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Zbytniewska, Monika; Rinderknecht, Mike D.; Lambercy, Olivier; Barnobi, Marco; RAATS, Joke; LAMERS, Ilse; FEYS, Peter; Liepert, Joachim & Gassert, Roger (2019) Design and Characterization of a Robotic Device for the Assessment of Hand Proprioceptive, Motor, and Sensorimotor Impairments. In: 2019 IEEE 16th International Conference on Rehabilitation Robotics (ICORR), IEEE, p. 441 -446.

DOI: 10.1109/ICORR.2019.8779507
Handle: http://hdl.handle.net/1942/30630

Design and Characterization of a Robotic Device for the Assessment of Hand Proprioceptive, Motor, and Sensorimotor Impairments

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***Abstract*— Hand function is often impaired after neurological injuries such as stroke. In order to design patient-specific rehabilitation, it is essential to quantitatively assess those deficits. Current clinical scores cannot provide the required level of detail, and most assessment devices have been developed for the proximal joints of the upper limb. This paper presents a new robotic platform for the assessment of proprioceptive, motor, and sensorimotor hand impairments. A detailed technical evaluation demonstrated the capabilities to render different haptic environments required for a comprehensive assessment battery, and showed that the device is suitable for human interaction due to its ergonomic design. A preliminary study on proprioceptive assessment using a gauge position matching task with one healthy, one stroke, and one multiple sclerosis subject showed that the robotic system is able to rapidly and sensitively quantify proprioceptive deficits, and has the potential to be integrated into the clinical settings.**

I. INTRODUCTION

Although neurological injuries such as stroke can affect both motor and somatosensory function [1]–[3], clinical assessments and rehabilitation typically focus on motor impairments. However, it has been shown that persistence of severe somatosensory deficits leads to a poor prognosis of functional recovery [4], [5]. Of particular importance is proprioception, as it contributes to the generation of coordinated and fine movements [6], [7]. To adapt the therapy to an individual patient's impairment profile, it is necessary to quantify both motor and somatosensory deficits in a sensitive and reliable way. The latter are particularly difficult to evaluate, especially using the traditional clinical assessment methods, which are subjective, unreliable, and prone to ceiling effects [8].

Technology-driven solutions provide a promising alternative to commonly used clinical assessments. While there exist sophisticated platforms for quantifying the level of sensorimotor impairment at the proximal joints of the upper limb (e.g., KINARM [9], MIT-Manus [10], VPIT [11]), solutions supporting the assessment of hand somatosensory function are limited. Some are primarily used for research purposes [12], [13], while others, although proven reliable and valid for quantifying hand proprioception [14], are not suitable for conducting multiple assessments (i.e., motor and sensorimotor) and take too much time to be integrated into the clinical routine. A rapid proprioception evaluation using a robotic platform has been shown feasible for the wrist [15]. Nonetheless, a primary focus should be given to the hand, as its impairment is common after neurological injuries and leads to significant limitations in executing Activities of Daily Living (ADL) [16], [17].

This work presents the development and evaluation of a new robotic device for a detailed assessment of proprioceptive, motor, and combined sensorimotor function of the hand. The ETH MIKE robot (Motor Impairment and Kinesthetic Evaluation) can provide well-controlled passive movement stimuli to the index finger metacarpophalangeal (MCP) joint in a standardized, automated way (e.g., for somatosensory assessment) and can render different haptic environments for an active interaction with the user (e.g., for motor assessments). It has been shown that there is a high level of agreement in somatosensory impairment between adjacent body parts [3]. Hence, we decided to focus on the evaluation of a single joint, which simplifies the design and enhances clinical usability of the device. The index finger was chosen due to its relevance in many ADL (grasping, precision tasks such as pinching [18]), and the MCP joint for its contribution to the synergistic finger motion during grasping [19].

This paper describes the requirements, design and manufacturing, as well as the technical evaluation of the device's performance with respect to its application as a haptic interface with the human hand. Moreover, results of a pilot study with three subjects (healthy, multiple sclerosis (MS) and stroke) are presented. The aim of the study was to evaluate the feasibility of using the robot, as well as to present typical robotic outcome measures in the context of assessing proprioceptive hand impairment.

