AMBER: A Device for Hand Motor and Cognitive Rehabilitation—Development and Proof of Concept

Laura Valenzuela-López, Marcos Moreno-Verdú, Roberto Alvarez, Gabriel Delgado-Oleas, Luis Soliverdi Mesa, Aida Arroyo-Ferrer, Francisco Jose Sánchez-Cuesta, Yeray González-Zamorano, Mercedes Barrachina Fernández, Carmen Sánchez Ávila, and Juan Pablo Romero

***Abstract*— Stroke survivors usually exhibit concurrent motor and cognitive impairment. Historically, rehabilitation strategies post-stroke occur separately in terms of motor and cognitive functions. However, recent studies show that hand motor interventions can have a positive impact on cognitive recovery. In this work, we introduce AMBER (portAble and Modular device for comprehensive Brain Evaluation and Rehabilitation), a new device developed for the evaluation and rehabilitation of both hand motor function and cognition simultaneously. AMBER is a simple, portable, ergonomic and cheap device based on Force Sensitive Resistors, in which every finger interaction is recorded to provide information about finger strength, processing speed, and memory status. This paper presents the requirements of the device and the design of the system. In addition, a pilot study was conducted with 36 healthy individuals using the evaluation module of the device to assess its psychometric properties, as test-retest reliability and measurement error. Its validity was also evaluated comparing its measurements with three different gold standards for strength, processing speed and memory. The device showed good test-retest reliability for strength (ICC = 0.741-0.852), reaction time (ICC = 0.715 – 0.900) and memory (ICC = 0.556-0.885). These measures were correlated with their corresponding gold standards (r = 0.780-890). AMBER shows great potential to impact hand rehabilitation, offering therapists a valid, reliable and versatile tool to comprehensively assess patients. With ongoing advancements and refinements, it has the opportunity to significantly impact rehabilitation practices and improve patient outcomes.**

***Index Terms*— Hand, upper limb, cognitive status, rehabilitation, robotics, stroke, cognitive evaluation, hand evaluation.**

Manuscript received 18 September 2023; revised 10 April 2024 and 6 June 2024; accepted 12 July 2024. Date of publication 19 July 2024; date of current version 26 July 2024. This work was supported in part by the Spanish Ministry of Science and Innovation under Grant PID2020-113222RBC21/AEI/10.13039/501100011033. *(Corresponding author: Juan Pablo Romero.)*

This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by CEIM H12O under Application No. 22/495, and performed in line with the 1964 Declaration of Helsinki.

Laura Valenzuela-López, Marcos Moreno-Verdú, Aida Arroyo-Ferrer, and Francisco Jose Sánchez-Cuesta are with the Faculty of Experimental Sciences and the Brain Injury and Movement Disorders Neurorehabilitation Group (GINDAT), Institute of Life Sciences, Universidad Francisco de Vitoria, 28223 Pozuelo de Alarcón, Spain.

Roberto Alvarez is with the Polytechnic School, Nebrija University, 28248 Madrid, Spain.

Gabriel Delgado-Oleas is with the Center for Automation and Robotics, Higher Council for Scientific Research–Polytechnic University of Madrid (CSIC-UPM), 28040 Madrid, Spain, and also with the Electronic Engineering Department, University of Azuay, Cuenca 010151, Ecuador.

Luis Soliverdi Mesa is with the Industrial Polytechnic School, Universidad Francisco de Vitoria, 28223 Pozuelo de Alarcón, Spain.

Yeray González-Zamorano is with the Department of Physical Therapy, Occupational Therapy, Rehabilitation and Physical Medicine, International Doctorate School, and the Cognitive Neuroscience, Pain, and Rehabilitation Research Group (NECODOR), Faculty of Health Sciences, Rey Juan Carlos University, 28933 Madrid, Spain, and also with the Brain Injury and Movement Disorders Neurorehabilitation Group (GINDAT), Institute of Life Sciences, Universidad Francisco de Vitoria, 28223 Pozuelo de Alarcón, Spain.

Mercedes Barrachina Fernández is with the Biomedical Engineering Program (Ph.D.), ETSI Telecomunicación, Polytechnic University of Madrid (UPM), 28040 Madrid, Spain.

Carmen Sánchez Ávila is with the Applied Mathematics Department, ETSI Telecomunicación, Polytechnic University of Madrid (UPM), 28040 Madrid, Spain.

Juan Pablo Romero is with the Faculty of Experimental Sciences and the Brain Injury and Movement Disorders Neurorehabilitation Group (GINDAT), Institute of Life Sciences, Universidad Francisco de Vitoria, 28223 Pozuelo de Alarcón, Spain, and also with the Brain Damage Unit, Beata María Hospital, 28007 Madrid, Spain (e-mail: p.romero.prof@ufv.es).

Digital Object Identifier 10.1109/TNSRE.2024.3429155

I. Introduction

STROKE is one of the leading causes of disability in adults, occurring in around 12.2 million new cases each year [1]. Approximately 80% of stroke survivors suffer from some level of motor impairment in their upper limbs (UL) [2], [3], hindering their ability to perform various activities of daily living (ADLs) over the long term. These alterations frequently affect hand function by provoking hand shaping difficulties, modifying muscle tone or impairing dexterous and fragmented finger movement [4], [5]. Besides motor disability, cognitive impairment is highly prevalent after stroke, with 80% of stroke survivors experiencing deficits in one or more cognitive domains. Attention, short-term memory, and executive function are among the most frequently affected

cognitive abilities [6], [7], [8]. Furthermore, over 20% of survivors exhibit concurrent motor and cognitive impairment in the long term [9]. These two pathological conditions could be correlated, as there are shared underlying neural pathways between motor and cognitive functions, and several studies show an association between motor performance and global cognition, memory and executive function [10], [11], [12], [13], [14].

Several studies have demonstrated a distinct correlation between handgrip strength and a hastened deterioration in overall cognitive performance [15], [16]. Additionally, post-stroke impairments in executive and attention functions have been found to impact the extent of improvement in hand motor function following training [17].

Historically, post-stroke rehabilitation strategies have typically focused separately on motor and cognitive functions [18]. These approaches, often delivered in varying intensities by different professionals, have not fully considered their potential interdependencies [19]. However, there is a growing body of research indicating overlapping effects between them. For instance, hand strength training has been found to have positive effects on cognition in healthy adults [20] and individuals with mild cognitive impairment [21]. Therefore, a comprehensive post-stroke rehabilitation program that incorporates both motor and cognitive aspects is crucial for achieving optimal recovery and the highest possible quality of life [22]. This is specially important during the first 3 months, as it is considered a valuable opportunity window where the own plasticity boosts the recovery of is repeated of strength and motor control after stroke [23], [24].

The paper is structured as follows: Section II provides an explanation of the reviewed literature. Section III outlines the product requirements. Section IV covers various aspects of product development. Section V outlines the evaluation procedure for the proof of concept, while Section VI presents the results of the evaluation. Finally, Section VII delves into the discussion, and Section VIII offers the conclusions.

II. Existing Upper Limb Rehabilitation Devices

Currently, several devices are used in clinical practice to aid UL motor rehabilitation [25], [26]. Specifically, hand rehabilitation devices are designed to rehabilitate any motor aspect of the hand and to be used in any phase of rehabilitation therapy [26]. Hand rehabilitation devices can be classified into three different categories: orthoses, exoskeletons, or end-effector devices.

Orthoses typically support the hand, protecting it from postures and movements that could cause structural damage. They primarily provide support and alignment for rehabilitation and are commonly low cost, light and easy to use, so the patient can use them from home. However, most of them do not have any actuators or sensors to perform therapy and to be able to track performance data. Examples of hand orthoses used for hand rehabilitation are: Saebo Stretch [27], Saebo Flex [28] and Script Orthosis [29].

