuation provides 1 Nm torque, leading to ≈ 14 N of force while the circumduction actuation is capable of 0.4 Nm torque. Both degrees of freedom can be either position or impedance controlled, depending on the task to be performed. The RoM is approximately 0° - 65° for flexion/extension and 0° - 80° for circumduction, which allows to bring the thumb in a functional opposed position for grasping (see exemplary grasp with prototype in Fig. 5).

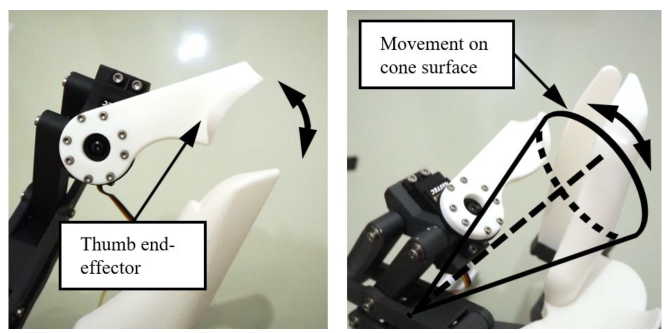

Fig. 4. Left: Prototype of the flexion/extension mechanism. Right: Remote center of motion mechanism that allows the circumduction movement. The entire flexion/extension mechanism is rotated around the circumduction axis.

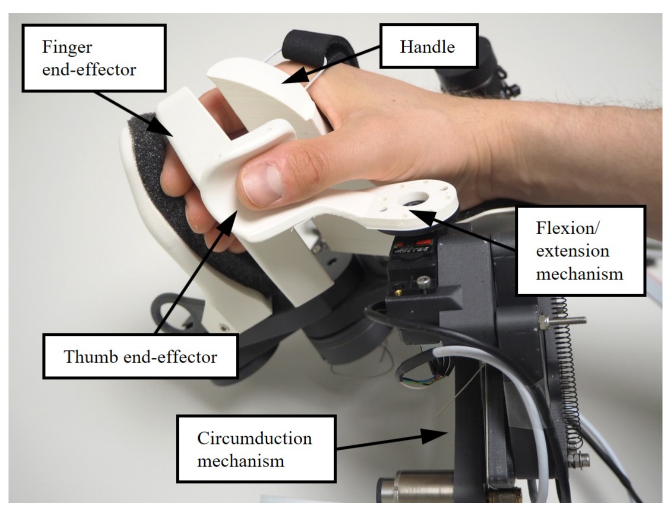

Fig. 5. Prototype of the PRIDE device with the presented thumb module during a grasping movement with opposed thumb.

IV. DISCUSSION AND CONCLUSION

We presented a novel robotic device for sensorimotor hand rehabilitation that combines collective finger movements with thumb flexion/extension and circumduction. Our device is a result of research that indicates the importance of sensorimotor training after stroke that resembles ADL as well as the demand for high usability in robotic devices. The novelties of our device are: 1) it reduces the complexity to a minimum from a user perspective while still allowing movements with a functional range of motion, and 2) it enables sensorimotor training due to high quality haptic rendering.

After identifying that a combined flexion/extension and circumduction thumb mechanism could greatly enhance the possibilities for training of prehensile hand functions in stroke patients, we employed an optimization approach to synthesize the design parameters for our design. Finally, we manufactured and assembled a first prototype.

Our work also has some shortcomings. The thumb flexion/extension actuation possesses a higher inherent impedance (i.e., large gear ratio and friction of the servomotor) compared to the cable-driven mechanisms of the thumb circumduction and finger flexion/extension actuation. However, we do not expect this to hamper grasping or the quality of haptic rendering because the effective thumb flexion/extension movement is relatively small during grasping [10]. Further, our quest for a device with a minimal number of adjustments – i.e., only the size-specific handle and the hand/finger attachments – is only possible with fixed kinematic designs, which might result in non-optimal finger and thumb paths for individuals that might differ considerably from our standard hand sizes. It is also noteworthy, that even in the found optimal solutions, a small amount of sliding of the thumb on the end-effector during large flexion/extension movements is inevitable due to the circular path of the end-effector. Finally, our thumb module needs further work to equip it with attachment straps for the thumb and to thoroughly test and validate the actuation.

After finalizing the integration of the new thumb module into our existing device, we plan to conduct a pilot study with stroke patients to investigate the usability and feasibility of our device.

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