II. REQUIREMENTS

A. Device Use Cases

The objective of the robot is to serve as a tool for objective assessment of finger MCP joint proprioceptive, motor, and combined sensorimotor function. As a main part of this assessment battery, the device should be capable of performing a gauge position matching task, based on the Wrist Position Sense Test [20]. This approach is selected as the most appropriate for clinical use, since, comparing to previously used psychophysical methods [14], [21], it is faster and simpler, yet reliable [15]. The subject is asked to indicate the perceived finger location after a flexion/extension movement stimulus is applied. The difference between the

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indicated and the actual position is the outcome measure of proprioceptive function. Therefore, the robot needs to be able to passively move the tested finger to different positions in an accurate and precise way (minimal steady-state error and backlash smaller than the just noticeable angular difference of around 1.5° [14]). As secondary objectives, complementary motor and sensorimotor assessments could include active target reaching [9] and trajectory following [22]. As in such tasks the user is actively moving the robot, the device should be transparent (i.e., minimal mechanical output impedance) to enable active, unresisted, movements. Another type of sensorimotor assessment could involve identification of different objects with various mechanical properties [23], which requires the device to have good haptic rendering abilities (wide range of output impedances [24]).

B. Human Factors

The device should be suitable for the assessment of both left and right hand, and adaptable to different hand sizes. The total range of motion needs to accommodate the possible movement of the left and right index finger. The active range of motion of the MCP joint is $-20°$ to $90°$ (extension to flexion) [25]. Moreover, the robot needs to sustain the forces applied by the user during active or passive interactions (e.g., resistive forces generated by neurologically impaired patients due to involuntary muscle contraction [26]). The maximum torque that can be generated by a healthy subject with the tip of the index finger (assuming a finger length of $0.1\,m$) is $5\,Nm$ [27]. Finally, the bandwidth of the device should accommodate the typical frequency of finger movements, which is below $12\,Hz$ [28].

C. Clinical Requirements

To be used in clinical practice, the device needs to be compact, usable on desks and tables already present in the clinics without the need for a tailored support, and should not require any external hardware to be operated. It is crucial for the robot to be intuitive to use and reliable to ensure safety and data quality. The set-up time as well as the total time for an assessment performed with the robot should be minimal (preferably below 15 minutes [29]), to allow regular longitudinal application in the clinical environment.

III. ETH MIKE

A. Mechanical Design and Implementation

The ETH MIKE is a 1 DOF robot, able to move the MCP joint of the index finger in both flexion and extension (Figure 1A). The finger is attached by Velcro straps to an ergonomic and adjustable finger module, which is a part of an rotating end-effector and can be flipped for use by the left and right hand. The center of rotation of the end-effector is aligned with the MCP joint. The hand is rested on a 3D-printed ergonomic handle. There is a separate handle for each hand, which can be easily removed and secured with two snapping pins. A tablet computer is placed above the hand, removing visual cues from the tested hand and providing an interactive graphical user interface (GUI).

The rotation of a DC motor is transformed through a cable transmission (ratio $5.2:1$) into the end-effector rotation (Figure 1B). Such solution has three main advantages: (i) eliminating backlash by selecting direct-drive with a cable transmission over a gear-based transmission, (ii) augmenting motor peak torque at the level of the end-effector, and (iii) enabling remote placement of the actuator, to minimize interference with the hand. The transmission system is based on two cables, to allow for bidirectional rotation ($-90°$ to $90°$). The cables are kept under tension by a pretension system, composed of two adjustable deflection pulleys.

B. Hardware Architecture

The system is actuated by a DC motor (RE40, maxon motor, Sachseln, Switzerland) without gearbox. It was chosen for its low rotor inertia ($121\,g/cm^2$) and high torque constant ($0.137\,Nm/A$). It can deliver $0.189\,Nm$ continuous and $1.02\,Nm$ peak torque. An incremental encoder (MR, Type L, maxon motor) with 1024 counts/ revolution is mounted on the motor axis. To improve angular velocity measurements, an unpowered DC motor (RE25, maxon motor) serving as tachometer is coupled through a round belt transmission to the actuator. A load beam (TAL220B, HT Sensor Technology, Xi'an, China) with a measurement range of 0–$50\,N$ (in finger flexion direction), amplified with custom electronics, is mounted between the end-effector and the finger module to monitor the interaction between the user and the device.