Exoskeletons, motorized devices designed to enhance physical performance, act on individual finger joints and can be adjusted to fit different hand sizes. They usually have different sensors to provide a safe and controlled rehabilitation, and a variety of exercises to be used in different phases of rehabilitation. They are also portable, so the patient can use them from home. However, their adjustment and adaptation to each hand require time, the control algorithms are complex, and their costs are usually much higher than orthoses. Exoskeletons can also incorporate gamified environments. Examples of hand exoskeletons are: X-glove [30], HandMate [31], ReHand [32].

End-effector devices tend to be stationary devices with several sensors to provide a high level of control and feedback during motor rehabilitation. They can incorporate higher sensing capabilities and games to engage the patients. However, they are usually complex and expensive, and cannot be portable, so their use is limited to a particular location. Examples of end-effector devices used for hand rehabilitation are: Tyromotion Amadeo [33], HandCare [34], RehaDigit [35].

Crucially, while existing devices enhance motor rehabilitation, the majority are not specifically engineered to simultaneously address cognitive rehabilitation, despite the evidence of indirect benefits to cognitive function [36]. Among the few devices that do explicitly target both domains are HandyKnob and HandyBot, which combine neurocognitive therapy with training and evaluation of motor and sensory functions [37]. However, their use is limited due to their non-portability and the need for specialized supervision. In contrast, AMBER stands out for its portability and ease of use, allowing both the evaluation and rehabilitation of motor and cognitive functions without constant supervision. This feature makes AMBER particularly advantageous for integration into diverse therapeutic environments and could be especially beneficial for home rehabilitation programs, expanding access to comprehensive therapy for patients with mobility restrictions or limited access to specialized centers.

Our goal was to create a small, durable, lightweight, and portable device capable of facilitating the assessment and training of both hand motor function (and individual fingers) and cognition. In this paper, we present the development and initial validation of such a device. Through a proof of concept, we aim to show the system's potential usability, feasibility, and its ability to evaluate a range of motor and cognitive functions. The study involved testing several healthy subjects to assess their hand motor function and general cognitive abilities. The paper offers a comprehensive description of the device's development process and presents the results of the pilot evaluation.

III. Device Requirements and Use Cases

The primary goal of the device is to facilitate the evaluation and training of both hand motor function and cognitive abilities. To achieve this, the device should possess several key features and capabilities. Firstly, it should be adaptable and ergonomic, capable of adjusting to both right and left hands, adapt to different hand sizes, and allow free movement of each of the fingers separately. Secondly, it should be small, robust, lightweight, and portable, allowing for easy use in various settings, including patients' homes, without the need for additional hardware. Additionally, the device

should feature a user-friendly interface that supports independent operation without the need for continuous clinician oversight. Affordability is also crucial, ensuring the device is cost-effective to manufacture and thus accessible to a wide range of users. In terms of evaluation, the device should incorporate preprogrammed tasks that enable accurate and reliable assessment of hand motor function and cognitive performance, while avoiding physical or mental fatigue that could affect test results. Clinicians should have access to assessment data to track the individual patient progress. By meeting these requirements, the device could effectively serve as a versatile tool for evaluating and rehabilitating hand motor function and cognitive abilities in various clinical settings.

IV. Product Development

A. Hardware

The system architecture proposed in this paper comprises a sensory cylinder and a website designed to function both as a device controller and as a platform for clinicians to access and review evaluation results.

The sensory cylinder, designed for use with either the right or left hand, consists of four individual modules as depicted in Figure 1. Each finger, excluding the thumb, has a dedicated module that can be rotated and adjusted to accommodate different hand sizes and finger lengths. The cylinders are engineered with stops inside, allowing for limited rotation to achieve an adjustable position without causing damage to the inner components of the device. With a height of 24mm, the cylinders provide ample space for finger placement, while their outer diameter of 65mm ensures compatibility with large hands and long fingers without overlapping the thumb when gripped. Moreover, the cylinders are easily graspable by small hands. The structure, designed with a 3D modeling software, is printed using PET (Polyethylene terephthalate) filament, a lightweight, durable, and flexible material, so the structure of the modules is highly resistant to various stresses. Each module features two holes: one small for a colorful light emitter and another larger for a force sensor positioned at the fingerprint area. The inner diameter of the cylinders is designed to accommodate all other electronics and wiring effectively.

The device's electronic system, powered by batteries, includes multiple components for data processing and control. A Raspberry Pi microprocessor serves as the core of the system, along with an analog-to-digital converter (ADC) called ADS1115. Four Force Sensitive Resistor sensors (FSRs) are incorporated to capture data, while four RGB LEDs are included for visual feedback. A power supply ensures the device's operational functionality.

The ADS1115 ADC is responsible for processing the data acquired from the four FSRs, transmitting it to the Raspberry Pi. The Raspberry Pi is equipped with an integrated Wi-Fi module, enabling a connection between the device and a website. This sensory cylinder will receive control signals from the website and transmit the data collected from the sensors back to the website. The utilization of RGB LEDs allows for dynamic color changes, serving different purposes during different operating modes. Furthermore, the device incorporates a USB-C port input, allowing to be connected to an external power source for charging while in use.

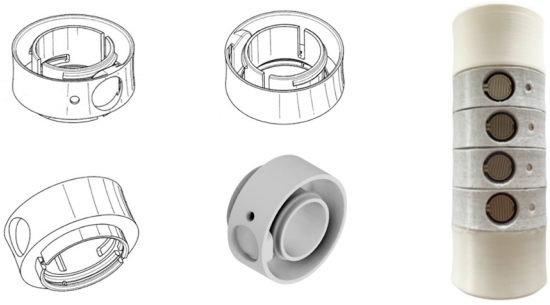

Fig. 1. The AMBER device. On the left side of the image, the sketch of the layout of the sensory cylinder modules of the device seen from various angles and the 3D layout. On the right side, the device prototype made up with four modules, each with one RGB LED and one FSR.

The prototype of the system is lightweight, weighing 252 grams, ensuring its practicality and ease of use.

B. Operation Modes

Based on the identified requirements and use cases, the subject's interaction with the device involves engaging with the sensors embedded in each cylinder. The subject will be prompted to press a specific sensor in response to one of the two pre-programmed modes: Evaluation Mode (EM) and Training Mode (TM). Each mode has 3 different exercises. Table I shows the explanation of the performace of each exercise, which differ on the feedback (which will be only shown in the EM) and the recorded data (which will be only in the TM).

In the evaluation mode (EM), the device assesses three different aspects: 1) hand and finger strength through grasping repetitions, 2) attention, reaction time, and coordination by having individuals press specific fingers when the corresponding LED lights up, 3) memory evaluation by repeating a previously presented LEDs sequence. The patient's interaction with the device is recorded, and the data is stored and transmitted to a dedicated website.

In the training mode (TM), the tasks are the same three used in the EM but, unlike the EM, the device provides visual feedback to the user in real-time while performing exercises. Different colors indicate the intensity of strength, repetition errors in sequences, or response time to stimuli. Each exercise within the TM offers three difficulty levels.

These exercises were developed using the Python programming language (main packages Adafruit_ADS1 $\times$ 15 and neopixel) and integrated into a HTML website with PHP programming languages and MySQL server for a database, allowing for control and exercise selection for each user through the web-based platform.

The performance of the 3 different exercises is explained in Table I, where the column "feedback" refers to the exercises on the TM and the column "recorded data" to the EM.

C. User Interface

The development of the device includes a website that serves as both a controller for the device and an evaluation

TABLE I
EXERCISES AND THEIR EXPLANATION

Exercise	Performance	Feedback	Recorded data
Task 1	The user must press the 4 finger FSRs individually or simultaneously at any time	Depending on the amount of force, the corresponding LED emits a colored light, distinguishing 3 grip force ranges: small force: red light; high force: green light; and intermediate force: yellow light.	The device will record the force exerted every 300 milliseconds and the maximum force achieved by each finger in each interaction.
Task 2	The device will emit a sequence of lights while the user must press the button corresponding to each light on as quickly as possible	When the user presses the button, the corresponding light changes its color depending on the reaction speed: the LED will turn green if the user presses the button quickly (in less than 1 second), red if the time is long (more than 2 seconds), and yellow if the time is an intermediate value between the previous established ranges.	The device records the time (in milliseconds) between each light turns on and the corresponding button is pressed.
Task 3	The device will emit a sequence of lights while the user must memorize it and repeat it once it has finished playing	If the button pressed is correct, its corresponding LED will emit green light, if it is wrong, the LED will emit red light.	The device records and check if the buttons pressed are correct, counting the errors, and the force applied in each of them.

platform to access the recorded assessment data. The website, designed in HTML, serves as a controller for the mode of operation and exercises selection and allows each patient to have a private user profile where all their evaluation information (from the EM) is stored.

