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Design of a Robotic Device for Assessment and Rehabilitation of Hand Sensory Function

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***Abstract*—This paper presents the design and implementation of the Robotic Sensory Trainer, a robotic interface for assessment and therapy of hand sensory function. The device can provide three types of well controlled stimuli: (i) angular displacement at the metacarpophalangeal (MCP) joint using a remote-center-of-motion double-parallelogram structure, (ii) vibration stimuli at the fingertip, proximal phalange and palm, and (iii) pressure at the fingertip, while recording position, interaction force and feedback from the user over a touch screen. These stimuli offer a novel platform to investigate sensory perception in healthy subjects and patients with sensory impairments, with the potential to assess deficits and actively train detection of specific sensory cues in a standardized manner. A preliminary study with eight healthy subjects demonstrates the feasibility of using the Robotic Sensory Trainer to assess the sensory perception threshold in MCP angular position. An average just noticeable difference (JND) in the MCP joint angle of 2.46° (14.47%) was found, which is in agreement with previous perception studies.**

I. Introduction

In addition to impaired motor function, deficits in sensory perception are common in stroke survivors. However, the prevalence reported in the literature varies widely, with values ranging from 10% to 90% [1]. Sensory impairments after a stroke can range all the way from reduced perception of touch, pressure, vibration, shape, position or pain – or a complete loss thereof – to light impairment mainly affecting fine manipulation of small objects. Impaired sensory function, especially at the level of the hand, can severely impair patients in performing activities of daily living (ADL), perceiving and interacting with the environment. Sensory feedback is essential for the learning and likely also the recovery of motor skills, as sensory feedback drives motor adaptation through sensory prediction errors [2]. Further, sensory feedback is also involved in on-line corrections, e.g. through spinal reflexes, or grip force modulation to manipulate small objects and prevent slipping [3].

Studies suggested that stroke patients suffering from high and persistent sensory impairment have a poor prognosis for functional recovery [4], [5]. However, conventional rehabilitation therapies after stroke focus strongly on motor training [6], and clinical assessment scales of sensory impairment (e.g. Semmes-Weinstein monofilament test, two-point discrimination, Nottingham Sensory Assessment) lack objectivity, sensitivity and suffer from high variability [7]. There is thus a need for the development of novel techniques to assess sensory impairments, gain insights into the prevalence

Fig. 1. The Robotic Sensory Trainer for assessment and therapy of hand sensory function. A touch screen computer placed over the interface collects responses from the user and can generate visual and auditory stimuli.

of different types of sensory deficits, and propose therapy focusing specifically on the retraining of sensory function.

Robotic devices offer new solutions to complement conventional stroke rehabilitation, as they can provide repetitive, well-controlled and intensive training [8]. Moreover, thanks to force, position and further sensors, robots offer the possibility to objectively measure participation and performance during training, allowing effective assessment of impairment [9]. Results of clinical trials using robotic devices for arm and hand rehabilitation suggest that robot-assisted treatment can contribute to improving arm and hand motor function and strength [10]–[14].

Robotic devices can also be used to stimulate the sensory pathways by providing haptic feedback or various types of force fields. However, most existing robotic systems are designed for motor rehabilitation and only use sensory stimulation as a communication channel with the user, e.g. as feedback signal when a task is performed correctly [15], or to simulate objects in virtual reality environments [16]. To our knowledge, there is currently no robotic interface that directly targets sensory training in order to improve the way subjects perceive and interpret various sensory stimuli.

This paper presents the design and development of a novel robotic device, the Robotic Sensory Trainer (Fig. 1). The objective of this device is to better assess and quantify hand sensory deficits in stroke survivors by measuring the ability of patients to detect and localize (spatially and temporally) three types of sensory modalities relevant to object manipulation, namely vibration, pressure, and displacement. These stimuli can be applied in a standardized, automated and repeatable way. This approach can be extended to sensory therapy, or even to concurrent therapy and assessment. Results of a preliminary study on a group of healthy subjects using the Robotic Sensory Trainer to assess the Just Noticeable Difference (JND) in index finger displacement are also presented to validate the use of the device to assess and quantify sensory perception.

II. Requirements

The hand plays a crucial role in our lives, and is the tool on which we typically rely for tactile exploration, object manipulation, and for sensory substitution, e.g. when vision is occluded or impaired. Impairment of hand sensory function is common after a stroke and is a major limitation preventing patients from using their hand in ADL.