The device is controlled by a real-time embedded board (myRIO-1900, National Instruments, Texas, USA). The real-time system is programmed in LabVIEW (National Instruments). The control loop and sensor data acquisition run at a sampling frequency of $1\,kHz$. The myRIO is connected either via Wi-Fi or USB to the tablet running a LabVIEW host application displaying the GUI for task selection and the user interface. The myRIO provides the motor current setpoint to a motor controller (ESCON 50/5, maxon motor).

C. Gauge Position Matching Task Implementation

As a proof of concept, the first assessment task implemented on the ETH MIKE focuses on proprioceptive assessment, using the gauge position matching paradigm [15]. A position control algorithm is implemented to move the finger to a desired position. A PID controller is tuned to follow a minimum jerk trajectory [30] of $1\,s$ duration. The error input to the PID is computed from the encoder signal, while the velocity estimate is obtained from the filtered tachometer signal (Butterworth low-pass filter with cut-off frequency of $20\,Hz$). After the finger is passively moved to a target angle by the motor, the user is prompted to indicate the perceived finger position on the tablet screen. This is done by aligning a virtual gauge on the tablet screen with the perceived location of the tip of the tested index finger, using the non-tested hand. (Figure 2B). The GUI is also designed to record subject information (i.e., name, age, gender, handedness, and neurological condition) prior to the assessment (Figure 2C).

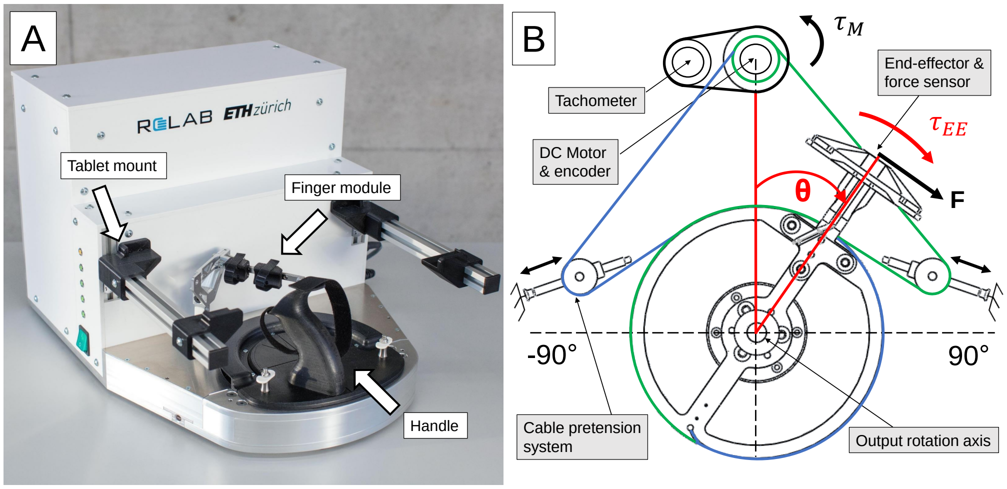

Fig. 1. **ETH MIKE. (A)** View of the developed device (without the tablet). **(B)** Schematic of the capstan mechanism with indicated actuator and sensor locations, and the output axis of the end-effector rotation.