When logged in, the website first acts as a remote control, enabling users to choose exercises and adjust difficulty levels as desired. Upon turning on the device and login, users (whether clinicians or patients) access the device's website to select the working mode: training or evaluation. In TM, users choose the exercise and desired difficulty level to be executed on the device. Subsequently, the exercise is initiated. In the EM, throughout the exercise, the device records and stores all interactions with the sensors, saving the data in CSV format on the website at the end of each exercise, and displaying them on the web platform. This data can be accessed by clinicians through the web, which provides a simple interface to monitor exercise performance and EM results, and which is accessible remotely. Access to this information is limited to physicians with their own private administrative accounts. The workflow diagram in shown in Figure 2.

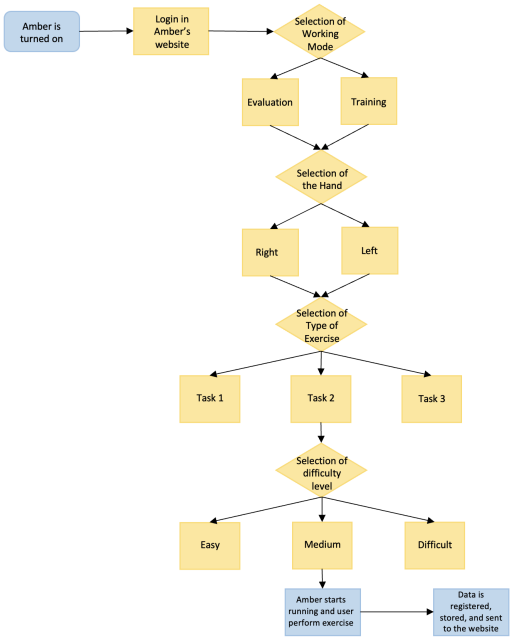

Fig. 2. Workflow diagram of the use of the device and its website.

V. EVALUATION PROCEDURE

First of all, the device was subjected to different stress conditions, proving to be structurally resistant and robust. Before testing the device functioning, we performed a focus group with 8 specialists in stroke, each with expertise in different areas (1 neurologist, 2 physiotherapists, 2 occupational therapists, and 1 neuropsychologist). Usability, ergonomy and user requirements were discussed to gather their insights and create the best evaluation protocol for testing the device's performance.

As a first validation of the device, the main purpose was to evaluate the device's reliability as a tool for assessing finger and hand strength and cognitive performance using its EM. Additionally, a correlation between the evaluation results and standardized cognitive and strength assessments was planned.

A. Study Design

To assess the device's EM, a test-retest reliability and validity study was conducted. The study followed the Guidelines for Reporting Reliability and Agreement Studies (GRRAS) [38]. All procedures were in accordance with the 1964 Declaration of Helsinki and ethical approval was obtained by an independent institutional review board (N° 22/495). All participants gave written informed consent before enrolment.

B. Participants

Participants were recruited among personnel of the hospital, healthy companions of patients and university students. They were included if they were adults (>18 years) and had neither of the following exclusion criteria: 1) presence of cognitive impairment (Montreal Cognitive Assessment

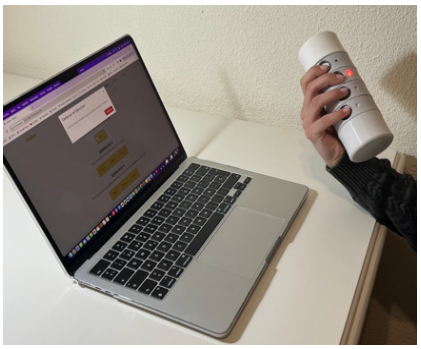

Fig. 3. Picture of a volunteer grasping and using AMBER device.

(MoCA) < 26 points), 2) known neurological diseases, motor or sensory disturbances that affect hand strength, 3) visual disturbances that prevent visualizing colors such as daltonism or blindness.

Thirty-six healthy individuals participated (19 males), with an average age of 43.27 ± 18.52 years, 31 of them right-handed (assessed through the Edinburgh Handedness Inventory), and with an average MoCA score of 28.42 ± 1.66.

C. Assessments

1) Device Evaluation Mode: The EM of the device was administered twice to all participants, with at least 3 days apart between sessions to assess test-retest reliability. In each session, the 3 different preprogrammed evaluation tasks described above were administered. As it is intentionally a very simple-to-use device, a relevant learning factor is not expected in any of the tasks.

Task 1 (strength) evaluated finger strength with digits 2, 3, 4, and 5 (which corresponds to the index, middle, ring, and little fingers). The subject was instructed to exert as much force as possible with each finger separately. As in traditional strength assessments, they were verbally encouraged by the examiner not to press any of the other sensors with their remaining fingers to ensure isolated measurements. The average of three attempts per finger (in kilograms) was the outcome measure.

Task 2 (tapping speed) is designed to assess attention and reaction time, and it offers three levels of difficulty: easy, medium, and hard. The user performed each level only once. For this task, the subject was presented with a visual stimulus, where one of the four LEDs corresponding to the four finger sensors would turn on. The subject was then instructed to respond as quick as possible by pressing the sensor corresponding to the illuminated LED using the corresponding finger. The easiest level consists of a sequence involving consecutive fingers. The difficulty increases in the medium and hard levels by introducing more challenging patterns with the omission and repetition of certain fingers. The outcome measure for this task was the average reaction time of the fingers of each hand, and it was recorded in milliseconds.

Task 3 (memory) was designed to evaluate short-term memory at three difficulty levels: easy, medium, and hard. The user performed each level only once with each hand. In this task, the subject was presented with a sequence of LED lights turning on sequentially. The sequence could be of 3, 5, and 7 elements for easy, medium, and hard levels, respectively.

TABLE II
MEASUREMENTS OF THE FIRST DAY OF EVALUATIONS

Variable	Measurements day 1	
	Mean	SD
Pinch Force – Device (kg)		
Dominant side		
Digit 2	4.76	1.12
Digit 3	3.13	1.19
Digit 4	2.29	1.08
Digit 5	1.37	0.76
Non-dominant side		
Digit 2	3.58	1.25
Digit 3	2.99	1.06
Digit 4	1.92	0.98
Digit 5	1.88	1.16
Pinch Force – Pinch gauge (kg)		
Dominant side		
Digit 2	4.71	1.22
Digit 3	4.10	1.21
Digit 4	3.11	1.15
Digit 5	1.94	0.92
Non-dominant side		
Digit 2	4.32	1.29
Digit 3	4.00	1.29
Digit 4	2.82	1.17
Digit 5	1.97	0.91
TS – Device (msec)		
Dominant side - overall	695.42	131.86
Digit 2	674.14	111.03
Digit 3	719.83	181.00
Digit 4	704.28	167.00
Digit 5	687.86	172.32
Non-dominant side - overall	689.03	140.55
Digit 2	627.97	145.18
Digit 3	668.42	185.10
Digit 4	695.75	110.17
Digit 5	762.72	171.40
TS – computerized (msec)		
Tapping speed		
Dominant side	164.85	24.11
Non-dominant side	185.21	31.25
Mean sides	173.93	26.50
Simple reaction time	281.89	30.46
Memory – Device		
Score	3.83	1.34
Memory – Digits-D WAIS-IV		
Score	4.53	1.11
Memory – CBT		
Score	4.47	1.16

SD, standard deviation; kg, kilograms; TS, Tapping Speed; msec, milliseconds; Digits-D WAIS-IV, Direct version of the Digit Test from Wechsler Adult Intelligence Scale-IV; CBT, Corsi Block-Tapping Test

Once the sequence was completed, the subject was asked to recall the sequence pressing the sensors corresponding to each finger in the correct order. Participants were explicitly indicated that there were no time constraints to respond to this task, and they had to prioritize accuracy over speed. The outcome measure for this task was the number of completely correct sequences recalled by the subject.