The hand has a high density and variety of mechanoreceptors, i.e. Meissner and Pacinian corpuscles for perception of low and high frequency vibrations, Ruffini corpuscles for the perception of sustained pressure, skin stretch and slip, Merkel discs for sustained touch and pressure and finally Aδ and C fibers, which detect temperature and pain. The distribution of these mechanoreceptors is well identified in the hand, and the best area to present various types of haptic stimuli is the fingertip [17], [18].

A. Sensory Stimuli

Three types of sensory stimuli have been selected for the first prototype of the Robotic Sensory Trainer based on their relevance for ADLs involving tactile exploration and object manipulation with the hand. Stimuli will be presented to the index finger and thenar eminence of the palm:

- **displacement**, i.e. flexion and extension of the index finger: movement detection and perception of the metacarpophalangeal (MCP) joint angle can be a measure of proprioception. Several studies investigated finger movement detection in healthy subjects [19], [20] and reported detection thresholds for position change to be between 1.0° and 18.0° depending on movement velocity and position of distal joints [21]. In motor-impaired subjects, JNDs of the position sense were found to be about 45% (13% for young healthy subjects) [20].
- **vibration**: surface texture and friction are important when exploring (by touch) or manipulating objects. These can be rendered on haptic displays through vibration, which is perceived by Meissner and Pacinian corpuscles in the range of 3 to 400 Hz [22]–[24]. In the case of healthy subjects, the amplitude detection threshold for vibration is less than 1 μm for frequencies above 30 Hz and becomes minimal around 250 Hz [23].
- **pressure**: detection of pressure at the fingertip is of high importance to achieve a stable grip and modulate the grasping force. The differential threshold of force perception in healthy subjects was found to be 7-10% over a force range of 0.5-200 N. For forces below 0.5 N the threshold increased to 15-27%. Also, it has been reported that the JND in pressure decreases as the contact area increases [25].

TABLE I
Parameters considered for the mechanical design of the Robotic Sensory Trainer

hand length	181.5 ± 10 *mm*
palm length	102.0 ± 6 *mm*
finger length (MCP to fingertip)*	97.3±7.6 *mm*
hand breadth (metacarpal)	81.5 ± 5 *mm*
hand thickness (metacarpal)	30.5 ± 3 *mm*
range of MCP rotation	-30° (ext.) to 90° (flex.)
force at index fingertip	60 *N* (flex.)
equivalent torque at MCP	1.45 *Nm* (ext.) and 4.86 *Nm* (flex.)
position JND at index MCP joint	1.7° to 2.7° [19]
range of vibration detection	4-300 *Hz* [22]–[24]
light touch detection threshold	0.047 - 0.169 *g* [28]
force JND at the index fingertip	10% (0.5 - 10 *N*) [28]

*measurements performed on 8 healthy subjects

B. Biomechanical Constraints

In order to obtain a biomechanically correct movement at the level of the MCP joint of the index finger and provide an adequate and comfortable support to the hand while attached to the device, anthropometric dimensions should be taken into account for the design of the robot. The range of motion of the MCP joint of the index finger θ varies from 90° (flexion) to -30° (hyperextension), where 0° is defined as the position in which the distal interphalangeal (DIP) joint and the MCP joint are aligned in a horizontal plane. The maximum flexion force at the fingertip is about 60 N (sustained force around 35 N, [26]) and the maximal hyperextension force is lower. The average of the 50th percentile of anthropometric estimates for the adult (men and women) hand [27] were considered to obtain an adjustable design for different hand and finger sizes. Table I summarizes the sensory perception thresholds/ranges and key anthropometric dimensions, based on literature and pilot measurements on healthy subjects, that were taken into consideration for the mechanical design of the Robotic Sensory Trainer.

III. The Robotic Sensory Trainer

A. Mechanical Design and Implementation

In order to control flexion/extension at the level of the MCP, a remote-center-of-motion mechanism composed of a double-parallelogram structure [29] connected to a geared DC motor was designed to provide the displacement stimuli (Fig. 2). This mechanism was preferred to a direct-drive solution as it allows direct control of the interaction at the level of the fingertip rather than at the level of the MCP joint, and guides the finger in a biomechanically correct manner within a range of motion from 70° (flexion) to -20° (hyperextension). It also offers the advantage of placing the actuator away from the fingers. However, positioning of the hand must be performed carefully to ensure that the virtual center of rotation of the robot is properly aligned with the MCP joint. For safety reasons, mechanical stops are implemented to prevent excessive finger flexion and extension. Connections between the different parts of the parallelogram structure are realized using off-the-shelf bushings and couplings to minimize friction and play in the structure.