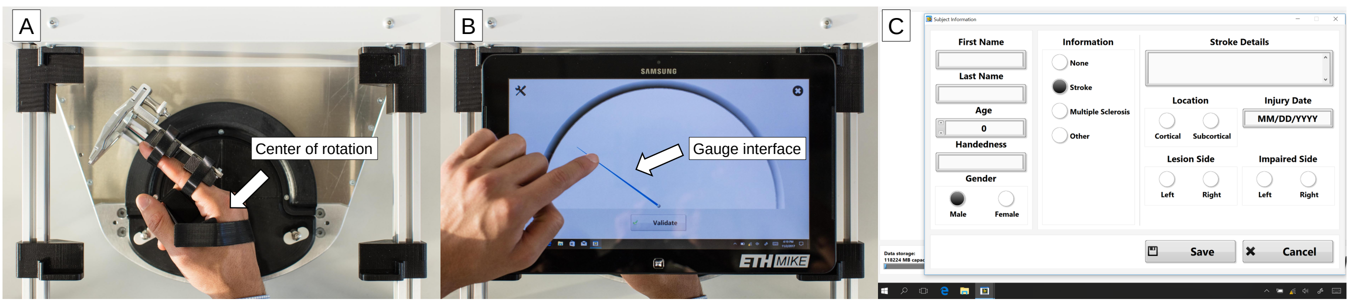

Fig. 2. **Finger interface and GUI. (A)** The hand and the finger can be easily attached to the handle and finger module (end-effector), via two Velcro straps each. **(B)** Tablet with the GUI for the gauge position matching assessment. **(C)** The GUI serves as an intuitive interface to save the subject's details.

TABLE I

SUMMARY OF THE TECHNICAL CHARACTERISTICS OF THE DEVICE. ALL VALUES REFER TO THE END EFFECTOR (CENTERED AT MCP JOINT).

Performace metrics	**Obtained values**	
Range of motion	± 90	$[deg]$
Angular position resolution	0.016	$[deg]$
Angular velocity resolution	0.1	$[deg/s]$
Peak torque	5.1	$[Nm]$
Maximum acceleration	$\pm 5.2 \times 10^4$	$[deg/s^2]$
Static friction	$< \lvert \pm 0.04 \rvert$	$[Nm]$
Position control bandwidth	12	$[Hz]$
PID steady-state error	0.06	$[deg]$
KB plot area	1.7×10^{-3}	$[Nm^2 s/deg^2]$
Device dimensions (LxWxH)	$468 \times 360 \times 360$	$[mm]$

IV. EVALUATION

A. Performance

The key parameters used to evaluate the performance of the device were: static and dynamic friction, maximum achievable acceleration, position bandwidth, and steady-state error (PID position control), as well as renderable virtual dynamics (interaction control). Other important evaluation metrics included: angular position and velocity resolution, peak torque, range of motion, and device dimensions. Performance metrics of the ETH MIKE are summarized in Table I.

The workspace of the end-effector is $\pm 90°$, with a position resolution of $0.016°$. The velocity resolution was acquired experimentally as $0.1°/s$. Using the derivative of the encoder position instead of the tachometer would provide a limited velocity resolution of $16°/s$, which could affect the haptic performance of the device. Given the transmission ratio, the peak torque that can be generated at the end effector is calculated as $5.1\,Nm$.

The maximum achievable acceleration at the end-effector was estimated from position measurement of the encoder when applying a maximum current step ($\pm 7.43\,A$) to the motor for $10\,ms$, and is on average equal to $\pm 5.2 \times 10^4\,°/s^2$.

Static friction was quantified by progressively increasing and decreasing motor current by steps of $\pm 1\,mA$, until minimal movement of the end effector was detected (in clockwise (CW) and counterclockwise (CCW) direction, respectively). This was performed at every $5°$ of the entire workspace, to determine if the static friction varies as a function of the position. Overall, static friction is below $\lvert \pm 0.04 \rvert Nm$ (Figure 3). For dynamic friction, a nonlinear relationship between velocity and torque ($y = \pm 1.2 \times 10^{-7} x^2 - 2.5 \times 10^{-5} x \pm 0.02$, $R^2 = 0.97$) was identified for velocities up to $600°/s$.

To determine the closed-loop position bandwidth, the end-effector movement was PD controlled to follow a sinusoidal trajectory with constant amplitude of $5°$ (realistic for imitating cycling finger movements) and varying frequency (0.1–