All tasks were performed first with the dominant hand and then with the non-dominant hand.

2) Comparison With Conventional Finger Pinch Force Evaluation: The pinch force assessment was administered once to all participants, the same day as the first evaluation with the device. All participants were instructed to sit on a chair approximately 60 cm ahead of the computer monitor.

According to the guidelines from the American Society of Hand Therapists, the participants were supposed to have a vertical positioning of the upper arm, a 90° -flex of the elbow, and neutral positions of the wrist and forearm [39]. The pinch force was placed over the device in a position that allowed the "pinch force sensor" to interact with the examined finger against the device during the full hand grip. Subjects were asked to produce as much force as possible with each finger using thumb pad to the evaluated finger pad pinch during 3 seconds separately with an analog baseline hydraulic pinch gauge (MVS in motion, Belgium) [40], in an analogous way as it was done with the device's sensors. The average of the kilograms of force of three attempts per finger was the outcome measure. This was performed first with each finger of the dominant hand, and then with the fingers of the non-dominant hand.

3) Comparison With Standardized Evaluation of Cognitive Variables: Processing speed and tapping speed evaluation was carried out through different computerized tasks controlled by Presentation® software (http://www.neurobs.com) as described elsewhere [41]. The first task was the Finger Tapping (FT), used as a measure of motor speed, providing quantitative information on slowing down of responses [42], [43], [44]. In this task, following the Strauss application norms [44], the participants were instructed to press the spacebar on the keyboard as fast as possible and repeatedly with the index finger (digit 2). Five 10-s attempts with each hand were performed. The average of response times (in milliseconds) recorded between 2 consecutive taps was the outcome measure of this first task. The second task, simple reaction time, is inspired by the SRT task of the Computerized Information Processing Testing battery [45]. This task was used as a measure of information processing speed [46]. It is the time elapsed between the presentation of a stimulus and the execution of a motor response [47]. Participants were instructed to press the left mouse button as fast as possible when the "+" stimulus appeared in the center of the screen at varying inter-stimulus times. Only the dominant hand was used for this task. The average time between the appearance of the stimulus and the motor response was the outcome measure in this task.

Immediate and working memory, as well as phonological learning, were assessed using the direct version of the digit test of the Wechsler Adult Intelligence Scale-IV (WAIS-IV) [48], [49], where the subject, after hearing a sequence of numbers from the examiner, had to memorize and immediately repeat the sequence out loud trying to avoid errors. The number of completely correct sequences was the outcome measure. Spatial and visual memory was tested through the Forward version of the Corsi Block-Tapping Test (CBT) [50], where the subject had to memorize and tap a sequence of blocks displayed on a table in the same order that the examiner had previously taped on a subset of nine blocks. The number of completely correct sequences was the outcome measure.

D. Usability Study

After both evaluations, a usability study was also carried out, asking all volunteers to answer a questionnaire where different questions were asked about the comfort and ease of use of the device. The questions were as follows: How easy (comfortable) was it for you to hold the device with your dominant hand? How easy (comfortable) was it to hold the device with your non-dominant hand? How complex was it for you to understand how the exercises work? Did the sensors on each finger seem to sensitively reflect the force you exerted (task 1)? How difficult were the tapping speed exercises (task 2) for you? How difficult were the memory exercises (task 3) for you? All questions were scored from 0 to 10, with 0 being the lowest score and 10 being the highest score. Finally, the volunteers were asked if they would recommend the use of this device to a family member with brain damage.

E. Statistical Analysis

Statistical analyses were performed using SPSS v 25.0 software (IBM Corp. Armond, NY). Specifically, the test-retest reliability of the device was analyzed to assess the stability of the measurements over time. This analysis was carried out through the Intraclass Correlation Coefficient (ICC) with a two-factor mixed model of average measures and consistency agreement. 95% confidence intervals of the ICC were obtained for measures of Tasks 1-3. ICCs were interpreted as <0.5, 0.5-0.75, 0-75-0.9 and >0.9 for poor, moderate, good, excellent reliability, respectively [51]. Additionally, limits of agreement were obtained by means of Bland-Altman plots, computing the difference between test and retest against the mean of the two measurements [52]. Standard Error of Measurement (SEM) was also obtained following the formula $\text{SEM} = \text{SD} * \sqrt{1\text{-ICC}}$ [53]. Test-retest reliability analysis was performed after removing outlier observations in which, for the same type of measurement of a specific subject, the test and retest values differed by more than 100%.

Construct validity was analyzed to assess the accuracy with which the device measures each construct in Tasks 1-3 against the standardized assessments used as gold standards. This was done through the Pearson correlation coefficient. Pearson's r was interpreted as showing negligible, weak, moderate, strong or very strong correlation for values 0.00-0.09, 0.10-0.39, 0.40-0.69, 0.70-0.89, 0.90-1.00, respectively [54]. For this analysis, alpha = 0.05 was set for statistical significance.

VI. Evaluation Results

Thirty-six participants initially enrolled in the study between February and May 2023 and completed both assessment sessions, with a mean interval of 6 ± 1.89 days between test and retest. Missing data for at least one task and session were present in 4 participants. The main results are shown in Table III.

A. Test-Retest Reliability

Reliability and SEM results for each Task and finger, are shown in Table III. In Task 1 (strength), ICC = 0.741-0.852 showed moderate to good test-retest reliability. The device was slightly more reliable with the non-dominant than the dominant hand (ICC = 0.784-0.852 vs ICC = 0.741-0.801, respectively). Accordingly, SEM was higher for the

TABLE III
RELIABILITY RESULTS OF VARIABLES MEASURED BY THE DEVICE

Variable	Device Test (day 1)		Device Retest (day 2)		ICC (95% CI)	SEM
	Mean	SD	Mean	SD		
Task 1 – Strength (kg)						
Dominant side						
Digit 2 (N=32)	4.76	1.12	3.97	1.52	0.741 (0.470-0.874)	0.570
Digit 3 (N=36)	3.13	1.19	3.13	1.25	0.801 (0.611-0.899)	0.531
Digit 4 (N=34)	2.29	1.08	2.07	1.08	0.786 (0.572-0.893)	0.500
Digit 5 (N=33)	1.37	0.76	1.24	0.67	0.784 (0.563-0.893)	0.353
Non-dominant side						
Digit 2 (N=35)	3.58	1.25	3.15	1.43	0.851 (0.704-0.925)	0.483
Digit 3 (N=35)	2.99	1.06	2.73	1.38	0.784 (0.572-0.891)	0.493
Digit 4 (N=35)	1.92	0.98	1.89	1.25	0.852 (0.707-0.925)	0.377
Digit 5 (N=32)	1.88	1.16	1.53	1.06	0.814 (0.619-0.909)	0.500
Task 2 – TS (msec), N=35						
Average of levels						
Dominant side (overall)	695.42	131.86	615.08	123.54	0.782 (0.568-0.890)	61.57
Non-dominant side (overall)	689.03	140.55	657.00	136.19	0.833 (0.668-0.916)	57.44
Easy Level						
Dominant side (overall)	679.39	170.43	627.76	128.54	0.707 (0.420-0.852)	92.253
Non-dominant side (overall)	669.59	177.55	630.50	171.21	0.684 (0.373-0.840)	99.808
Medium Level						
Dominant side (overall)	661.17	100.99	623.10	127.13	0.805 (0.610-0.903)	44.596
Non-dominant side (overall)	686.97	161.49	659.59	137.94	0.718 (0.442-0.858)	85.757
Hard Level						
Dominant side (overall)	756.36	130.00	657.22	126.53	0.696 (0.392-0.848)	71.677
Non-dominant side (overall)	725.90	175.38	686.96	130.78	0.554 (0.107-0.777)	117.124
Task 3 – Memory (number of right answers), N=36						
Score	3.83	1.34	4.53	1.23	0.774 (0.556-0.885)	0.637

Note: Different sample sizes correspond to the actual number of participants analyzed after removing observations that were statistical outliers (i.e. if the test and retest values differed by more than 100%, being considered execution or measurement errors). Abbreviations: SD, standard deviation; kg, kilograms; TS, Tapping Speed; msec, milliseconds; ICC, Intraclass Correlation Coefficient; CI, confidence interval; SEM, standard error of measurement.

dominant hand compared to the non-dominant side (SEM = 0.353-0.570 kg vs SEM = 0.377-0.500 kg, respectively).