To maintain the finger on the moving parallelogram structure and assure good contact with the stimulation mechanisms, an adjustable finger carriage (length of 80 *mm* and width of 20 *mm*), into which the fingertip of the user is inserted, was designed (Fig. 3). The carriage is realized by rapid prototyping material (photopolymer, Vero Blue Full Cure840) and is fixed to a linear guide placed on the parallelogram structure, which makes it easily adjustable to different finger lengths (from 75 to 95 *mm*). The form of the finger carriage allows for a natural rest position of the index finger, with 30° flexion at the proximal interphalangeal (PIP) joint [30].

To provide vibration stimuli to different areas of the hand and finger, four small vibration motors are integrated into the system. Two vibration motors are mounted on the finger carriage, at the level of the proximal phalange and at the fingertip (Fig. 3), while two additional vibration motors are placed at the level of the palm, integrated into an ergonomic hand support made from thermoplastic material. This padded support provides a comfortable arm position in the device, allows for right and left hand use, and can be adjusted to different wrist orientations. A major challenge for the vibration stimulation is to isolate each motor and prevent the vibration from being transmitted to the entire structure. For this purpose, the vibration motors are attached over a polymer damping element [31] (Fig. 3B).

For the pressure stimuli, a latex membrane was integrated into the finger carriage, located over the tip of the finger (Fig. 3C). Pressure can be applied to the fingertip by inflating the membrane. By applying minimal pressure, this system can also ensure that the finger does not move within the finger carriage and stays in good contact with the force sensor and vibration motor located at the fingertip. The applied pressure

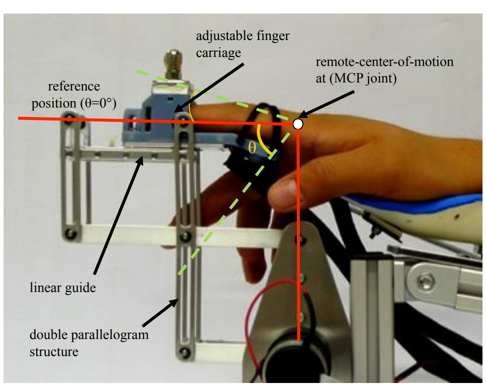

Fig. 2. Remote-center-of-motion mechanism composed of a double parallelogram structure to control MCP angle θ in flexion (maximal 70°) and extension (maximal -20°). An adjustable finger carriage connected through a linear guide allows to adapt the device to different finger lengths.

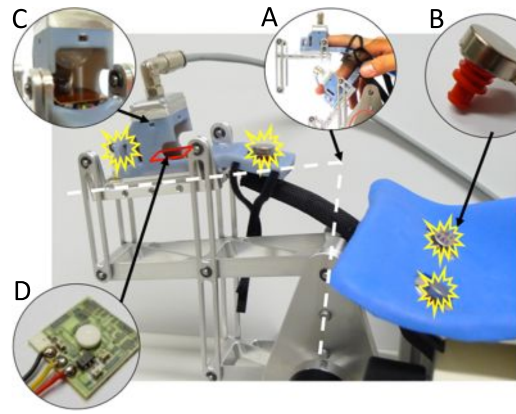

Fig. 3. Detailed view of the Robotic Sensory Trainer and the different stimulation systems. Displacement is provided over a remote-center-of-motion mechanism supporting the finger, with a virtual center of rotation aligned with the MCP joint of the index finger (A). Vibration is provided by 4 vibration motors placed at the fingertip, proximal phalange and palm (B). A pressure system inflates a latex membrane located over the fingertip to provide pressure stimuli (C), while a force sensor monitors the force applied at the fingertip (D).

is continuously monitored through a force sensor with a force range of 40 N (CentoNewton 40N, LPM-EPFL, Switzerland) placed below the fingertip (Fig. 3D). This force sensor can also be used to monitor the interaction force during passive finger displacements, or to drive an admittance controller in order to enable active finger motion (assisted or resisted).