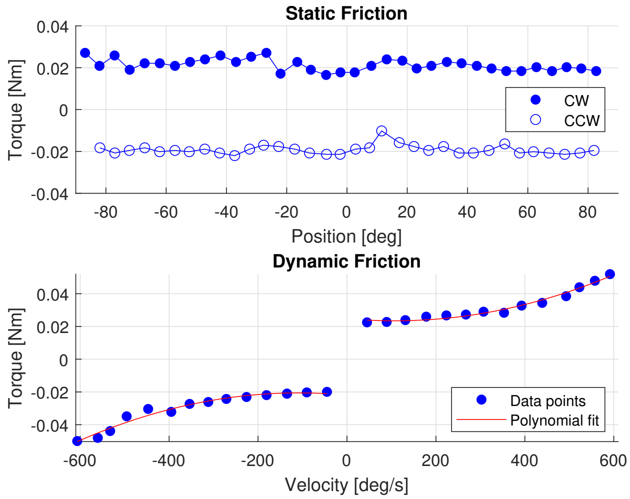

Fig. 3. *Top*: static friction torque as a function of the end-effector position. *Bottom*: dynamic friction torque as a function of the end-effector velocity.

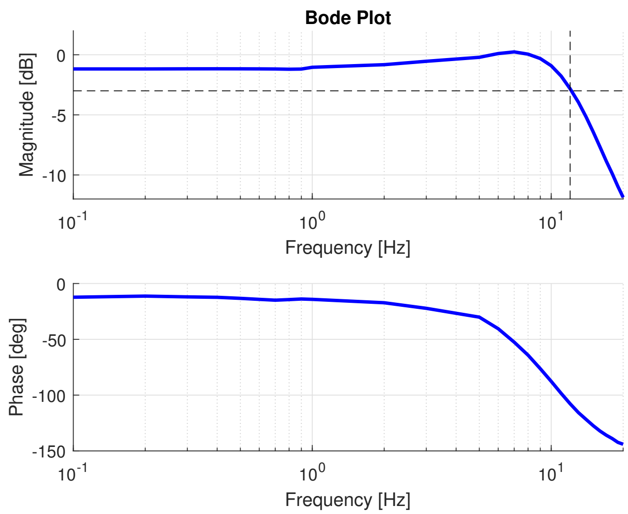

Fig. 4. Bode plot revealing a position bandwidth of $12 Hz$, which is above the bandwidth of human finger movement.

$20 Hz$). The Bode plot is presented in Figure 4. A resonance peak is observed at $7 Hz$, and the bandwidth equals $12 Hz$.

The capability of the system to render virtual dynamics (e.g., virtual wall) was evaluated using a KB plot [31]. The highest stable parameter combinations of virtual damping B and virtual stiffness K are plotted in Figure 5. An approximation of the impedance width (Z-width) of the system was calculated as the area under the resulting curve. This measurement was performed with velocity estimated using either (i) filtered tachometer, or (ii) adaptive windowing FOAW [32] of the encoder signal. The maximum KB plot area was obtained when using the tachometer (what emphasizes the advantage of this design choice) and equals to $1.7 \times 10^{-3} Nm^2 s/deg^2$.

Finally, the steady-state error of the controller when executing a minimum jerk trajectory was measured as $0.06°$.

B. Preliminary Study

In addition to the technical evaluation, a preliminary study was conducted to test the feasibility of the robotic device to assess proprioception at the level of the MCP joint of the index finger using the implemented gauge position matching task.

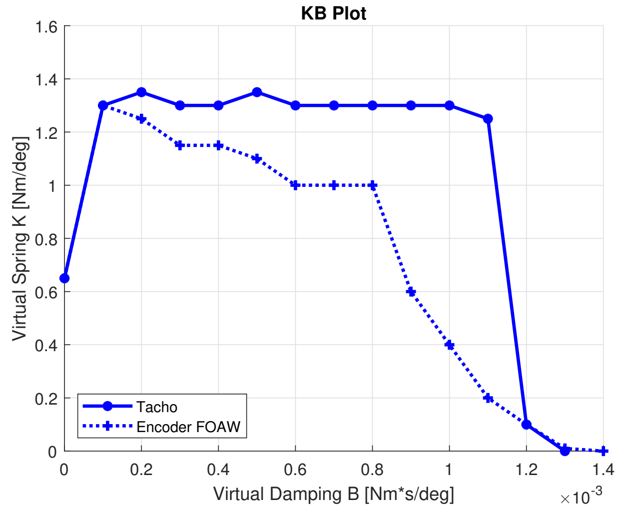

Fig. 5. KB plot visualizes the stability of a rendered virtual wall [31]. Here, impedance control with 1st order low-pass filtered tachometer signal renders the largest K-B virtual wall area.