In Task 2 (tapping speed), ICC = 0.715 – 0.90 showed moderate to good test-retest reliability. In this case, the device was also slightly more reliable with the non-dominant than the dominant hand (ICC = 0.74-0.90 vs ICC = 0.715-0.863, respectively). Accordingly, SEM was higher for the dominant hand compared to the non-dominant side (SEM = 0.059-0.090 sec vs SEM = 0.037-0.094 kg, respectively). It is also important to highlight the significant difference between levels. Specifically, this difference takes place between the medium and difficult levels on the dominant side: Mean Difference = −93.96 milliseconds 95% CI [−146.40, −41.32], t(34) = −3.63, p = 0.001.

In Task 3 (memory), ICC = 0.774 showed good test-retest reliability.

B. Construct Validity

Correlation analysis between each Task and conventional evaluation of finger pinch force and cognitive variables are shown in Table IV and Table V.

In Task 1 (strength), the device showed moderate to strong correlations with its pinch force counterparts (ρ = 0.563-0.781, all $p < 0.001$). Comparable correlations between the device and pinch force were found across fingers in each hand, and in finger pairs (i.e., index-index) across hands.

In Task 2 (ttaping speed), correlations with computerized finger tapping were higher as the difficulty of the exercise increased (ρ = 0.383-0.702, all $p < 0.05$). Comparable correlations were found between the device and simple reaction time task, higher correlations were seen comparing the hardest level of the device and also comparing the average value of all the 3 difficulty levels for both hands with the computerized task.

TABLE IV
CORRELATION RESULTS OF THE FORCE MEASURED BY THE DEVICE AND THE PINCH GAUGE

Device	Pinch gauge	
	Pearson's r	P-value
Dominant side		
Digit 2	0.766	< 0.001
Digit 3	0.597	< 0.001
Digit 4	0.563	0.001
Digit 5	0.671	< 0.001
Non-dominant side		
Digit 2	0.781	< 0.001
Digit 3	0.648	< 0.001
Digit 4	0.744	< 0.001
Digit 5	0.756	< 0.001

In Task 3 (memory), the device showed moderate correlations with the direct version of the Digit test from WAIS-IV (ρ = 0.637, $p < 0.001$). To calculate this correlation, since the memory exercise of the device has 3 levels of difficulty with memorization of sequences of 3, 5 and 7 digits, we used a subscore of the Digits test, comprising only the sequences of 3, 5 and 7 digits among all those in the test. On the other hand, the Task 3 of the device showed a weak correlation with

TABLE V
CORRELATION RESULTS OF THE REACTION TIME MEASURED BY THE DEVICE AND COMPUTERIZED TAPPING SPEED AND DEVICE TASKS

Variable	Tapping		Simple reaction time	
	Pearson's r	P-value	Pearson's r	P-value
Average of levels				
Dominant side*	0.592	< 0.001	0.373	0.025
Non-dominant side*	0.649	< 0.001	-	-
Easy level				
Dominant side*	0.383	0.021	0.138	0.422
Non-dominant side*	0.444	0.007	-	-
Medium level				
Dominant side*	0.447	0.006	0.334	0.006
Non-dominant side*	0.426	0.010	-	-
Hard level				
Dominant side*	0.592	< 0.001	0.422	< 0.001
Non-dominant side*	0.702	< 0.001	-	-

* Overall value calculated as the mean of the values of all fingers of each side.

the forward version of the CBT, which was not statistically significant ($\rho = 0.236$, $p = 0.116$).

C. Usability Test With Healthy Subjects

A usability test was carried out through a questionnaire on the healthy volunteers who participated in the validation study, with the aim of knowing how complex the use of the device had been for them and whether they found it responsive to its interaction. Through different questions, we saw that 90.9% of the volunteers found the device easy or very easy to grab while using it with their dominant hand. While with the non-dominant hand the percentage decreased to 54.5%, with 4.5% of them finding it difficult to grasp. Regarding understanding the functioning of the device, 95.4% found it easy or very easy to understand how the device and its exercises work. About the difficulty on the performance of the exercises, 31.8% of the users did not find the reaction speed exercises (task 2) difficult at all, while the remaining 68.2% found them easy. With respect to the memory exercises (task 3), 9.1% found them quite difficult, 72.7% found them somewhat difficult, and the remaining 9.1% found them easy. Furthermore, all participants thought that the device was reasonably accurate with respect to the force they were doing. Finally, 81.8% stated with certainty that they would recommend the use of this device to a family member with stroke, and no volunteer rejected it.

VII. DISCUSSION

An extensive review of the literature on current technological devices for diagnosing and treating hand and cognitive functions reveals that almost none of them are designed to simultaneously train both skills. This finding underscores the importance of developing and utilizing a device that integrates both dimensions [26], [31], [33], [34], [37]. Moreover, the majority of existing devices lack the capability for continuous data recording and storage, crucial for monitoring user progress and status. Often, these devices are often large, heavy, expensive, and difficult to use, restricting their accessibility to many patients. This issue is particularly relevant among stroke patients, who frequently cannot resume daily activities and become reliant on caregivers. Furthermore, in rural areas or during difficult health situations, such as the recent Covid-19 pandemic, accessing a hospital for rehabilitation sessions can be a significant challenge.

Among the few devices that do explicitly target both domains are HandyKnob and HandyBot, which combine neurocognitive therapy with training and evaluation of motor and sensory functions [24], [37]. However, their use is limited due to their non-portability and the need for specialized supervision. In contrast, AMBER stands out for its portability and ease of use, allowing both the evaluation and rehabilitation of motor and cognitive functions with the use of pre-programmed tasks. This feature makes AMBER particularly advantageous for integration into diverse therapeutic environments and could be especially beneficial for home rehabilitation programs, expanding access to comprehensive therapy for patients with mobility restrictions or limited access to specialized centers.

Therefore, this paper aims to introduce the development of a novel device designed for assessing and training fingers motor functions and cognitive features in a portable, easy and gamifying procedure, and validating the precision and reliability of the evaluation mode of such a device.

Targeted at individuals with neurological impairments, particularly stroke, the device underwent a comprehensive evaluation process in line with the specified requirements, taking into consideration its intended application, human factors as handedness, and potential future clinical use.

The device demonstrates technical capabilities that allow the desired assessments to be performed with minimal measurement error. Furthermore, the precision of its EM was thoroughly assessed. It can measure the precise force performed with each finger and is able to provide an assessment of several cognitive functions that could be used to evaluate processing speed, attention and memory. Test-retest reliability for the three measurements (strength, reaction time and memory) shows moderate to good results The results of this preliminary study conducted with healthy subjects are presented and discussed in the following subsections.

A. Strength

Strength measures show moderate to good reliability, comparable to the available gold standard (i.e. pinch force) [55]. In our study, the digit 2 (index) of the dominant hand was the finger with lower reliability values. The reason behind this lower reliability is likely attributed to the notably higher strength values recorded for the dominant hand's digit 2 on the first day compared to the second day. This discrepancy is possibly due to the testing protocol, where all evaluations began with the digit 2 first, followed sequentially by the other fingers, without providing the option of a first familiarization trial. The subjects, when confronted with this new device, might have felt uncomfortable during their initial grip of the device with their digit 2. This discomfort may have been the reason they did not exert force in the same way on both days. However, as they progressed to the second day, familiarity with the grip of the device and the specific way they needed to press each finger may have led to more consistent strength measurements for the digit 2.