B. Electronics and Control

The remote center-of-motion mechanism is actuated over a geared DC motor (Maxon motor, RE-max 29; planetary gearhead GD 32 A, 111:1 reduction) mounted at the base of the parallelogram structure. A magneto-resistant encoder (Type ML, 128-1000 CPT) is attached to the motor in order to monitor the position of the MCP joint. Different types of vibration motors were evaluated to provide a vibration up to 100 *Hz*, which is adequate to stimulate the Pacinian and Meissner corpuscles. Coin type vibrator motors (Samsung Electro-Mechanics DMJBRK30O) were found to be the best solution due to their small size (10 *mm* diameter, 3 *mm* thickness) which makes them easily implementable in the proposed design. A proportional pressure regulator (FESTO MPPES-3-1/4-6-010) controls pressure in the latex membrane in the range of $0-6$ *bar*.

Data communication is realized over a USB data acquisition card (National Instruments, NI USB-6216) used to control the vibration motors, pressure regulator and servo amplifier commanding the motor (Maxon motor, LCS 4-Q-DC), and to sample signals from the encoder and force sensor. In order to initialize the angular position of the remote center-of-motion mechanism before running experiments, a mechanical switch is placed at the lower end of the structure. This switch is also used as a software safety limit during finger movements.

The control program of the Robotic Sensory Trainer is implemented in LabVIEW 9.0 (National instruments, USA) and

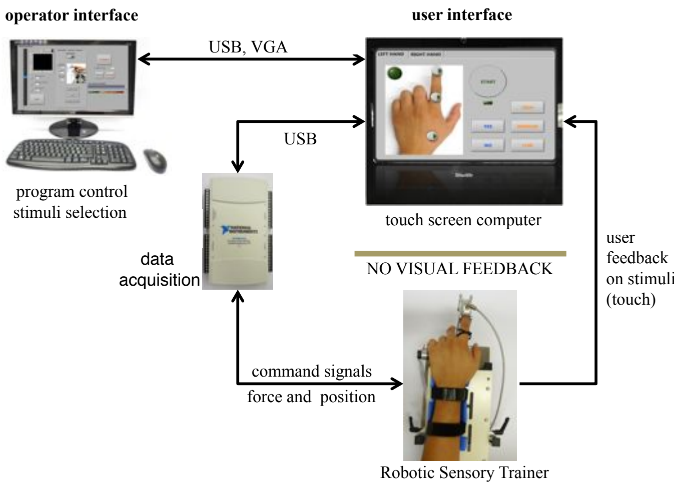

Fig. 4. Connection diagram and components of the Robotic Sensory Trainer. A touch screen computer is fixed above the robotic device and allows the user to provide feedback during assessment or therapy with the Robotic Sensory Trainer. The evaluated hand is occluded and the user has to rely on hand sensory perception during the use of the robotic system. A control interface is displayed on an additional computer for the operator to control and monitor the experimental procedure.

runs on a touchscreen PC (Shuttle Barebone, Intel Atom 1.66 GHz, Windows 7 Enterprise) at a frequency of 300 *Hz*. This control frequency is sufficient for our application considering the bandwidth of human movements and the slow speed of the movements that will be generated with the Robotic Sensory Trainer. The touchscreen computer is mounted on a hinge structure over the Robotic Sensory Trainer so that the screen can cover the hand of the user when placed inside the device.

A PID position controller with gravity compensation is used to actuate the parallelogram structure. The gravity compensator follows the simple law:

$$\tau_g = A \cos\theta \tag{1}$$

where θ is the angle at the MCP joint measured from the horizontal (0°), and A a constant corresponding to the radius to the center of gravity times the gravitational force of the parallelogram structure. This value was tuned to obtain a symmetric response to a square wave input with $\pm 10°$ amplitude around the reference point (0°) in PD control.

C. Graphical User Interface

A graphical user interface (GUI) was implemented to allow the user of the Robotic Sensory Trainer to interact with the device in an intuitive and motivating way and to collect subject's feedback on the perceived stimuli (type, intensity and location) during assessment or therapy with the robotic system. An interface with a virtual representation of a hand is displayed on the touch screen computer and is superimposed on the hand of the subject. While offering the possibility to the user to manually select the type of exercise to perform and directly provide answers to perceived sensory signals by pointing on the touch screen at the hand area that is stimulated. It also prevents subjects from using vision as a substitution modality and forces them to rely on their hand sensory function. A control interface is displayed for the operator of the Robotic Sensory Trainer on a second monitor, on which experimental parameters, e.g. type of presented stimuli, amplitude and duration of movement, stimuli location, etc., are displayed and can be controlled. Information on patient's feedback, e.g. whether the stimuli was properly perceived, as well as the time the subject took to provide an answer, are also displayed on the control interface and stored for post processing. Figure 4 shows a connection diagram and the different components of the Robotic Sensory Trainer.