1) Participants and Experimental Protocol: One healthy subject (62 years old, male), one stroke patient (80 years old, female, left hemispheric stroke, right side impaired, scored 10 blocks/min and 17 blocks/min for the right and left limb on the Box and Block Test (BBT) [33]), and one MS patient (27 years old, male, right side impaired, rated 2 on the Expanded Disability Status Scale (EDSS) [34], scored 51 blocks/min for both right and left limb on BBT) participated in this pilot study. All subjects were right handed (before the injury for stroke and MS), as identified with the Edinburgh Handedness Inventory [35]. All subjects gave written informed consent in accordance with the Declaration of Helsinki prior to participation. The study was approved by the institutional ethics committee of the Hasselt University, Belgium (document #89115201734043).

The subjects sat directly in front of the device to ensure visual alignment of the MCP joint with the gauge indicator on the screen and minimize parallax errors. The hand and the index finger were strapped to the handle and the finger module. The touchscreen was placed on the frame above the hand. One assessment consisted of 21 trials. Every trial started with the robot moving the finger from the resting position ($0°$ flexion) to one of 21 angles (integer values $[10°, 30°]$ flexion). Each angle was presented once, in a random order. There was no time constraint to indicate the perceived position on the tablet and no feedback was given about the subject's performance. Three assessments of each hand were performed on each of the two days.

This gauge position matching experiment can provide four different outcome measures [15] (i.e., constant error, absolute error, variable error and total variability). However, here we chose to only present the constant error (CE) for illustration. The error is calculated by subtracting the presented angle from the reported angle. CE is the average error across all 21 trials in one assessment, where a positive CE indicates

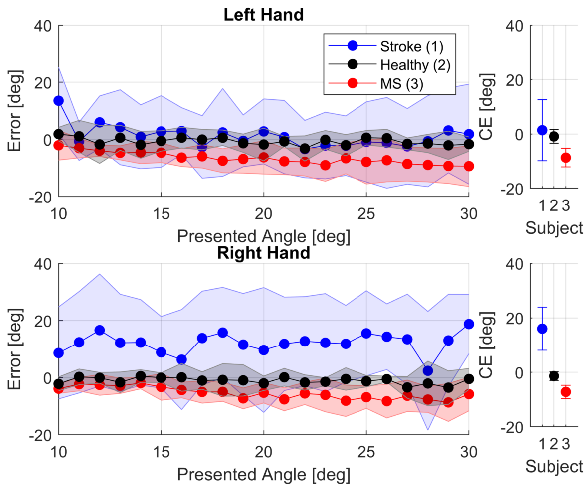

Fig. 6. Mean and standard deviation (SD) of the gauge position matching error for each presented angle, as well as mean and SD of the constant error (CE), calculated over 6 repetitions of the assessment for each hand of one healthy, one stroke, and one multiple sclerosis (MS) subject.

overestimation of the MCP flexion angle.

2) Results: Over the 6 measurements, *CE* for the right hand resulted in $-1.37° \pm 1.59°$ for the healthy, $-7.20° \pm 2.44°$ for the MS, and $16.03° \pm 7.86°$ for the stroke subject. As a comparison, for the left hand, *CE* for the healthy subject is $-0.90° \pm 2.55°$, for MS $-8.71° \pm 3.40°$, and for the stroke subject $-1.39° \pm 11.24°$. These results are summarized in Figure 6. Moreover, the relationship between the presented angle and the error is plotted as mean $\pm$ standard deviation over the 6 measurements for each of the three subjects for both right and left hand. The error of the healthy subject stayed around $0°$ for all presented angles. The MS subject tended to underestimate the finger position with increasing presented angles for both hands. The stroke subject notably overestimated all angles when assessed on the right hand. For both hands, the standard deviation was larger in the stroke subject, indicating a higher variability in the responses. The duration of one assessment ranged from 3 to 5 min and the set-up time took approximately 5 min.