Regarding the correlation between fingers strength measured by the device and its "gold standard", the pinch gauge, there is a moderate to good correlation.

B. Processing Speed (Tapping Speed)

In terms of the reliability of reaction times, there is a moderate to good correlation between the test and retest results. To calculate this correlation, the reaction times of each finger at each difficulty level were averaged.

Reaction time is a measure of how quickly the brain processes information and responds to it. It includes the time it takes to detect a stimulus and the time it takes to produce a motor response. In between, there are complex cognitive processes that happen in a graded manner.

The simplest task is the finger tapping task, where no cognitive processing is involved. This task allows us to directly evaluate motor skills, the reliability on the execution of this task rules out the influence of motor components in cognitive processing. The second task of our device, although it is the simpler reaction time, is a more complex task, participants need to detect a stimulus and respond to it while sensory and motor components interact. Additionally, the response is done with just one finger while inhibiting the rest, thus not only attention but also inhibitory control is expected to be involved.

For the analysis of the results of the assessment with the device, the finger that executed the response is not differentiated. This is because the different motor control capabilities of each finger cannot be controlled, as they largely depend on individual differences between participants.

Among the three levels of difficulty, the medium level demonstrates the highest reliability (ICC $= 0.805$ with the dominant hand and ICC $= 0.718$ with the non-dominant hand). While one might assume that the reliability would decrease as the level of difficulty increases, in this case, the easiest level actually exhibits lower reliability than the medium level. This could be attributed to the fact that subjects didn't undergo any training trial, and the easy level helps them understand the exercise dynamics better.

Regarding the hardest level, the lower reliability could be due to a greater increase in difficulty than intended, leading subjects to face a more challenging task compared to the transition from the first level to the second. Furthermore, at all difficulty levels, a decrease in reaction time is observed during the retest compared to the initial test. This suggests that subjects become more familiar with the exercises during the first assessment.

Regarding the correlation with the computerized evaluation of reaction times, it is worth specifying the two reaction time constructs used: Tapping, which is a simple motor task with no cognitive processing involved, and simple reaction time, a more complex cognitive task involving sensory and motor elements. It was only evaluated the simple reaction time construct using the dominant hand, as assessing the non-dominant hand could introduce unexpected motor variables due to the ease of using the computer mouse.

Overall, a significant positive correlations between the device's measurements and both tapping and simple reaction times is observed. On the dominant side, the device's measurements show a moderately strong correlation with tapping (Pearson's r range: 0.383 to 0.592) and a relatively weaker correlation with simple reaction time (Pearson's r range: 0.138 to 0.422). These correlations are statistically significant for all difficulty levels.

On the non-dominant side, it is also observed significant positive correlations between the device's measurements and tapping (Pearson's r range: 0.426 to 0.702).

Regarding the different levels of difficulty, the correlations remain consistent with the overall trend. At the easy level, the device's measurements exhibit a moderate correlation with tapping on both dominant and non-dominant sides. However, for the simple reaction time task, the correlations are weaker and non-significant, which suggests that the device's measurements might be more reflective of simple motor tasks rather than cognitive tasks involving perception at this level.

Moving to the medium level, the correlations between the device's measurements and tapping are moderate and statistically significant on both dominant and non-dominant sides. The same occurs for the simple reaction time task. The strength of the correlations increases compared to the easy level, indicating that the device's measurements captured variations in both simple motor tasks and simple reaction time tasks more effectively at this level.

At the hard level, the correlations between the device's measurements and tapping on both sides are strong and statistically significant. The correlation with the simple reaction time task are also better than at the moderate level.

In summary, the results suggest that our device's capability to measure reaction times is positively correlated with both tapping (simple motor task) and simple reaction time (more complex cognitive task) across different difficulty levels. The device appears to be more sensitive to simple motor tasks' reaction time overall and shows stronger correlations compared to tasks requiring cognitive involvement as perception, especially at easier levels. These findings may reflect that the response to easiest levels is done in an automatic manner, similarly to the tapping paradigm in computerized evaluation, as the cadence of appearance of the stimulus is constant, so the activation of complex cognitive processes is not needed. The poorer correlation might be justified by the fact that the stimulus presentation in the computerized simple reaction task is variable, whereas in our device, it is done at a regular frequency, just varying the location of the stimuli.

C. Memory

Finally, evaluating memory exercise shows good reliability and demonstrates a strong positive correlation when compared to conventional evaluations as a subscore of the direct version of the Digit test from WAIS-IV, despite the auditive learning paradigm used in that test. Our device utilizes different stimulus locations that need to be memorized, leading us to also employ the forward version of the Corsi Block-Tapping Test (CBT) for comparison. However, the correlation with CBT was not statistically significant ($\rho = 0.236$, p $= 0.116$). This lack of significance may be attributed to the fact that fingers are often associated with numerical symbols, and their memorization

might be following the phonologic learning pathway, similar to the digits test, rather than the CBT [56].

D. Limitations and Future Development

During the evaluations, several limitations of the device were identified. First, the device's operation has a drawback in terms of battery capacity. The limited battery charge may restrict its extensive use, often necessitating connection to a power source for prolonged usage. This could be addressed by incorporating higher capacity batteries to enhance its usability. Another limitation is the absence of a specific sensor for the thumb (digit 1). Since many daily activities heavily rely on the use of this finger, its exclusion may limit the device's full potential in interactions with users. Moreover, the fact that the patient must hold the device could be a challenge, particularly for those with impairments or limited abduction capabilities. Survey feedback from healthy subjects highlights this issue; specifically, 46% of participants reported difficulties in gripping and using the device effectively with their non-dominant hand, which they described as their less skilled hand. This may be because of the high demand for motor and cognitive control required to operate the cylinder with a flexed wrist to see the LED indicators. To address this, the design of a wrist strap or a table support will be considered, allowing the device to be used while supported. Future changes in light positions, so they can be seen without flexing the wrist, may also help reduce the difficulty. However, it should always be noted that this device is intended as a complementary tool to other techniques and devices, and may not be appropriate for all users. Regarding the tasks, Task 2 has a potential for improvement making it more close to computerized finger tapping test by incorporating a simple motor task, such as repeatedly pressing one sensor as fast as possible. Additionally, introducing more variability in the sequences of the LED signals during the evaluation of reaction times may enable a more complex assessment and yield a stronger correlation with computerized tasks. Task 3 could be enhanced by including more sequence levels to make it more similar to the Direct Digits task. Even the possibility of programming an inverse sequence, after the inverse digits test in WAIS-IV evaluation, could facilitate a more comprehensive evaluation of memory function. Regarding the assessment procedure, the lack of a counterbalanced order for the first finger to be tested is a limitation, as a random assignment to finger order would have been desirable. Finally, a calibration of the tasks according to each subject's abilities would be very useful to be used more easily and widely by different profiles of patients.

Addressing these limitations would lead to an improved and more versatile device, broadening its potential applications and increasing its overall utility in various clinical and research settings. Since this article and study is a proof of concept and validation with healthy subjects, subsequent studies such as a clinical trial to test the effectiveness of the TM, in stroke populations, are needed in the future. This will serve to validate its usefulness as a therapeutic tool.

VIII. Conclusion

The uniqueness of this device lies in its ergonomic design, adaptability, robustness, and reliability as a comprehensive tool for measuring force, memory, attention and coordination. AMBER holds great promise as a valuable tool for therapists, enabling them to conduct reliable evaluations and potentially address motor and cognitive variables in patients using a single, portable, and cost-effective device. It has the potential to offer flexible programming and establish stronger correlations with more complex cognitive evaluations. In comparison to other hand rehabilitation devices, AMBER goes beyond them by incorporating cognitive rehabilitation tasks, a feature absent in existing devices.