IV. Evaluation

A. Performance

Table II summarizes the performance of the Robotic Sensory Trainer. The robot can generate torques in flexion or extension up to 4.5 *Nm* at the MCP joint (corresponding to about 50 *N* at the fingertip). The workspace of the device allows for large finger movement in flexion and extension with a high angular resolution at the level of the MCP joint, enabling the implementation of different psychophysiological studies to assess JND in joint angle position or velocity. Fig. 5 shows the performance of the device when controlled in position and moving at three different predefined velocities (5°/s, 10°/s and 20°/s) during a movement of 20° in flexion.

To identify the dynamic behavior of the Robotic Sensory Trainer, the position bandwidth of the system was determined by applying a sinusoidal position command with an amplitude of 5° over a frequency range from 0.1 *Hz* to 28 *Hz* in steps of 0.5 *Hz*, for a period of 5 seconds per frequency. Figure 6 presents the magnitude and phase Bode plots for the implemented PID controller, and shows that the position bandwidth of the system is around 8.1 *Hz*, which is well above the requirements for our application.

B. Preliminary Study with Healthy Subjects

In order to evaluate the usability of the Robotic Sensory Trainer as an assessment tool, a pilot study investigating the

TABLE II
Technical specifications of the Robotic Sensory Trainer

maximal continuous motor torque (MCP)	4.5 *Nm*
maximal fingertip force	50 *N*
friction torque (extension)	-0.8 *mNm*
friction torque (flexion)	0.02 *mNm*
position resolution	0.00081 °
velocity resolution	0.081 °/*s* at 100 *Hz*
range of motion (extension)	-20 °
range of motion (flexion)	70 °
maximal velocity	>20 °/s
minimal stable velocity	0.125 °/s
bandwidth in position control	8.1 *Hz*
force sensor measuring range	0 - 40 *N*
force sensor resolution	<0.05 *N*
pressure resolution	0.05 *bar*
maximal pressure on the fingertip	1.2 *bar*
width of the finger carriage	24 *mm*
dimensions of the Robotic Sensory Trainer	380x240x200 mm^3

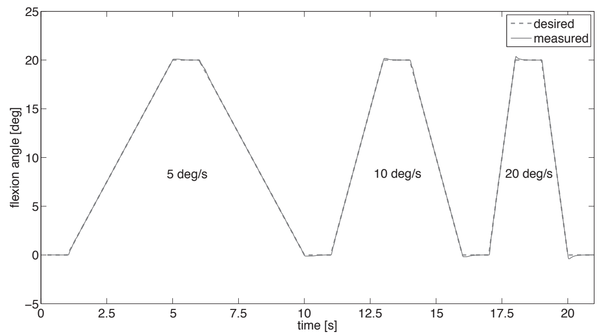

Fig. 5. Velocity performance at 5°/s, 10°/s and 20°/s (20° flexion at the MCP joint).

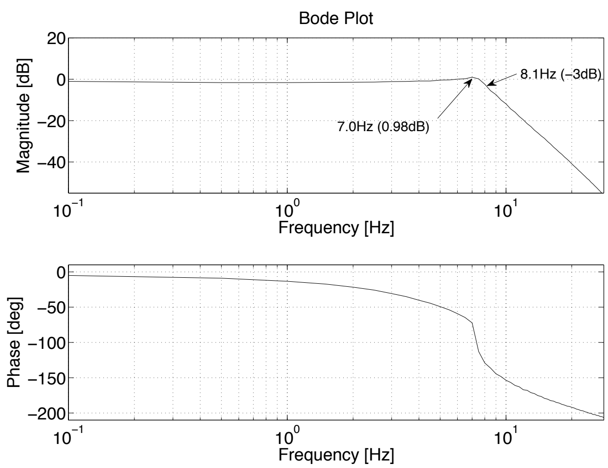

Fig. 6. Magnitude and phase Bode plots of the Robotic Sensory Trainer in closed loop PID control over a frequency range of 0.1 Hz to 28 Hz. The bandwidth in position control is about 8.1 Hz. A resonance peak can be observed at the frequency of 7 Hz.