V. DISCUSSION

The aim of this paper was to present the development and evaluation of a new robotic device for the assessment of proprioceptive, motor and sensorimotor hand functions in neurologically impaired individuals. Specifically, the robot can induce and measure movements and interaction forces of the MCP joint of the index finger (e.g., for passive sensory assessments), as well as render haptic environments (e.g., for active motor assessments). In this paper, the device was evaluated with respect to the described requirements, considering its desired application, human factors, as well as its future clinical use.

Firstly, the robot has the technical capabilities to perform the desired assessments. It can execute accurate finger displacements, with a steady-state error below the average human perception limits at the MCP joint [14], which is required for the gauge position matching experiment. Static friction is not compensated, but low (below 1% of the peak motor torque). However, transparency of the device could be improved through force feedback control and best characterized with transparency planes [24]. Importantly for future sensorimotor tasks, rendering high-quality virtual dynamics is possible, as illustrated by the KB plot. To represent more complex virtual environments, impedance or admittance control with force feedback could be used, utilizing the force sensor located at the end-effector. Secondly, the ETH MIKE is well suited for interactions with the human hand. Maximum torque at the end effector is $5.1\,Nm$, which matches the maximum MCP torque generated by a healthy subject ($5\,Nm$). The closed-loop position bandwidth is $12\,Hz$, accommodating the typical frequency of finger movements. In terms of ergonomics, the device can be used with both hands, and accommodates for the whole range of MCP joint movement. Finally, due to the simple and intuitive interface, as well as compactness and fast set-up time, the system should be easily introduced in clinical practice.

The feasibility of the device was further evaluated, in particular for proprioception assessments using the gauge position matching task. The results of this preliminary study are comparable to literature (healthy subjects) and in line with clinical scores describing upper limb functional deficits (patients). As expected, *CE* of the healthy subject was close to zero. Similarly, in a study assessing wrist proprioception [15], *CE* was reported as $0.87° \pm 5.43°$. In another study involving ipsilateral wrist joint position matching of previously experienced target position, the reported matching error for young adults was $3.63° \pm 0.25°$ [36]. According to the EDSS scale, the MS patient has a minimal disability. Moreover, the BBT score was only marginally below healthy average (51 blocks/min comparing to the norm of 65 blocks/min [33]). While not being direct measures of proprioception, these clinical scores confirm the small errors observed in the robotic assessment, highlighting that hand function is only slightly impaired in this patient. The stroke patient scored much below the healthy norm in the BBT (10 blocks/min), indicating severe functional deficits. In the robotic assessment, an overall increase in errors, as well as variability could be observed, thereby suggesting the presence of proprioceptive impairment, which could contribute to the reduced hand function. Generally, the right hand performed worse than the left, which is in accordance with the side affected by stroke. An additional factor to the overall decreased proprioceptive performance may be the age of the stroke subject [37]. However, in order to appropriately validate the robotic outcome measures against clinical scores, a clinical proprioception measure should be used, such as the proprioceptive up-down test [8].

Overall, the results of the technical evaluation and the feasibility study underline the potential of the ETH MIKE as a quantitative platform for rapid sensorimotor assessment of the index finger. Compared to other finger assessment platforms [12], [13], [21], [38], the presented device offers more versatility, increased ease of use and improved ergonomics. Specifically, multiple assessments, e.g., involving haptic interactions, can be implemented without modifying the platform. Furthermore, the modular design of the device also allows for the assessments of other fingers, by adapting the handle and the finger interface. Finally, the gauge position matching task was successfully implemented and tested with different neurologically impaired patients. This method is faster and less prone to attention confounds, compared to the psychophysical assessment paradigms implemented on previous robotic platforms [14]. Future work will focus on evaluating additional assessment tasks (addressing individual motor and combined sensorimotor functions), as well as validating the outcome measures against clinical and neurophysiological scores.

ACKNOWLEDGMENT

The authors would like to thank R. Ranzani, D. Wyser, W. L. Popp, and A. Manurung for discussions regarding the design and implementation of the robotic device, S. Schneller for helping with ergonomic design, and B. Kaufmann for manufacturing. We also thank the colleagues of the Rehabilitation and MS center Overpelt and Jessa Hospital Hasselt in Belgium for patient recruitment and providing the test facilities. This work is supported by the Swiss National Science Foundation, project 320030*L*_170163.

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