Acknowledgment

The authors would like to thank María Teresa Boccanera, Jesús Rodríguez Herranz, and Guillermo Catalán Sarrié for their advice during the completion of this study.

References

[1] V. L. Feigin et al., "Global, regional, and national burden of stroke and its risk factors, 1990–2019: A systematic analysis for the global burden of disease study 2019," *Lancet Neurol.*, vol. 20, no. 10, pp. 795–820, Oct. 2021.

[2] S. C. Cramer et al., "A functional MRI study of subjects recovered from hemiparetic stroke," *Stroke*, vol. 28, no. 12, pp. 2518–2527, Dec. 1997.

[3] V. M. Parker, D. T. Wade, and R. L. Hewer, "Loss of arm function after stroke: Measurement, frequency, and recovery," *Int. Rehabil. Med.*, vol. 8, no. 2, pp. 69–73, Jan. 1986.

[4] H. Eschmann, M. E. Héroux, J. H. Cheetham, S. Potts, and J. Diong, "Thumb and finger movement is reduced after stroke: An observational study," *PLoS ONE*, vol. 14, no. 6, Jun. 2019, Art. no. e0217969, doi: 10.1371/journal.pone.0217969.

[5] J. Plantin et al., "Quantitative assessment of hand spasticity after stroke: Imaging correlates and impact on motor recovery," *Frontiers Neurol.*, vol. 10, p. 836, Aug. 2019, doi: 10.3389/fneur.2019.00836.

[6] F. Farokhi-Sisakht, M. Farhoudi, S. Sadigh-Eteghad, J. Mahmoudi, and G. Mohaddes, "Cognitive rehabilitation improves ischemic stroke-induced cognitive impairment: Role of growth factors," *J. Stroke Cerebrovascular Diseases*, vol. 28, no. 10, Oct. 2019, Art. no. 104299, doi: 10.1016/j.jstrokecerebrovasdis.2019.07.015.

[7] M. Lesniak, T. Bak, W. Czepiel, J. Seniów, and A. Członkowska, "Frequency and prognostic value of cognitive disorders in stroke patients," *Dementia Geriatric Cognit. Disorders*, vol. 26, no. 4, pp. 356–363, 2008, doi: 10.1159/000162262.

[8] G. M. S. Nys, M. J. E. van Zandvoort, P. L. M. de Kort, B. P. W. Jansen, E. H. F. de Haan, and L. J. Kappelle, "Cognitive disorders in acute stroke: Prevalence and clinical determinants," *Cerebrovascular Diseases*, vol. 23, nos. 5–6, pp. 408–416, 2007, doi: 10.1159/000101464.

[9] M. S. Einstad et al., "Associations between post-stroke motor and cognitive function: A cross-sectional study," *BMC Geriatrics*, vol. 21, no. 1, p. 103, Feb. 2021, doi: 10.1186/s12877-021-02055-7.

[10] J. H. Kang, Y. H. Kim, and Y.-A. Choi, "Montreal cognitive assessment and frontal assessment battery test as a predictor of performance of unaffected hand function after subcortical stroke," *Int. J. Rehabil. Res.*, vol. 44, no. 1, pp. 45–50, Mar. 2021, doi: 10.1097/mrr.0000000000000445.

[11] E. Low, S. G. Crewther, B. Ong, D. Perre, and T. Wijeratne, "Compromised motor dexterity confounds processing speed task outcomes in stroke patients," *Frontiers Neurol.*, vol. 8, p. 484, Sep. 2017, doi: 10.3389/fneur.2017.00484.

[12] S. S. Rycroft, L. T. Quach, R. E. Ward, M. M. Pedersen, L. Grande, and J. F. Bean, "The relationship between cognitive impairment and upper extremity function in older primary care patients," *J. Gerontology, Ser. A*, vol. 74, no. 4, pp. 568–574, Mar. 2019, doi: 10.1093/gerona/gly246.

[13] A. Sunderland, M. P. Bowers, S.-M. Sluman, D. J. Wilcock, and M. E. Ardron, "Impaired dexterity of the ipsilateral hand after stroke and the relationship to cognitive deficit," *Stroke*, vol. 30, no. 5, pp. 949–955, May 1999.

[14] I. F. Uwa-Agbonikhena, V. A. Gryb, and V. R. Gerasymchuk, "Associations between the upper extremity function and cognition in post-stroke patients," *Wiadomosci Lekarskie*, vol. 74, no. 8, pp. 1917–1920, 2021.

[15] D. G. Taekema, J. Gussekloo, A. B. Maier, R. G. J. Westendorp, and A. J. M. de Craen, "Handgrip strength as a predictor of functional, psychological and social health. A prospective population-based study among the oldest old," *Age Ageing*, vol. 39, no. 3, pp. 331–337, May 2010, doi: 10.1093/ageing/afq022.

[16] A. Alfaro-Acha, S. A. Snih, M. A. Raji, Y.-F. Kuo, K. S. Markides, and K. J. Ottenbacher, "Handgrip strength and cognitive decline in older Mexican Americans," *J. Gerontology Ser. A, Biol. Sci. Med. Sci.*, vol. 61, no. 8, pp. 859–865, Aug. 2006, doi: 10.1093/gerona/61.8.859.

[17] J. Lingo VanGilder, A. Hooyman, D. S. Peterson, and S. Y. Schaefer, "Post-stroke cognitive impairments and responsiveness to motor rehabilitation: A review," *Current Phys. Med. Rehabil. Rep.*, vol. 8, no. 4, pp. 461–468, Dec. 2020, doi: 10.1007/s40141-020-00283-3.

[18] K. D. Cicerone et al., "Evidence-based cognitive rehabilitation: Systematic review of the literature from 2009 through 2014," *Arch. Phys. Med. Rehabil.*, vol. 100, no. 8, pp. 1515–1533, Aug. 2019, doi: 10.1016/j.apmr.2019.02.011.

[19] C. J. Winstein et al., "Guidelines for adult stroke rehabilitation and recovery | stroke," *Stroke*, vol. 47, pp. e98–e169, Sep. 2016.

[20] Y. Yamada et al., "The impact of isometric handgrip exercise and training on health-related factors: A review," *Clin. Physiol. Funct. Imag.*, vol. 42, no. 2, pp. 57–87, Mar. 2022, doi: 10.1111/cpf.12741.

[21] J.-G. Yang et al., "Virtual reality and exercise training enhance brain, cognitive, and physical health in older adults with mild cognitive impairment," *Int. J. Environ. Res. Public Health*, vol. 19, no. 20, p. 13300, Oct. 2022, doi: 10.3390/ijerph192013300.

[22] S.-H. Lin, T.-R. Yang, I.-C. Chuang, C.-L. Chen, and C.-Y. Wu, "Upper extremity motor abilities and cognitive capability mediate the causal dependency between somatosensory capability and daily function in stroke individuals," *Sci. Rep.*, vol. 12, no. 1, pp. 1–19, Jan. 2022, doi: 10.1038/s41598-021-04491-2.

[23] C. E. Skilbeck, D. T. Wade, R. L. Hewer, and V. A. Wood, "Recovery after stroke," *J. Neurol. Neurosurg. Psychiatry*, vol. 46, no. 1, pp. 5–8, Sep. 1983.

[24] J. Xu et al., "Separable systems for recovery of finger strength and control after stroke," *J. Neurophysiology*, vol. 118, no. 2, pp. 1151–1163, Aug. 2017, doi: 10.1152/jn.00123.2017.

[25] S. Lee et al., "Autonomous multi-joint soft exosuit with augmentation-power-based control parameter tuning reduces energy cost of loaded walking," *J. NeuroEng. Rehabil.*, vol. 15, no. 1, p. 66, Jul. 2018, doi: 10.1186/s12984-018-0410-y.

[26] R. Kabir, M. Sunny, H. Ahmed, and M. Rahman, "Hand rehabilitation devices: A comprehensive systematic review," *Micromachines*, vol. 13, no. 7, p. 1033, Jun. 2022, doi: 10.3390/mi13071033.