JND in angular position at the MCP joint was conducted. The aim of this study was to evaluate the perception threshold in healthy subjects using the Robotic Sensory Trainer, and provide a baseline for comparison and assessment of sensory perception in stroke patients.

a) Study Design and Subjects: Eight healthy right handed subjects (six men and two women, 25-32 years old, mean age 27 years) participated in this study. Subjects were recruited among university students and employees. The task consisted in passive index finger flexion movements to different angular positions, imposed by the Robotic Sensory Trainer. A reference MCP joint angle θ_{ref} was defined at θ=17° and three joint angle increments $\Delta\theta_1$=0.5°, $\Delta\theta_2$=1.5° and $\Delta\theta_3$=3.5° were chosen to investigate the JND. Each trial started from the rest position, i.e. θ_0=0°, then the device moved the right index finger to the reference joint angle position θ_{ref} with a velocity of $10°/s$. After two seconds, the index finger was moved back to the initial position θ_0 with a velocity of $5°/s$. The finger was then flexed again at $10°/s$ until it reached either θ_{ref} or θ_{ref}+$\Delta\theta_i$ with i=1, 2 or 3. High movement velocities were chosen to prevent subjects from relying on movement duration to estimate the MCP angles. During the experiment, each angle was presented 40 times. In addition, 20 practice trials were performed before the beginning of the experiment for subjects to familiarize with the experimental protocol.

TABLE III
JND OF MCP JOINT ANGLE POSITION.

Subject	Finger length* (mm)	JND (%)	JND (°)
1	97	16.32	2.77
2	84	10.20	1.73
3	106	12.72	2.16
4	104	6.65	1.13
5	104	12.93	2.20
6	99	10.94	1.86
7	92	12.72	2.16
8	92	33.30	5.66
mean±std	97.25±7.57	14.47±8.09	2.46±1.38

*measured from the MCP joint to the tip of the index finger

At the beginning of the experiment, subjects sat down comfortably on a chair in front of the Robotic Sensory Trainer. The length of the right index finger (from the MCP joint to the fingertip) was measured and the finger was inserted into the finger carriage. The forearm, wrist, and proximal phalange were strapped to the Robotic Sensory Trainer to prevent the hand from moving inside the device. The position of the arm support and finger carriage were adjusted to the subject to ensure a proper alignment with the wrist resting in a neutral position. The alignment of the MCP joint with the virtual center of motion of the robot was inspected visually. During the experiment, the other fingers were flexed and rested on the forearm support. The apparatus and hand were then hidden by the touch screen panel displaying the graphical user interface (Fig. 4). To initiate the experiment, the subject pressed the start button on the touch screen with his/her left hand. At the completion of each trial, the subject had to press a button on the graphical user interface to indicate whether the two angles were perceived as being the same or different. Note that the correct answer was not presented to the subject.

b) Results: Based on signal detection theory which enables measuring the sensitivity of subjects, the JND of the MCP joint angle position was estimated using the method described in [32]. A stimulus response matrix was computed for each subject in order to calculate the sensitivity index d'. The JND is defined as the inverse of the average slope $\bar{\delta} = d'/(\Delta\theta/\theta_{ref})$, and was found to be 14.47% (2.46°) in average (Table III).

V. DISCUSSION

This paper presents the design, development and evaluation of one of the first robotic devices specifically targeting assessment and therapy of hand sensory function. The Robotic Sensory Trainer can provide three types of well-controlled sensory stimuli to the index finger and palm, namely displacement at the level of the MCP joint, vibration and pressure. These stimuli can be presented in combination or independently, and can be precisely controlled in time, location and intensity in order to investigate sensory detection thresholds. A double-parallelogram structure provides a compact means to control the flexion/extension angle at the MCP joint of the index finger, assuring a biomechanically correct movement by allowing the virtual center of rotation to be aligned with the MCP joint. A preliminary study with healthy subjects investigated the JND of the MCP joint angle position by passively flexing the index finger to various MCP joint angles. The results of this preliminary study are comparable to data from the literature (about 2.3° with similar conditions [20]; 1.7° to 2.7° for active movement [19]). Performance of the Robotic Sensory Trainer and results form a preliminary psychophysiological experiment indicate that the proposed system has the potential to assess and train hand sensory function, and provide quantitative data on sensory perception. Future work will focus on the implementation of several haptic sensory perception studies with the Robotic Sensory Trainer based on different stimuli. Tests with stroke subjects with impaired hand sensory function will be performed to semi-objectively compare sensory perception between healthy and stroke subjects, and investigate the prevalence of sensory deficits in stroke patients. The extension of the Robotic Sensory Trainer to the four other fingers will also be investigated, with the aim of developing a device that could assess and train sensory function in the whole hand. Additional types of sensory stimuli such as temperature or two point-discrimination could also be included, providing a more complete assessment of sensory function.

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