[27] *SaeboStretch Dynamic Resting Hand Splint*. Accessed: Aug. 2, 2023. [Online]. Available: https://www.saebo.com/shop/saebostretch/

[28] *SaeboFlex | Dynamic Hand Splint | Grasping & Neurorehabilitation*. Accessed: Aug. 2, 2023. [Online]. Available: https://www.saebo.com/shop/saeboflex/

[29] (2023). *SCRIPT Passive Orthosis: Design of Interactive Hand and Wrist Exoskeleton for Rehabilitation At Home After Stroke | SpringerLink*. Accessed: Aug. 2, 2023. [Online]. Available: https://link.springer.com/article/10.1007/s10514-016-9589-6

[30] H. C. Fischer et al., "Use of a portable assistive glove to facilitate rehabilitation in stroke survivors with severe hand impairment," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 24, no. 3, pp. 344–351, Mar. 2016.

[31] M. Sandison et al., "HandMATE: Wearable robotic hand exoskeleton and integrated Android app for at home stroke rehabilitation," in *Proc. 42nd Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. (EMBC)*, Jul. 2020, pp. 4867–4872, doi: 10.1109/EMBC44109.2020.9175332.

[32] D. Wang, Q. Meng, Q. Meng, X. Li, and H. Yu, "Design and development of a portable exoskeleton for hand rehabilitation," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 26, no. 12, pp. 2376–2386, Dec. 2018, doi: 10.1109/TNSRE.2018.2878778.

[33] *AMADEO: The Pioneer in Finger-Hand-Rehabilitation | Tyrotherapy*. Accessed: Aug. 2, 2023. [Online]. Available: https://tyromotion.com/en/products/amadeo/

[34] L. Dovat et al., "HandCARE: A cable-actuated rehabilitation system to train hand function after stroke," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 16, no. 6, pp. 582–591, Dec. 2008, doi: 10.1109/TNSRE.2008.2010347.

[35] S. Hesse, H. Kuhlmann, J. Wilk, C. Tomelleri, and S. G. Kirker, "A new electromechanical trainer for sensorimotor rehabilitation of paralysed fingers: A case series in chronic and acute stroke patients," *J. NeuroEngineering Rehabil.*, vol. 5, no. 1, p. 21, Sep. 2008, doi: 10.1186/1743-0003-5-21.

[36] L. Valenzuela-López, M. Moreno-Verdu, J. N. Cuenca-Zaldívar, and J. P. Romero, "Effects of hand motor interventions on cognitive outcomes post-stroke: A systematic review and Bayesian network meta-analysis," *Arch. Phys. Med. Rehabil.*, vol. 1, no. 1, pp. 1–23, Jan. 2024, doi: 10.1016/j.apmr.2023.12.013.

[37] J.-C. Metzger, O. Lambercy, D. Chapuis, and R. Gassert, "Design and characterization of the ReHapticKnob, a robot for assessment and therapy of hand function," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Sep. 2011, pp. 3074–3080, doi: 10.1109/IROS.2011.6094882.

[38] J. Kottner et al., "Guidelines for reporting reliability and agreement studies (GRRAS) were proposed," *Int. J. Nursing Stud.*, vol. 48, no. 6, pp. 661–671, Jun. 2011, doi: 10.1016/j.ijnurstu.2011.01.016.

[39] L. Li, Y. Li, P. Jia, S. Wang, W. Wang, and Y. Liu, "Effect of pinch types on pinch force sense in healthy adults," *Frontiers Human Neurosci.*, vol. 16, Oct. 2022, Art. no. 990431, doi: 10.3389/fnhum.2022.990431.

[40] M. S. V. Mathiowetz, B. S. K. Weber, B. S. G. Volland, and B. S. N. Kashman, "Reliability and validity of grip and pinch strength evaluations," *J. Hand Surg.*, vol. 9, no. 2, pp. 222–226, Mar. 1984.

[41] A. Arroyo-Ferrer et al., "Computerized simple reaction time and balance in nondemented Parkinson's patients," *Neurodegenerative Diseases*, vol. 20, nos. 5–6, pp. 193–199, 2020, doi: 10.1159/000517437.

[42] R. M. Reitan and D. Wolfson, "Relationships between specific and general tests of cerebral functioning," *Clin. Neuropsychologist*, vol. 10, no. 1, pp. 37–42, Jan. 1996, doi: 10.1080/13854049608406661.

[43] R. Rausch, "A compendium of neuropsychological tests: Administration, norms, and commentary," *Electroencephalogr. Clin. Neurophysiology*, vol. 90, no. 3, p. 251, Mar. 1994.

[44] H. M. Bronte-Stewart, L. Ding, C. Alexander, Y. Zhou, and G. P. Moore, "Quantitative digitography (QDG): A sensitive measure of digital motor control in idiopathic Parkinson's disease," *Mov. Disord.*, vol. 15, no. 1, pp. 36–47, 2000.

[45] L. Reicker, T. Tombaugh, L. Walker, and M. Freedman, "Reaction time: An alternative method for assessing the effects of multiple sclerosis on information processing speed," *Arch. Clin. Neuropsychology*, vol. 22, no. 5, pp. 655–664, Jun. 2007, doi: 10.1016/j.acn.2007.04.008.

[46] J. DeLuca and Y. J. H. Kalmar, *Information Processing Speed in Clinical Populations*. London, U.K.: Psychology Press, 2013.

[47] S. L. Costa, H. M. Genova, J. DeLuca, and N. D. Chiaravalloti, "Information processing speed in multiple sclerosis: Past, present, and future," *Multiple Sclerosis J.*, vol. 23, no. 6, pp. 772–789, May 2017, doi: 10.1177/1352458516645869.

[48] L. Strober et al., "Symbol digit modalities test: A valid clinical trial endpoint for measuring cognition in multiple sclerosis," *Multiple Sclerosis J.*, vol. 25, no. 13, pp. 1781–1790, Nov. 2019, doi: 10.1177/1352458518808204.

[49] J. A. Holdnack, "The development, expansion, and future of the WAIS-IV as a cornerstone in comprehensive cognitive assessments," in *Handbook of Psychological Assessment*. New York, NY, USA: Academic, 2019, pp. 103–139.

[50] T. Arce and K. Mcmullen, "The corsi block-tapping test: Evaluating methodological practices with an eye towards modern digital frameworks," *Comput. Human Behav. Rep.*, vol. 4, Aug. 2021, Art. no. 100099, doi: 10.1016/j.chbr.2021.100099.

[51] O. Gerke, "Reporting standards for a bland–altman agreement analysis: A review of methodological reviews," *Diagnostics*, vol. 10, no. 5, p. 334, May 2020, doi: 10.3390/diagnostics10050334.

[52] A. Kalra, "Decoding the bland–altman plot: Basic review," *J. Pract. Cardiovascular Sci.*, vol. 3, no. 1, p. 36, 2017.

[53] L. Furlan and A. Sterr, "The applicability of standard error of measurement and minimal detectable change to motor learning research—A behavioral study," *Frontiers Human Neurosci.*, vol. 12, p. 95, Mar. 2018, doi: 10.3389/fnhum.2018.00095.

[54] P. Schober, C. Boer, and L. A. Schwarte, "Correlation coefficients: Appropriate use and interpretation," *Anesth. Analg.*, vol. 126, pp. 1763–1768, May 2018.

[55] L. Li, Y. Li, C. Wu, and X. Zhang, "Test–retest reliability of tip, key, and palmar pinch force sense in healthy adults," *BMC Musculoskeletal Disorders*, vol. 21, no. 1, p. 189, Mar. 2020, doi: 10.1186/s12891-020-3187-7.

[56] S. Di Luca and M. Pesenti, "Finger numeral representations: More than just another symbolic code," *Frontiers Psychol.*, vol. 2, pp. 1–18, Nov. 2011. [Online]. Available: https://www.frontiersin.org/research-topics/262/handy-numbers-finger-counting-and-numerical-cognition/articles